HYDROGEOLOGY AND PRELIMINARY SIMULATION OF GROUND-WATER FLOW IN THE LOWER ANIMAS AND LORDSBURG BASINS GRANT AND HIDALGO COUNTIES, NEW MEXICO

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SUMMARY

As part of a regional water planning investigation of southwestern New Mexico, the Interstate Stream Commission requested that Hydrology Bureau evaluate ground-water supplies in the Animas and Lordsburg areas. The study area is located in Grant and Hidalgo Counties, New Mexico, and includes the Lower Animas and Lordsburg Basins, and parts of the Virden-Duncan and Redrock sub-basins of the Gila River Basin. The climate is arid to semiarid, and potential evaporation greatly exceeds average annual precipitation of less than 12 inches. Water is or has been used in the study area for agricultural, municipal, domestic, commercial, industrial, mining, power generation and livestock watering purposes. Ground water supplies all water use in the Lower Animas and Lordsburg Basins, and the greatest single water use is for irrigated agriculture. The only significant municipal use is at Lordsburg. The Gila River is the only major surface water feature in the study area, and is the regional discharge for ground-water flow.

Gila Group and younger (post-Gila) basin-fill deposits form the only important aquifers in the area. Although total thickness of the basin-fill may exceed 2,000 feet in the study area, only the uppermost 600 to 700 feet, generally consisting of Upper Gila and (locally) post-Gila units, is considered productive. The older basin-fill below this depth generally consists of Middle and Lower Gila units of relatively low permeability. Hydraulic conductivity values reported for the Upper Gila and post-Gila units range from less than 3 to 100 feet per day. Storage coefficient values ranging from 0.06 to 0.14 have been estimated for the basin-fill aquifer. Mountain-front recharge to the aquifer in the study area is estimated at 13,000 acre-feet per year, and occurs along the Peloncillo, Pyramid, Big Burro, South Burro, and Cedar Mountain Ranges. An estimated 4,600 acre-feet per year also enters the study area as underflow from the Upper Animas sub-basin. Evapotranspiration losses from the aquifer are minor; under pre-development conditions essentially all ground-water discharge occurred to the Gila River.

A one-layer model simulating ground-water flow in the upper basin-fill aquifer in the study area was developed using MODFLOW. The model was calibrated to regional steady-state conditions using estimated flows and synoptic pre-development water-level data. The Gila River was simulated as a constant-head boundary; all other boundaries were simulated as no-flow boundaries. Hydrostratigraphic units were used to delineate initial hydraulic conductivity zones, which were adjusted during calibration. Hydraulic conductivity values at calibration ranged from 0.12 to 50 feet per day, and are generally within published ranges for the hydrostratigraphic units simulated. For the model area as a whole, inflow of 12,950 acre-feet per year from mountain-front recharge, underflow of 4,600 acre-feet per year from the Upper Animas sub-basin, and inflow of 580 acre-feet per year from the Gila River were simulated. Simulated outflows consisted of discharges of 4,240 acre-feet per year to the Gila River between gages near Redrock and below Blue Creek, and 13,890 acre-feet per year to the river between the Blue Creek gage and the Arizona-New Mexico state line. Simulated heads and flows reasonably match measured or estimated values. Limited transient testing of the model using estimated ground-water withdrawals for irrigation, municipal and industrial uses for the period 1920 to 2000, and a single storage coefficient of 0.1, was reasonably successful at replicating observed water-level changes in the Lower Animas and Lordsburg Basins.

INTRODUCTION

Purpose and scope

As part of a water supply and demand investigation related to regional planning in southwestern New Mexico, the Interstate Stream Commission (ISC) requested that Hydrology Bureau evaluate existing ground-water supplies and estimate the hydrologic effects of attempting to meet projected future demands through continued ground-water pumping in selected task areas. Two of the five task areas identified by ISC for that investigation were situated in the Lordsburg and Animas Valleys in Hidalgo County. Specific tasks included evaluating the ability of existing ground-water supplies to meet municipal, agricultural and power generation demands for 40 years in the Lordsburg and Animas Basins (Johnson and others, 2002).

To accomplish these tasks a numerical ground-water flow model of the Lower Animas and Lordsburg Basins was developed to calculate water-level declines due to historical and projected pumping. Due to time constraints imposed by the ISC regional planning project, the model was developed in a compressed timeframe of a few weeks using existing information. The purpose of this report is to document the development of this preliminary Lower Animas-Lordsburg model.

Previous studies

Earlier investigations include Schwennesen (1918) and Reeder (1957), who defined the hydrogeology of the Lower Animas Basin. Turner (1960) and Turner and Manera (1965) studied parts of the Lordsburg Basin. Trauger (1972) briefly discusses that part of the study area located in Grant County, while Stone and O’Brien (1990) and Lazarus and Morgan (1989) provide overviews of the hydrology of Hidalgo County. Hawley and others (2000) integrated previous studies and data to redefine the regional hydrogeologic framework and present a conceptual model of ground-water flow.

O’Brien and Stone (1981; 1982a; 1982b) compiled basic water-level, water chemistry, and drill hole data for the Lower Animas Basin, in support of development of a two-dimensional numerical ground-water flow model simulating the basin hydrologic system (O’Brien and Stone, 1983). Hawkins (1981) also developed a model of the Lower Animas Basin. West (1961) developed an analytical model of the Lordsburg Valley Underground Water Basin, for use in water rights evaluations.

Location and physiographic setting

The study area includes the Lower Animas and Lordsburg Basins, which are located in Grant, Hidalgo and Luna Counties, New Mexico (plate 1). They are part of the larger Animas Basin, a topographically closed, internally drained surface water basin. (Throughout this report, the Lower Animas and Lordsburg sub-basins of the Animas Basin, from Hawley and others (2000), will be referred to as the Lower Animas and Lordsburg Basins, respectively.) The study area also includes those parts of the Virden-Duncan and Redrock sub-basins of the Gila River Basin that are located south of the Gila River in New Mexico. The Lower Animas and Lordsburg Basins are intermontane basins bounded by narrow mountain ranges that include the Peloncillo and Pyramid Mountains. Broad piedmont slopes extend out from the mountain fronts, grading into relatively flat basin floor areas that include narrow alluvial flats, broad bolson plains, and playas.

The Lower Animas Basin is 888 square miles in area. The northern boundary is a relatively low topographic divide between the Animas and Gila River Basins. The western boundary runs along the Peloncillo Mountains, forming the divide between the Animas and San Simon Basins. The eastern boundary extends southwest from Burro Peak to the north end of the Pyramid Mountains, forming part of the divide between the Lower Animas and Lordsburg Basins. This divide runs south along the Pyramid Mountains to intersect the Continental Divide at South Pyramid Peak. The Continental Divide extends south into the Northern Animas Mountains, forming the divide between the Lower Animas and Playas Basins. The southern boundary with the Upper Animas sub-basin reflects a change in average slope. Some streams have perennial reaches in the Upper Animas sub-basin, but all are ephemeral in the Lower Animas Basin. Elevation in the Lower Animas Basin ranges from 8,035 feet at Burro Peak to about 4,143 feet at the South Alkali Flat, one of several playas in the north central part of the basin.

The Lordsburg Basin is 938 square miles in area. The southern, eastern and northeastern boundaries of the basin are the Continental Divide, which forms a common watershed boundary with (from west to east) the Playas, Hachita and Mimbres Basins. The remaining boundary with the Lower Animas Basin was described above. Lordsburg Draw and its tributaries are ephemeral streams that occasionally drain to the playas in the Lower Animas Basin. Elevation in the Lordsburg Basin ranges from almost 7,300 feet south of Burro Peak to about 4,180 feet where Lordsburg Draw exits the basin.

Parts of the divides between the Lower Animas and Lordsburg Basins and adjacent basins cross broad, topographic and structural saddles or "gaps" between ranges. These include the "Animas-Pyramid Gap" between the Northern Animas and Pyramid Mountains, and the "Brockman-Pyramid Gap" between the Pyramid Mountains and Brockman Hills (plate 1). These are situated along the Continental Divide separating the Playas Basin from the Lower Animas and Lordsburg Basins, respectively. Another broad saddle on the Continental Divide between the Coyote Hills and the northern end of the Cedar Mountain Range forms part of the divide between the Lordsburg and Hachita Basins. These gaps may be important hydrogeologic features (Hawley and others, 2000).

The Virden-Duncan and Redrock sub-basins of the Gila River Basin are separated from the Animas Basin by a topographic divide that extends from Burro Peak generally west-southwest across Lordsburg Mesa and the Summit Hills to the Peloncillo Mountains. The lowest point on this divide near Summit (4,239 feet) is less than 100 feet higher than the lowest points in the Lower Animas (4,143 feet) and Lordsburg (about 4,180 feet) Basins. Although this divide closes the Animas Basin to surface-water outflow, ground-water underflow from south to north occurs beneath it to drain the Animas Basin system (Schwennesen, 1918; Reeder, 1957; O'Brien and Stone, 1983; Hawley and others, 2000).

Climate

Temperature and precipitation data from 10 climate stations in and around the study area (plate 2) are summarized in table 1. The climate of the study area is arid to semiarid. Mean minimum temperatures at these stations average about 42 degrees Fahrenheit (°F), while mean maximum temperatures average about 76°F. From 1961-1990 mean annual precipitation at these stations ranged from less than 10 inches at San Simon, Arizona, to over 15 inches at White Signal, New Mexico. On average winter precipitation at these stations supplies less than one quarter of the annual total, while about one half of the annual total comes during the months of July through September. Precipitation during these summer months comes mainly in the form of scattered thunderstorms generally of short duration that may produce locally intense rainfall. The average annual Class A pan evaporation rate at the Animas station is 99.7 inches, indicating that potential evapotranspiration greatly exceeds precipitation in the study area.

Table 1. Climate data from stations in and around the Lower Animas and Lordsburg Basins (source: http://www.wrcc.dri.edu)

Station name (number)[a]	Location[b]		Elevation (feet above mean seal level)	Period of record (POR)	Mean annual precipitation (inches)		Mean temperature (degrees Fahrenheit)	
	Latitude	Longitude			POR	1961-1990	Max	Min
Animas (290417)	31º57'	108º49'	4420	1923 to 2000	11.03	11.70	77.3	43.1
Duncan, AZ (022754)	32º45'	109º07'	3680	1901 to 2000	10.88	11.58	78.3	40.7
Eicks Ranch (292757)	31º29'	108º56'	5310	1933 to 1961	14.67	--	73.0	41.6
Gage 4 ESE (293368)	32º13'	108º01'	4410	1914 to 2000	10.40	11.09	76.6	42.9
Hachita (293775)	31º56'	108º19'	4510	1914 to 2000	10.59	11.03	76.6	43.4
Lordsburg 4 SE (295079)	32º18'	108º39'	4250	1914 to 2000	10.83	11.80	78.4	43.1
Redrock (297340)	32º42'	108º44'	4150	1914 to 2000	12.74	13.51	77.2	41.0
Rodeo (297534)	31º50'	109º02'	4120	1914 to 1978	11.21	11.53	79.2	42.6
San Simon 9 ESE AZ (027567)	32º10'	109º05'	3880	1962 to 1986	9.86	9.89	78.1	47.2
White Signal (299691)	32º33'	108º22'	6070	1948 to 2000	14.97	15.44	69.5	39.3
Averages				All stations	11.72	11.95		
				>50 year POR	11.58	12.21		

[a]National Climatic Data Center cooperative network station name and number
[b]Station location by north latitude and west longitude, in degrees and minutes

Table 2. Climate data from stations in and around the Redrock sub-basin, Gila River basin (source: http://www.wrcc.dri.edu)

Station name (number)[a]	Location[b]		Elevation (feet above mean seal level)	Period of record (POR)	Mean annual precipitation (inches)		Mean temperature (degrees Fahrenheit)	
	Latitude	Longitude			POR	1961-1990	Max	Min
Cliff 11 SE (290417)	32º52'	108º31'	4800	1937 to 2000	14.42	15.08	74.6	37.7
Clifton AZ (021849)	33º03'	109º17'	3470	1893 to 2000	12.91	13.53	80.9	51.6
Duncan, AZ (022754)	32º45'	109º07'	3680	1901 to 2000	10.88	11.58	78.3	40.7
Redrock (297340)	32º42'	108º44'	4150	1914 to 2000	12.74	13.51	77.2	41.0
Silver City (298324)	32º46'	108º17'	5910	1914 to 1964	16.08	--	69.5	40.3
White Signal (299691)	32º33'	108º22'	6070	1948 to 2000	14.97	15.44	69.5	39.3
Averages				All stations	13.67	13.83		

[a]National Climatic Data Center cooperative network station name and number
[b]Station location by north latitude and west longitude, in degrees and minutes

Water use and administration

Water is used in the study area for agricultural, municipal, domestic, commercial, industrial, mining, and livestock watering purposes. Water use for power generation also occurred from around 1937 until 1995 at the Lordsburg Power Plant. Essentially all of the water use in the Lower Animas and Lordsburg Basins is supplied by ground-water wells, while irrigated agriculture in the Virden-Duncan and Redrock sub-basins is mainly supplied by surface water from the Gila River, supplemented with ground water.

The greatest single water use in the Lower Animas and Lordsburg Basins is for irrigated agriculture. Irrigation began in the Lower Animas Basin around 1947, with acreage peaking in the late 1970s at about 14,700 acres. In the Lordsburg Basin irrigation began around 1956, with acreage peaking in 1970 at about 9,900 acres. In 1995 (plate 3), 23,852 acre-feet of ground water was pumped to irrigate 7,322 acres in the Animas Basin, and 4,562 acre-feet of ground water was pumped to irrigate 1,281 acres in the Lordsburg Basin (Wilson and Lucero, 1997; table 8).

The City of Lordsburg is the only incorporated municipality in the study area. Other communities include Animas, Cotton City, Redrock and Virden. Water use by Lordsburg peaked at 1,256 acre-feet in 1970, and was 818 acre-feet in 2000 (Johnson, 2002). Commercial uses in Hidalgo County totaled about 512 acre-feet in 2000, over 460 acre-feet of which was attributed to a greenhouse in the Lower Animas Basin that uses geothermal water (B. Wilson, written communication). Current industrial uses are minor and include a pipeline compressor station in the Lordsburg Basin, and a chile processing plant in the Lower Animas Basin. Mining uses in the study area are not significant. Future water use for power production is projected at the former Lordsburg Power Plant and at the proposed Pyramid Facility in the Lordsburg Basin (TSGTA, 2001).

The Office of the State Engineer (OSE) has declared parts of the Lower Animas and Lordsburg Basins (plate 3) as Underground Water Basins (UWBs). The Lordsburg UWB, declared in 1960, is 329 square miles in area. Only that part of the Animas Valley UWB that is located within the Lower Animas Basin was included in the study area. This includes all of the 205 square miles originally declared in 1948, and about 100 square miles of the 1956 extension. Proposed extensions of both UWBs currently under review were also included within the study area. The Gila River Basin portion of the study area includes parts of the Virden Valley and Gila-San Francisco UWBs (plate 3).

SURFACE WATER

The Gila River is the only perennial surface water feature in the study area. The river enters the study area below the Middle Gila Box, a canyon cut through the Burro Mountains, then flows southwest through the Redrock Valley. Below Blue Creek the river flows through another canyon called the Lower Gila Box before entering the Virden Valley. The Gila River leaves the study area at the Arizona-New Mexico state line.

The U. S. Geological Survey (USGS) has measured Gila River flows in the study area at a gage near Redrock (09431500) at the mouth of the Middle Gila Box, and at a gage below Blue Creek (09432000), located at the head of the Lower Gila Box (plate 4). Mean annual flow and runoff at the Redrock gage averaged 248 cubic feet per second (cfs) and 180,000 acre-feet, respectively, from 1963-2000, and 210 cfs and 152,500 acre-feet at the Blue Creek gage from 1932-2000. Over these periods of record instantaneous flows at both gages have varied significantly, ranging from 2.2 to 48,800 cfs at the Redrock gage, and from 1.0 to 58,700 cfs at the Blue Creek gage. Monthly mean flows at both gages are highest in March (over 400 cfs) and lowest in June (less than 60 cfs).

A total of 1,648 acre-feet of Gila River water was diverted for irrigation of 146 acres in the Redrock Valley in 1995 (Wilson and Lucero, 1997). Diversions at the Grandpa Harper Ditch for irrigation in the Redrock Valley were 1,270 acre-feet in 2000. From 1961-1967 annual mean flows in the Sunset and New Model canals in the Virden Valley averaged 14 cfs and 5.2 cfs, respectively. A total of 6,501 acre-feet was diverted for irrigation of 2,019 acres in the Virden Valley in 1995 (Wilson and Lucero, 1997).

The main drainages in the Lower Animas and Lordsburg Basins, Animas Creek and Lordsburg Draw respectively, are ephemeral streams that occasionally transport flood runoff to playas that include the North and South Alkali Flats in the Lower Animas Basin. South Alkali Flats is the lowest point in the Animas Basin (4,143 feet), and is also the ultimate discharge point for Lordsburg Draw. Floodwater that reaches these playas collects there until it evaporates, with very little infiltration (Reeder, 1957).

It should be noted here that a 122-square mile area called the China Draw section, located in the eastern Lordsburg Basin just west of the Continental Divide and adjacent to the Mimbres Basin, was excluded from the study area. Although part of the Lordsburg surface-water basin, the China Draw section is located east of a ground-water divide and does not contribute ground-water flow to the basin (Hawley and others, 2000).

GEOLOGIC SETTING

Structural setting

The following discussion is drawn primarily from the hydrogeologic framework of the study area constructed by Hawley and others (2000). The study area is located within the Basin and Range tectonic province. Two major structural trends in the study area reflect deformation events of different styles and ages (Stone and O'Brien, 1990). The Lordsburg Basin and Burro uplift exhibit a northwest-southeast trend, reflecting Laramide (late Cretaceous) age compression and thrusting. The north-south trend evident in the Lower Animas Basin and the Peloncillo and Pyramid uplifts reflects later (mid-late Tertiary) Basin-and-Range normal faulting in response to east-west tensional stresses.

The north-south trending Lower Animas Basin has been interpreted as a symmetrical graben structure, bounded by major normal faults separating the basin on either side from the Peloncillo (west) and Pyramid (east) uplifts. The northwest-trending structural depression underlying the Lordsburg Basin has been interpreted as a northeast-tilted, half-graben block bounded to the northeast by the frontal fault zone of the Burro uplift. Both basins are closed to the south, but open northward to the Gila River Basin.

The two structural trends intersect north of the Pyramid Mountains in the northern Lower Animas Basin, complicating the structural setting of that area. The Summit Hills appear to be located at the southern end of an uplifted block that extends north to the Gila River. Adjacent and to the west of the Summit Hills block is a narrow graben that widens northward into the Virden-Duncan sub-basin (plate 4). These structures appear to be truncated to the south by the Animas Valley fault zone, which arcs northwestward from the northern Pyramid Mountains across the northern end of the Lower Animas Basin (plate 4). East of the Summit Hills uplift is an eastward-tilted half-graben, that extends into the Redrock sub-basin at least as far north as the Gila River. This half-graben terminates to the east at a fault zone against a buried bedrock high, which appears to be the westward subsurface expression of the Burro uplift.

Complex northwest-trending, cross-basin graben and horst structures located about six miles south of Animas associated with a Laramide-age thrust zone define the structural boundary between the Upper and Lower Animas Basins. The ground-water flow regimes to the north and south of this structural accommodation zone are distinctly different, as will be discussed in the section entitled "Ground water--Movement".

Geologic units

The geology and stratigraphy of the study area have been described in detail in various reports and will only be briefly discussed here. Geologic units in the study area range from Quaternary to Precambrian in age, and can be broadly generalized into basin-fill units and bedrock units (plate 4). The bedrock units include Precambrian intrusive igneous rocks, Paleozoic and Mesozoic sedimentary rocks, Tertiary-Cretaceous intrusives, and Tertiary volcanics and associated sedimentary rocks. Some of these units provide water to wells and springs locally, but in general in the study area they exhibit relatively low permeabilities and do not form important aquifers. Because the Neogene and Quaternary age basin-fill and valley-fill deposits form the only important aquifers in the study area (Hawley and others, 2000), and are the focus of this study, only these units will be discussed in any detail in this report.

Hawley and others (2000) categorized the basin-fill deposits into lithofacies assemblages, and related these to depositional environments. Deposits of the Tertiary Gila Group comprise the bulk of the basin fill. The Gila Group has been divided informally into Lower, Middle and Upper lithostratigraphic units, based on stratigraphic position, depositional environment, and lithofacies characteristics (Hawley and others, 2000; p. 89). Lithofacies assemblages of the Lower Gila Group include fine to coarse-grained, proximal to distal piedmont slope, alluvial fan, and basin-floor deposits. These deposits are partly to well-indurated and generally have low permeabilities. Middle Gila Group lithofacies are similar, but are generally less indurated and somewhat more permeable than the Lower Gila deposits. The Upper Gila Group deposits include fine to coarse-grained proximal to distal piedmont slope and alluvial fan deposits, and alluvial, fluvial, lacustrine and related basin-floor deposits. These are generally non-indurated or poorly indurated, and exhibit significantly higher permeabilities than the Middle and Lower Gila units (Hawley and others, 2000).

The Gila Group basin-fill deposits are overlain by younger, unconsolidated basin- and valley-fill deposits representing eolian, alluvial, fluvial, deltaic, lacustrine, and related environments. For the most part these post-Gila deposits are relatively thin and are situated entirely above the water table in the vadose zone (Hawley and others, 2000). In the Lower Animas Basin, these include the fluvial, deltaic and lacustrine basin-floor deposits associated with the ancestral Animas River and Pluvial Lake Animas.

GROUND WATER

Hydrostratigraphic units

The basin-fill geologic units have been organized into hydrostratigraphic units (HSUs) by Hawley and others (2000), based on lithofacies assemblages and how these relate to hydraulic behavior. Hawley and others (2000; plate 1; figs. 7-2a and 8-2a) mapped these HSUs, and presented cross sections depicting their subsurface distribution. Total thickness of the basin-fill is as much as 2,000 feet in the Lower Animas Basin, and possibly as much as 2,500 feet in the Lordsburg Basin adjacent to the Burro uplift frontal fault zone (Hawley and others, 2000; plate 1, cross section C-C'). The greatest thickness of basin-fill penetrated by drilling in the Lordsburg Basin was over 1,438 feet; in the Lower Animas Basin 1,890 feet has been penetrated (Hawley and others, 2000; p. 89).

Even though total saturated thickness of the basin-fill may be as great as 2,000 feet in the study area, "the thickness of productive aquifer zones rarely exceeds 200 m[eters] (660 feet)" (Hawley and others, 2000; p. 92). The older basin-fill below this depth generally consists of mostly fine-grained, partly indurated to well consolidated Middle and Lower Gila Group lithofacies with relatively low porosity and permeability.

The principal aquifer in the study area consists of Upper Gila HSUs. Where overlying post-Gila HSUs are thick enough to extend below the water table, these units also form an important part of the flow system. In the Lower Animas Basin, ancestral Animas River deposits (HSU: RAF) and fine-grained deposits associated with Pluvial Lake Animas (HSUs: LL, LP, and LPs) overlying the Upper Gila units are as much as 100 feet thick. Gila River fluvial deposits (HSU: RG) with up to 100 feet of saturated thickness overlie Upper Gila HSUs in the Redrock and Virden-Duncan sub-basins. In the Lordsburg Basin the post-Gila HSUs generally do not extend below the vadose zone.

Transmissivity values determined from pumping tests in the study area range from 2,940 to 32,890 feet squared per day (ft^2/d). Hydraulic conductivity ranges reported for the Upper Gila and post-Gila HSUs vary considerably depending on the lithofacies, ranging from less than 3 feet per day (ft/d) to 100 ft/d (Hawley and others, 2000; table 3-5). Storage coefficient values ranging from 0.06 to 0.14 and averaging 0.11 have been estimated for the basin-fill aquifer in the Lower Animas Basin (Reeder, 1957; O'Brien and Stone, 1983). West (1961) determined that a transmissivity of 2,670 ft^2/d and storage coefficient of 0.10 were representative of the basin-fill aquifer in the Lordsburg Basin.

Recharge

Recharge to the basin-fill aquifer in the study area occurs primarily as mountain-front recharge. Precipitation on the piedmont and basin-floor areas does not contribute recharge, and infiltration through streambeds is not a major portion of the total recharge (Hawley and others, 2000). Most of the occasional runoff that collects in the various playas in the study area evaporates and does not contribute to recharge (Reeder, 1957).

Previous studies have assumed or estimated total recharge in the study area or portions thereof at about one percent of the average annual precipitation (Reeder, 1957; Turner, 1960; Trauger, 1972; Hawkins, 1981; Hawley and others, 2000). Precipitation data from 10 climate stations in and around the Lower Animas and Lordsburg Basins (plate 2) is summarized in table 1. The average of mean annual precipitation at all stations (over their entire periods of record) is 11.7 inches. Over the entire 1,700-square mile combined Lower Animas and Lordsburg Basin area, this amounts to 1.06 million ac-ft/yr. Assuming one percent of the total precipitation recharges the aquifer, recharge in these basins would be 10,600 ac-ft/yr.

Mountain-front recharge in the Lower Animas Basin was simulated by O'Brien and Stone (1983) at 2,500 ac-ft/yr along about 40 miles of the eastern flank of the Peloncillo Mountains, and 3,000 ac-ft/yr along about 20 miles of the western side of the Pyramid Mountains, for a total of 5,500 ac-ft/yr. Reeder (1957) estimated recharge in the Lower Animas Basin at slightly less than one percent of precipitation. Using an average annual precipitation of 11.7 inches over the 888-square mile Lower Animas Basin area, one percent of total precipitation is about 5,500 ac-ft/yr, which matches the value used by O'Brien and Stone (1983).

Water-level contours of Trauger (1972; fig. 3) and Hawley and others (2000; figs. 7-3 and 8-3) indicate that recharge in the Lordsburg Basin may occur along the southwest flanks of the Big Burro and South Burro Mountains, the east flank of the Pyramid Mountains, and possibly along segments of the Continental Divide such as the northwest end of the Cedar Mountain Range. Turner (1960) estimated recharge over 790 square miles of the Lordsburg Basin at one percent of a mean annual precipitation of 10 inches, or about 4,150 ac-ft/yr. Using one percent of an average annual precipitation of 11.7 inches (table 1) over the 816-square mile basin area, estimated recharge in the Lordsburg Basin would be about 5,100 ac-ft/yr. The steady-state model simulation of O'Brien and

Stone (1983) indicated that 2,600 ac-ft/yr discharges as underflow from the Lordsburg Basin to the Lower Animas Basin. Assuming all of this discharge originates as recharge in the basin, recharge in the Lordsburg Basin would be about 2,600 ac-ft/yr.

Gage data indicate gains from ground-water inflow of 20 cubic feet per second (cfs) for the 14-mile reach of the Gila River from the Redrock gage site to the gage below Blue Creek, or about 1.5 cfs per mile (Trauger, 1972), for a total of about 14,500 ac-ft/yr. These gains reflect ground water discharge primarily from the basin-fill aquifer from both sides of the river in this 374 square mile portion of the Redrock sub-basin. The average of mean annual precipitation for the periods of record at six climate stations in and around the Redrock sub-basin is 13.7 inches (table 2). If all of the gain to the river in this reach comes from recharge, about five percent of mean annual precipitation contributes to recharge. This is within the range of values from other studies in the region (O'Brien and Stone, 1983; table 1), and is reasonable given the greater topographic relief and higher average precipitation in the Redrock sub-basin. Recharge in the Redrock sub-basin south of the river is estimated at about one-third (4,850 ac-ft/yr) to at most one-half (7,250 ac-ft/yr) of the total discharge to the river in this reach. No mountain-front recharge is likely to occur in the Virden-Duncan sub-basin within the study area.

Geothermal water from deeper flow systems also may provide recharge to the basin-fill aquifer in the Lightning Dock Known Geothermal Resource Area (KGRA) in the Lower Animas Basin (plate 4). There geothermal fluids are heated by a basaltic magma body at depth, and rise along faults and fractures associated with the intersection of the Animas Valley fault zone and the outer ring-fracture zone of the Muir Cauldron in the southern Pyramid Mountains (Elston and others, 1983). Thus the location of this recharge to the basin-fill aquifer approximately corresponds with the location of mountain-front recharge along the west flank of the Pyramid Mountains. Elston and others (1983) estimated that the hot water from wells in the area represents a mix of 75 percent deep geothermal fluid with 25 percent shallow cold ground water. This recharge may in part account for the fact that the average recharge rate along the Pyramid Mountains (about 150 acre-feet per linear mile of mountain front; or ac-ft/mi) estimated from model simulations (O'Brien and Stone, 1983) is more than double the estimated average rate along the Peloncillo Mountains (about 62.5 ac-ft/mi). The rate of upward flow of geothermal water in the Lightning Dock KGRA was not estimated in this study.

Movement

Ground-water movement generally follows topography. Ground water in the basin-fill aquifer in the study area generally flows from highland recharge areas on the basin margins toward the lower basin interiors. The predominant directions of flow in the interior basins are northward in the Lower Animas Basin, and northwestward in the Lordsburg Basin (plate 4). Water-level contours in the Redrock and Virden-Duncan sub-basins indicate ground-water flow is towards the Gila River.

About 4,600 ac-ft/yr enters the Lower Animas Basin from south to north as underflow from the Upper Animas sub-basin (O'Brien and Stone, 1983). This underflow is joined by recharge along the fronts of the Peloncillo and Pyramid Mountains, flowing northward. Water-level gradients in the interior of the Lower Animas Basin are relatively low (0.001), indicating relatively high aquifer saturated thicknesses and/or hydraulic conductivities, while gradients in the Upper Animas sub-basin are higher (0.002). A shallow perched aquifer exists in younger valley-fill deposits in the Upper Animas sub-basin (Reeder, 1957). Water levels in wells in this perched flow system near the boundary between the two basins are as much as 200 feet higher than water levels in nearby wells completed in the deeper Lower Animas Basin flow system (Reeder, 1957).

A prominent ground-water divide has been mapped in the eastern Lordsburg Basin, west of the Continental Divide (Hawley and others, 2000; fig. 7-3). This divide separates the China Draw section from the remainder of the Lordsburg (ground-water) Basin (plate 4). The China Draw section apparently is part of the Mimbres Basin ground-water flow system, and does not contribute to ground-water flow in the Lordsburg Basin (Hawley and others, 2000).

An area of relatively steep water-level gradients occurs in the Lordsburg Basin along the southwestern front of the South Burro Mountains (plate 4). In the basin interior just southwest of the frontal fault zone of the Burro uplift gradients are much less steep. The steep gradients are probably indicative of low transmissivities in the aquifer northeast of the fault zone due to reduced saturated thicknesses and/or lower hydraulic conductivities of the basin-fill deposits in this area. The relatively low gradients indicate higher aquifer saturated thicknesses and/or hydraulic conductivities in the basin-fill aquifer in the interior of the Lordsburg Basin. Ground water flows generally west and northwest from the Lordsburg Basin into the Lower Animas Basin north of Lordsburg.

In the Redrock sub-basin water-level contours indicate that ground water flows from the recharge area along the front of the Burro Mountains generally west and north towards the Gila River (plate 4). Some ground water may flow west into the Virden-Duncan sub-basin. A ground-water divide located in the Redrock sub-basin, north of the topographic divide between the Animas and Gila River Basins (Hawley and others, 2000; fig. 8-3), indicates that some ground water flows southwest from the Redrock sub-basin into the Lower Animas Basin in the area between the Burro Mountains and the Black Hills (plate 4). Water-level contours (Hawley and others, 2000; figs. 7-3 and 8-3) indicate that this ground water joins ground water flowing north into the Virden-Duncan sub-basin from the Lower Animas Basin.

Ground water moving from the Lower Animas Basin into the Virden-Duncan sub-basin flows north between the Peloncillo Mountains and the Summit Hills, and northwest beneath Lordsburg Mesa between the Summit Hills and Black Hills (plate 4). In the Virden-Duncan sub-basin ground water flows generally north towards the Gila River.

Discharge

Ground water in the Lordsburg Basin discharges to the northwest into the Lower Animas Basin in an area north of Lordsburg. O'Brien and Stone (1983) estimated this underflow at 2,600 ac-ft/yr. This ground water joins northward flowing ground water in the Lower Animas Basin, which leaves the basin as underflow to the Virden-Duncan sub-basin in the Gila River Basin, and ultimately discharges to the Gila River (plate 4). O'Brien and Stone (1983) estimated this underflow at 12,700 ac-ft/yr.

As discussed under the section "Recharge", the gains from ground-water inflow of about 14,500 ac-ft/yr for the 14-mile reach of the Gila River from the Redrock gage site to the gage below Blue Creek reflect discharge primarily from the basin-fill aquifer. Hydrogeologic conditions are similar in the next downstream reach of the Gila River, from the Blue Creek gage to the Arizona-New Mexico state line. Assuming similar baseflow gains of 1.5 cfs per mile in this 16-mile reach results in estimated gains of 24 cfs, or about 17,400 ac-ft/yr. Again these ground-water inflows are contributed from both sides of the river. Underflow of 12,700 ac-ft/yr from the Lower Animas Basin would be about 73 percent of the total estimated gain in this reach of the Gila River, which seems reasonable given the relative contributing areas north and south of the river.

In most parts of the study area depth to the water table is great enough that losses from evapotranspiration are not a major discharge component. Most of the runoff that collects in the various playas in the study area evaporates and does not contribute to recharge. Reeder (1957) and O'Brien and Stone (1983) concluded that the North and South Alkali Flats in the Lower Animas Basin are not areas of ground-water discharge through evaporation; presumably this is true of the other minor playas in the area.

SIMULATION OF GROUND-WATER FLOW

Conceptual model

Time constraints on the project required that a numerical model of the study area be developed as efficiently as possible. Fortunately recent work by Hawley and others (2000) has defined the hydrogeologic framework and provided a conceptual model of the flow system in the study area. For this investigation their conceptual model, the major features of which have been discussed in previous sections, was used as the basis for development of a numerical model. Parts of the conceptual model were adapted as necessary to simplify the system in the interest of completing the project on schedule. These simplifications are discussed where appropriate.

Finite-difference grid

The numerical model of the basin-fill aquifer in the Lower Animas and Lordsburg sub-basins was developed using Groundwater Vistas (ESI, 1998) and the USGS modular finite-difference code MODFLOW (Harbaugh and McDonald, 1996). The model area covers about 2,520 square miles of southern Grant and northern Hidalgo Counties, the active area including all or parts of T18S through T28S, R14W through R21W (plate 5). The area modeled includes the Lower Animas and Lordsburg sub-basins of Hawley and others (2000), and those portions of the Redrock and Virden-Duncan sub-basins located south of the Gila River in New Mexico.

The finite-difference grid consists of one layer divided into 60 rows and 42 columns, with 1,464 active cells. Model cells are uniformly one mile square (plate 5). This discretization was chosen in part because one purpose of the model was to calculate drawdowns at model nodes that could be adjusted to estimate drawdowns in pumping wells, and a uniform grid simplifies this adjustment (Anderson and Woessner, 1992).

Model grid columns are oriented N.8ºW, in an attempt to parallel the grid of O'Brien and Stone (1983). The western and southern limits of the model grid correspond approximately with the limits of the model area of O'Brien and Stone (1983; fig. 10). To the east the model area extends to the ground-water divide between the Animas and Mimbres Basins, excluding the China Draw section (see discussion under "Movement"). The model area extends about 12 miles north of O'Brien and Stone's (1983) model boundary, in order to include the regional discharge area for the flow system: the reach of the Gila River from the gage site near Redrock to the point where the river crosses the Arizona-New Mexico state line, some 2.5 miles west of Virden (plate 5).

The model grid includes the entire Lordsburg UWB, and that part of the Animas Valley UWB located within the Lower Animas Basin. According to the WATERS database and the OSE Deming district office (C. Jackson, written communication), essentially all of the irrigated agriculture in the Animas Valley UWB occurs in that part of the administrative basin included in the model. The grid extent also encompasses almost all of the areas proposed as extensions to these administrative basins (plate 3).

The model simulates the upper basin-fill aquifer, primarily various Upper Gila Group hydrostratigraphic units (HSUs), and younger (post-Gila) HSUs where these units extend below the water table. In some areas flow in the Middle Gila HSU is simulated, where this HSU forms the upper part of the basin-fill aquifer. Generally where Middle and Lower Gila HSUs underlie the Upper Gila HSUs, the permeability contrast between the underlying units and the Upper Gila HSUs was assumed to be sufficiently great that vertical flow could be ignored. Virtually all hydrogeologic data in the study area have been derived from wells completed in the Upper Gila and post-Gila HSUs.

For simplicity these units were simulated using a single model layer, with the layer bottom set at the base of the Upper Gila HSUs. Altitudes of the base of the Upper Gila HSUs were estimated at points along cross sections A-A', B-B', C-C', and D-D' on plate 1, and cross section A-A' on plate 7-2b of Hawley and others (2000), and then these points were contoured. Altitudes assigned to the model layer bottom were zoned in 50-foot intervals ranging from 3,300 feet above mean sea level (feet) to 4,250 feet. During steady-state model calibration it was necessary to lower the layer bottom elevations in some cells in areas with steep water-level gradients and/or near the model edges, to prevent water levels from falling below the base of the cell.

Boundary conditions

The model boundaries generally coincide with known natural hydrologic boundaries. Contacts between the Upper Gila and post-Gila HSUs and both bedrock units (in the Peloncillo, Pyramid, and Northern Animas Mountains, the Brockman and Coyote Hills, the Cedar Mountain Range, the South Burro and Big Burro Mountains), and Middle and Lower Gila HSUs (underlying the flow system at depth), were simulated as no-flow boundaries (plate 5). Likewise contacts with bedrock units within the model area at the Summit and Black Hills were simulated as no-flow boundaries. For simplicity those parts of the model boundary corresponding with the Animas-Pyramid and Brockman-Pyramid Gaps were also simulated as no-flow boundaries, as was the saddle between the Coyote Hills and Cedar Mountain Range. The regional ground-water divide along the west side of the China Draw section was also simulated as a no-flow boundary (plate 5). The no-flow boundary simulated along the western limit of the model grid north of the Peloncillo Mountains roughly represents a flow line simplified from water-level contours (plate 4). While these areas may not actually be barriers to ground-water flow, they are sufficiently distant from historical and current pumping locations that they should not significantly affect model results.

The Gila River was simulated as a constant-head boundary at the northern limit of the model area (plate 5). The river was represented as two reaches: (1) from the USGS gage site near Redrock to the gage below Blue Creek; and (2) from the Blue Creek gage to the point where the river crosses the state line. Information about the constant-head model cells used to simulate the river is summarized in table 3. Heads were assigned using average elevations interpolated from USGS 7.5-minute topographic quadrangles.

Mountain-front recharge and underflow across the boundary between the Upper Animas sub-basin and the Lower Animas Basin was simulated using injecting wells. Recharge wells were located in cells grouped in seven recharge reaches along the edges of the active model area. Reaches 1-3 represent the Upper Animas-Lower Animas boundary, the Peloncillo Mountain front and the Pyramid Mountain front, respectively, in the Lower Animas Basin (table 4; plate 5). Reaches 4-6 represent the Pyramid Mountain front, the Cedar Mountain Range, and the South Burro Mountain front, respectively, in the Lordsburg Basin (table 5; plate 5). Reach 7 represents recharge along the Big Burro Mountains in the Redrock sub-basin (table 5; plate 5).

Table 3. Constant-head boundary cells and reaches representing the Gila River, assigned heads and calibrated steady-state fluxes, Lower Animas-Lordsburg model.

Model cell		Gila River reach name (number)	Boundary type	Head (feet above sea level)	Boundary flux ("-" = outflow)[a]		
Row	Col				cubic feet per day	cubic feet per second	acre-feet per year
1	25	Redrock to Blue Creek (1)	Constant head	4,100	-77,810		
2	24	Redrock to Blue Creek (1)	Constant head	4,080	-191,700		
2	23	Redrock to Blue Creek (1)	Constant head	4,060	-56,430		
2	22	Redrock to Blue Creek (1)	Constant head	4,040	-21,390		
3	21	Redrock to Blue Creek (1)	Constant head	4,020	-55,000		
4	20	Redrock to Blue Creek (1)	Constant head	3,990	-76,600		
4	19	Redrock to Blue Creek (1)	Constant head	3,970	-9,240		
4	18	Redrock to Blue Creek (1)	Constant head	3,950	-5,160		
4	17	Redrock to Blue Creek (1)	Constant head	3,940	-1,050		
5	16	Redrock to Blue Creek (1)	Constant head	3,920	-7,890		
5	15	Redrock to Blue Creek (1)	Constant head	3,900	-2,200		
5	14	Redrock to Blue Creek (1)	Constant head	3,880	-1,000		
				Reach 1 net	-505,470	-5.85	-4,240
6	13	Blue Creek to stateline (2)	Constant head	3,870	-3,930		
6	12	Blue Creek to stateline (2)	Constant head	3,850	68,700	0.80	580
5	11	Blue Creek to stateline (2)	Constant head	3,830	-23,100		
5	10	Blue Creek to stateline (2)	Constant head	3,810	-65,640		
5	9	Blue Creek to stateline (2)	Constant head	3,790	-136,300		
4	9	Blue Creek to stateline (2)	Constant head	3,780	0		
4	8	Blue Creek to stateline (2)	Constant head	3,770	-145,900		
3	7	Blue Creek to stateline (2)	Constant head	3,760	-33,820		
2	6	Blue Creek to stateline (2)	Constant head	3,740	-147,000		
2	5	Blue Creek to stateline (2)	Constant head	3,730	-176,500		
1	4	Blue Creek to stateline (2)	Constant head	3,710	-236,900		
1	3	Blue Creek to stateline (2)	Constant head	3,700	-687,200		
				Reach 2 net	-1,587,590	-18.37	-13,310
				TOTAL NET	-2,093,060	-24.22	-17,550

[a]Boundary flux at steady-state in cubic feet per day; cubic feet per second; and acre-feet per year; negative values represent outflow from the aquifer.

Table 4. Summary of specified flux model cells simulating underflow and recharge in the Lower Animas Basin (recharge reaches 1-3), Lower Animas-Lordsburg model.

Model cell		Reach	Boundary type (Modflow module)	Recharge source area	Boundary flux[a]	
Row	Col				ft^3/day	ac-ft/yr
60	4	1	Specified flux (well)	Upper Animas underflow	68,575	575.0
60	5	1	Specified flux (well)	Upper Animas underflow	68,575	575.0
60	6	1	Specified flux (well)	Upper Animas underflow	68,575	575.0
60	7	1	Specified flux (well)	Upper Animas underflow	68,575	575.0
60	8	1	Specified flux (well)	Upper Animas underflow	68,575	575.0
60	9	1	Specified flux (well)	Upper Animas underflow	68,575	575.0
59	9	1	Specified flux (well)	Upper Animas underflow	68,575	575.0
58	9	1	Specified flux (well)	Upper Animas underflow	68,575	575.0
19	1	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
20	1	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
21	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
22	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
23	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
24	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
25	3	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
26	3	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
27	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
28	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
29	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
30	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
31	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
32	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
33	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
34	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
35	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
36	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
37	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
38	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
39	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
40	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
41	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
42	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
43	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
44	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
45	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
46	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
47	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
48	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
49	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
50	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
51	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
52	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
53	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
54	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
55	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
56	2	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
56	3	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5
57	3	2	Specified flux (well)	Peloncillo Mountains	7,454	62.5

Table 4. Summary of specified flux model cells simulating underflow and recharge in the Lower Animas Basin (recharge reaches 1-3), Lower Animas-Lordsburg model (concluded).

Model cell		Reach	Boundary type (Modflow module)	Recharge source area	Boundary flux[a]	
Row	Col				ft^3/day	ac-ft/yr
29	12	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
30	11	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
31	11	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
32	11	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
33	11	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
34	11	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
35	10	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
36	10	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
37	10	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
38	10	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
39	10	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
40	10	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
41	10	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
42	10	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
43	10	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
44	10	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
45	10	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
46	10	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
47	10	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
48	10	3	Specified flux (well)	Pyramid Mountains	17,889	150.0
				Lower Animas Basin TOTAL	1,204,540	10,100

[a]Boundary flux in cubic feet per day (ft^3/day) and acre-feet per year (ac-ft/yr).

Table 5. Summary of specified flux model cells simulating recharge in the Lordsburg Basin (recharge reaches 4-6) and Redrock sub-basin (reach 7), Lower Animas-Lordsburg model.

Model cell		Reach	Boundary type (Modflow module)	Recharge source area	Boundary flux[a]	
Row	Col				ft^3/day	ac-ft/yr
29	18	4	Specified flux (well)	Pyramid Mountains	4,770	40.0
30	19	4	Specified flux (well)	Pyramid Mountains	4,770	40.0
31	19	4	Specified flux (well)	Pyramid Mountains	4,770	40.0
32	19	4	Specified flux (well)	Pyramid Mountains	4,770	40.0
33	19	4	Specified flux (well)	Pyramid Mountains	4,770	40.0
34	19	4	Specified flux (well)	Pyramid Mountains	4,770	40.0
35	19	4	Specified flux (well)	Pyramid Mountains	4,770	40.0
36	19	4	Specified flux (well)	Pyramid Mountains	4,770	40.0
37	19	4	Specified flux (well)	Pyramid Mountains	4,770	40.0
38	19	4	Specified flux (well)	Pyramid Mountains	4,770	40.0
39	19	4	Specified flux (well)	Pyramid Mountains	4,770	40.0
40	19	4	Specified flux (well)	Pyramid Mountains	4,770	40.0
41	19	4	Specified flux (well)	Pyramid Mountains	4,770	40.0
42	19	4	Specified flux (well)	Pyramid Mountains	4,770	40.0
43	19	4	Specified flux (well)	Pyramid Mountains	4,770	40.0
44	19	4	Specified flux (well)	Pyramid Mountains	4,770	40.0
45	19	4	Specified flux (well)	Pyramid Mountains	4,770	40.0
50	41	5	Specified flux (well)	Cedar Mountain Range	4,770[b]	40.0
50	42	5	Specified flux (well)	Cedar Mountain Range	4,770[b]	40.0
51	40	5	Specified flux (well)	Cedar Mountain Range	3,975	33.3
52	38	5	Specified flux (well)	Cedar Mountain Range	3,975	33.3
52	39	5	Specified flux (well)	Cedar Mountain Range	3,975	33.3
53	37	5	Specified flux (well)	Cedar Mountain Range	3,975	33.3
54	37	5	Specified flux (well)	Cedar Mountain Range	3,975	33.3
54	36	5	Specified flux (well)	Cedar Mountain Range	3,975	33.3
55	35	5	Specified flux (well)	Cedar Mountain Range	4,770[b]	40.0
14	29	6	Specified flux (well)	South Burro Mountains	6,815	57.1
15	29	6	Specified flux (well)	South Burro Mountains	6,815	57.1
16	28	6	Specified flux (well)	South Burro Mountains	6,815	57.1
17	28	6	Specified flux (well)	South Burro Mountains	6,815	57.1
18	28	6	Specified flux (well)	South Burro Mountains	6,815	57.1
19	28	6	Specified flux (well)	South Burro Mountains	6,815	57.1
20	27	6	Specified flux (well)	South Burro Mountains	6,815	57.1
21	26	6	Specified flux (well)	South Burro Mountains	6,815	57.1
22	26	6	Specified flux (well)	South Burro Mountains	6,815	57.1
23	27	6	Specified flux (well)	South Burro Mountains	6,815	57.1
24	28	6	Specified flux (well)	South Burro Mountains	6,815	57.1
25	28	6	Specified flux (well)	South Burro Mountains	6,815	57.1
26	28	6	Specified flux (well)	South Burro Mountains	6,815	57.1
27	29	6	Specified flux (well)	South Burro Mountains	6,815	57.1
28	30	6	Specified flux (well)	South Burro Mountains	6,815	57.1
29	31	6	Specified flux (well)	South Burro Mountains	6,815	57.1
30	32	6	Specified flux (well)	South Burro Mountains	6,815	57.1
31	33	6	Specified flux (well)	South Burro Mountains	6,815	57.1
32	33	6	Specified flux (well)	South Burro Mountains	6,815	57.1
33	34	6	Specified flux (well)	South Burro Mountains	6,815	57.1
34	35	6	Specified flux (well)	South Burro Mountains	6,815	57.1
34	36	6	Specified flux (well)	South Burro Mountains	6,815	57.1

Table 5. Summary of specified flux model cells simulating recharge in the Lordsburg Basin (recharge reaches 4-6) and Redrock sub-basin (reach 7), Lower Animas-Lordsburg model (concluded).

Model cell		Reach	Boundary type (Modflow module)	Recharge source area	Boundary flux[a]	
Row	Col				ft^3/day	ac-ft/yr
34	37	6	Specified flux (well)	South Burro Mountains	6,815	57.1
35	38	6	Specified flux (well)	South Burro Mountains	6,815	57.1
35	39	6	Specified flux (well)	South Burro Mountains	6,815	57.1
34	40	6	Specified flux (well)	South Burro Mountains	6,815	57.1
33	41	6	Specified flux (well)	South Burro Mountains	6,815	57.1
32	42	6	Specified flux (well)	South Burro Mountains	6,815	57.1
				Lordsburg Basin TOTAL	310,070	2,600
2	27	7	Specified flux (well)	Redrock sub-basin	57,841	485.0
3	27	7	Specified flux (well)	Redrock sub-basin	57,841	485.0
4	27	7	Specified flux (well)	Redrock sub-basin	57,841	485.0
5	27	7	Specified flux (well)	Redrock sub-basin	57,841	485.0
5	28	7	Specified flux (well)	Redrock sub-basin	57,841	485.0
5	29	7	Specified flux (well)	Redrock sub-basin	57,841	485.0
6	29	7	Specified flux (well)	Redrock sub-basin	57,841	485.0
7	29	7	Specified flux (well)	Redrock sub-basin	57,841	485.0
8	29	7	Specified flux (well)	Redrock sub-basin	57,841	485.0
9	30	7	Specified flux (well)	Redrock sub-basin	57,841	485.0
				Redrock sub-basin TOTAL	578,410	4,850

[a]Boundary flux in cubic feet per day (ft^3/day) and acre-feet per year (ac-ft/yr).
[b]Fluxes in these cells, which were added to reach 5 during calibration, were removed cells in reach 4 but were not changed in value.

Aquifer parameters

The surface and subsurface geology, as classified into HSUs by Hawley and others (2000), provided the basis for delineating initial hydraulic conductivity (K) zones, and for assigning K values based on ranges estimated for these HSUs. During steady-state model calibration the distribution of these zones and assigned K values were adjusted, and new zones added to achieve the best match (in the time available) to measured or estimated pre-development heads and flows. The resulting nine zones based on HSUs or combinations of HSUs were assigned K values ranging from 0.12 to 50 ft/d (table 6; plate 6). All of the hydraulic conductivity values used in the model were kept within published ranges for each HSU (Trauger, 1972; Hawley and others, 2000).

One zone represents the axial drainageways in the basin floors of the Lower Animas and northern Lordsburg Basins. South of the alkali flats in the northern Lower Animas Basin this zone consists of basin-floor and fluvial fan deposits of the ancestral Animas River, overlying fine-medium grained Upper Gila basin-floor deposits (table 6). North of the flats this zone consists of only the Upper Gila deposits in the half-graben between the Summit Hills and Burro uplifts. Because the Lordsburg Basin is an open and drained basin or semi-bolson, it is possible that relatively coarse-grained (and therefore more permeable) fluvial deposits may exist along the axial drainageway of the basin (Hawley and others, 2000; p. 89). As a result of steady-state model calibration this zone was assigned a hydraulic conductivity of 50 ft/d. In the axial Lower Animas Basin this resulted in transmissivity (T) values ranging up to 43,150 ft^2/d, which compares with values of up to 300,000 gallons per day per foot (40,100 ft^2/d) simulated by O'Brien and Stone (1983; fig. 12). The constant-head cells representing ancestral and modern Gila River fluvial deposits were also assigned a K of 50 ft/d (table 6).

The basin-floor Upper Gila HSU (UG2) and overlying fine-grained playa lake and lake plain (LP) deposits in the alkali flats area in the northern Lower Animas Basin were assigned a K of 24 ft/d during model calibration. The basin-floor area in the central and southern Lordsburg Basin, consisting of UG2 overlain by basin-floor and piedmont deposits (AB, BFP, PA; plate 6), was designated as a zone and assigned a K of 10 ft/d (table 6). Differences in K values between these two zones, which are both based primarily on UG2, may reflect differences in depositional environments between the two basins and/or the wide range of basin-floor lithofacies included in this HSU.

Table 6. Hydraulic conductivity (K) values in feet per day assigned to individual and combined basin-fill hydrostratigraphic units (HSU) in the Lower Animas-Lordsburg model.

HSU	Facies	Description	General Location	K range	K in model
RG	a1, a2	Channel, floodplain and low terrace deposits of the Gila River	Gila River Valley, Redrock and Virden sub-basins	3 to 100	50
UG2r	1, 2, 3	Ancestral Gila River channel and floodplain deposits		3 to 100	
AB	b, c	Recent unchanneled axial basin floor deposits	Axial northern and southern Lower Animas Basin, northern Lordsburg Basin	<3 to 33	50
RAF	a2, a3	Basin floor/fluvial fan deposits of Animas River		3 to 33	
UG2	3	Fine-medium grained Upper Gila basin floor deposits		3 to 33	
UG2r	1, 2, 3	Ancestral Gila River channel/floodplain deposits	Outcrop area north and west from Summit Hills to Gila River	3 to 100	40
UG1	5	Medial to distal Upper Gila piedmont slope deposits	Piedmont slopes along range fronts, mostly basinward of major basin-bounding fault zones	<3 to 33	25
LP LPs	9 10	Fine grained playa lake and lake plain deposits	Playa flats in axial north-central Lower Animas Basin	< 3	24
UG2	3	Fine-medium grained Upper Gila basin floor deposits		3 to 33	
AB BFP PA	b, c c 5, 6	Recent axial basin floor (AB), playa (BFP), and piedmont (PA) deposits	Axial central and southern Lordsburg Basin	<3 to 33	10
UG2	3	Fine-medium grained Upper Gila basin floor deposits		3 to 33	
UG1c	6 (6b?)	Fine-coarse grained, poorly sorted proximal to medial piedmont deposits	Uppermost piedmont slopes adjacent to Big Burro and South Burro Mountains	<3 to 33	0.60
UG2r	1, 2, 3	Ancestral Gila River channel/floodplain deposits	Near Gila River from west of fault to Black Hills; mostly UG1 below water table, with thin overlying UG2r mostly in vadose zone	3 to 100	0.24
UG1	5 (5b?)	Medial to distal Upper Gila piedmont slope deposits		<3 to 33	
UG1	5 (5b?)	Medial to distal Upper Gila piedmont slope deposits	Piedmont slopes north and east of Burro uplift frontal fault zone	<3 to 33	0.18
MG1	7 8	Middle Gila consolidated conglomeratic piedmont deposits	Piedmont slopes of the southern Pyramid Mountains, Brockman and Coyote Hills, and Cedar Mountain Range	< 3	0.12

Note: HSU abbreviations, descriptions, locations and K ranges (converted from meters per day) from Hawley and others (2000; plate 1, table 3-5).

The most widespread zone in the model consists of medial to distal Upper Gila piedmont slope deposits classified as HSU UG1, generally overlain by younger piedmont slope deposits (PAU; plate 6). In the Lower Animas Basin this zone occupies areas along the Peloncillo and Pyramid Mountain fronts. In the northern Lordsburg Basin this zone is situated basinward of the Burro uplift frontal fault zone. In the southern part of the basin it generally occupies an area between the basin-floor zone and Middle Gila Group deposits situated around the basin margins. This zone also extends over part of the buried westward extension of the Burro uplift (plate 6). This zone was assigned a hydraulic conductivity of 25 ft/d. A K value of 24 ft/d can be derived from a T of about 4,800 ft^2/d determined from a pumping test in this HSU near Lordsburg (Murray, 1942).

Water-level gradients in the piedmont slope areas north and east of the Burro uplift frontal fault zone indicated lower aquifer permeabilities, so a zone of HSU UG1 in that area was assigned a relatively low K of 0.18 ft/d (plate 6). An area located in the Redrock sub-basin consisting of UG1 in the half-graben west of the Burro uplift was assigned a K of 0.24 ft/d. These values are two orders of magnitude lower than the K assigned to the other UG1 zone (see above), which may indicate the presence of the more proximal, poorly sorted subfacies 5b in these areas adjacent to the Burro uplift (table 6).

The outcrop area of ancestral Gila River channel and floodplain deposits (UG2r) located in the Virden-Duncan sub-basin north and west of the Summit Hills uplift to the Gila River, was assigned a hydraulic conductivity of 40 ft/d (table 6; plate 6). Areas of proximal to medial piedmont slope deposits (UG1c) adjacent to the Burro Mountain and South Burro Mountain fronts were assigned a K of 0.6 ft/d during calibration, indicating the possible presence of the more proximal, poorly sorted subfacies 6b in these areas.

The geologic map and cross section D-D' on plate 1 of Hawley and others (2000) indicate that only the Middle Gila Group, with no overlying Upper Gila Group or post-Gila HSUs, is present in a belt extending eastward from the Animas Valley fault zone on the east side of the southern Lower Animas Basin, through the Animas-Pyramid Gap, along the eastern flank of the southern Pyramid Mountains, and across the Brockman-Pyramid Gap and the saddle between the Coyote Hills and Cedar Mountain Range. The extent of this area to the north and east in the Lordsburg Basin was estimated from the geologic map and cross sections (plate 6). As a result of steady-state model calibration this area was assigned a hydraulic conductivity of 0.12 ft/d.

Steady-state model calibration

The steady-state Lower Animas-Lordsburg model was calibrated to observed and estimated pre-development heads and flows. Calibration was achieved by systematically adjusting hydraulic conductivity values and zonation, with some adjustment of recharge rates and locations. Calibration to heads is discussed below; calibration to steady-state flows is discussed in the section entitled “Water budget”.

Heads for the steady-state calibration were taken from Schwennesen (1918), who tabulated depth to water at some 100 wells in the active model area. This data set was chosen because it was considered synoptic and representative of pre-development conditions, in that all the measurements were made within three months (September-November) in 1913. Only 88 of these data points were used; 12 wells located at the southernmost end of the Lower Animas Basin were excluded because water levels in these wells represented heads in the shallow, perched flow system, and not the deeper flow system simulated by this model. One well in this area from Reeder (1957; table 3) with a water level representative of the deeper flow system was added. Depth to water reported by Schwennesen (1918; table 1) was converted to water-level altitude at each well location by estimating land surface altitudes using a digital elevation model (DEM). Land surface altitudes estimated from the DEM compare closely to those estimated from topographic maps by O’Brien and Stone (1981)--all are within about ±20 feet, and over 90 percent are within ±10 feet--and are considered somewhat more accurate.

Water-level altitudes at 28 sites in the Lordsburg Basin portion of the model were used as calibration targets for the steady-state model (plate 7). In the Lower Animas Basin water-level altitudes at 61 sites were used. Table 7 lists observed and simulated heads at these targets, and residuals (observed minus simulated). Figure 1 shows the relationship between observed and simulated heads at the calibration targets, and figure 2 is a histogram of the residuals. Simulated heads at target locations were interpolated in Groundwater Vistas from values calculated at model nodes. Simulated pre-development heads are compared to observed water-level contours from Hawley and others (2000) in plate 7. The observed contours are derived from water-level measurements taken at various times, and therefore are not representative of pre-development conditions in all areas. However, no other contour map of the entire study area exists, and these contours provide information in areas that contours of the Schwennesen data would not.

Table 7. Head residuals and calibration statistics, steady-state Lower Animas-Lordsburg model.

Calibration target			Model cell		Observed head (feet above sea level)	Simulated head (feet above sea level)	Residual (feet)
Number		Location	Row	Col			
WSP 422[a]	This study						
3	5001	25S.14W.20	47	39	4,260	4,233.47	26.53
4	5002	26S.15W.15.3	51	34	4,196	4,211.34	-15.34
5	5003	24S.15W.19.3	40	33	4,211	4,190.80	20.20
6	5004	24S.15W.19.3	40	33	4,199	4,190.55	8.45
8	5005	25S.16W.26.1	46	30	4,168	4,193.26	-25.26
10	5006	25S.16W.16.4	44	28	4,191	4,188.06	2.94
11	5007	24S.17W.35.4	41	25	4,194	4,178.34	15.66
12	5008	24S.17W.35.2	40	25	4,192	4,177.61	14.39
13	5009	24S.17W.26.1	39	24	4,196	4,175.93	20.07
14	5010	24S.17W.09	36	23	4,185	4,170.34	14.66
15	5011	24S.17W.08.4	36	22	4,197	4,169.13	27.87
16	5012	24S.17W.08.2	36	22	4,186	4,168.30	17.70
17	5013	24S.17W.08.1	36	22	4,191	4,167.79	23.21
18	5014	24S.17W.04	35	23	4,181	4,167.47	13.53
19	5015	24S.17W.05.4	35	22	4,182	4,166.37	15.63
20	5016	23S.17W.32.2	34	23	4,175	4,162.95	12.05
21	5017	23S.28W.01.3	29	21	4,153	4,136.36	16.64
22	5018	23S.18W.02.2	28	21	4,131	4,129.86	1.14
23	5019	22S.18W.34.2	27	20	4,122	4,119.23	2.77
24	5020	22S.18W.34.1	27	19	4,126	4,115.33	10.67
25	5021	22S.18W.34.3	27	20	4,137	4,121.48	15.52
26	5022	22S.18W.33.2	27	19	4,117	4,110.41	6.59
27	5023	22S.18W.33.2	27	19	4,118	4,111.33	6.67
28	5024	22S.18W.28.4	26	19	4,122	4,109.23	12.77
30	5025	22S.18W.28.3	26	19	4,125	4,106.95	18.05
31	5026	22S.18W.28.3	26	19	4,128	4,107.36	20.64
32	5027	22S.18W.29.1	26	18	4,108	4,097.52	10.48
33	5028	22S.18W.29.2	26	18	4,106	4,100.76	5.24
34	5029	22S.18W.19.2	25	17	4,094	4,092.62	1.38
35	5030	22S.19W.13.4	24	16	4,098	4,085.08	12.92
38	5031	22S.19W.29.1	25	12	4,049	4,078.39	-29.39
40	5032	21S.20W.34.4	19	9	3,960	4,039.60	-79.60
41	5033	21S.21W.25.3	18	5	3,993	4,015.02	-22.02
42	5034	22S.20W.18.4	22	5	4,007	4,055.83	-48.83
43	5035	22S.20W.23.2	23	9	3,988	4,067.88	-79.88
45	5036	23S.20W.30.3	30	4	4,116	4,126.19	-10.19
46	5037	23S.20W.31.1	30	4	4,117	4,129.11	-12.11
47	5038	24S.21W.01.2	31	3	4,124	4,135.12	-11.12
48	5039	23S.19W.31.1	31	9	4,123	4,130.71	-7.71
49	5040	23S.19W.31.1	32	9	4,116	4,133.98	-17.98
50	5041	24S.19W.06.3	33	9	4,138	4,141.35	-3.35
51	5042	24S.19W.07.1	33	9	4,148	4,144.82	3.18
52	5043	24S.19W.07.3	34	9	4,153	4,149.41	3.59
53	5044	24S.19W.18.3	35	9	4,142	4,154.52	-12.52
56	5045	24S.20W.01.4	33	9	4,137	4,141.40	-4.40
57	5046	24S.20W.01.4	33	9	4,137	4,143.38	-6.38
58	5047	24S.20W.03.3	32	6	4,140	4,141.55	-1.55
59	5048	24S.20W.07.1	32	3	4,137	4,142.07	-5.07
60	5049	24S.20W.11.3	33	7	4,144	4,147.95	-3.95
61	5050	24S.20W.14.1	34	8	4,145	4,153.36	-8.36

Table 7. Head residuals and calibration statistics, steady-state Lower Animas-Lordsburg model (concluded).

Calibration target			Model cell		Observed head (feet above sea level)	Simulated head (feet above sea level)	Residual (feet)
Number		Location	Row	Col			
WSP 422[a]	This study						
62	5051	24S.20W.14.2	34	7	4,145	4,153.45	-8.45
63	5052	24S.20W.14.2	35	7	4,148	4,155.91	-7.91
64	5053	24S.20W.14.4	34	7	4,146	4,154.71	-8.71
65	5054	24S.20W.15.4	34	6	4,146	4,154.39	-8.39
66	5055	24S.20W.15.1	34	6	4,144	4,152.35	-8.35
67	5056	24S.20W.16.4	34	5	4,147	4,153.15	-6.15
68	5057	24S.20W.18.2	34	3	4,140	4,149.28	-9.28
69	5058	24S.20W.20.3	35	4	4,150	4,157.60	-7.60
70	5059	24S.20W.21.2	35	5	4,149	4,156.27	-7.27
71	5060	24S.20W.22.1	35	6	4,147	4,157.35	-10.35
72	5061	24S.20W.22.4	35	6	4,149	4,159.84	-10.84
73	5062	24S.20W.23.1	35	7	4,148	4,158.19	-10.19
74	5063	24S.20W.23.2	35	7	4,149	4,156.83	-7.83
75	5064	24S.20W.26.2	36	7	4,151	4,161.31	-10.31
76	5065	24S.20W.26.3	37	7	4,154	4,163.93	-9.93
77	5066	24S.20W.32.2	36	4	4,153	4,163.25	-10.25
78	5067	24S.20W.36.4	38	8	4,160	4,168.56	-8.56
79	5068	25S.20W.01.3	39	7	4,168	4,171.76	-3.76
80	5069	25S.20W.04.1	38	4	4,158	4,167.96	-9.96
82	5070	25S.20W.06.4	38	3	4,165	4,168.77	-3.77
83	5071	25S.20W.13.2	40	7	4,170	4,176.64	-6.64
84	5072	25S.20W.13.2	40	7	4,173	4,177.70	-4.70
85	5073	25S.20W.13.4	41	7	4,174	4,179.08	-5.08
86	5074	25S.20W.13.4	41	7	4,177	4,179.53	-2.53
87	5075	25S.20W.16.3	40	4	4,174	4,178.53	-4.53
88	5076	25S.20W.33.3	43	3	4,172	4,191.77	-19.77
90	5077	26S.20W.14.2	46	6	4,221	4,204.77	16.23
94	5079	26S.20W.32.1	48	2	4,210	4,222.27	-12.27
95	5080	26S.20W.32.4	49	3	4,203	4,227.80	-24.80
96	5081	26S.20W.36.2	49	7	4,241	4,228.67	12.33
98	5082	27S.19W.17.2	52	8	4,274	4,256.66	17.34
99	5083	27S.19W.17.3	53	7	4,271	4,258.28	12.72
100	5084	27S.19W.18.2	52	7	4,263	4,253.57	9.43
101	5085	27S.19W.19.2	53	7	4,270	4,257.98	12.02
102	5086	27S.19W.20.2	53	8	4,282	4,261.25	20.75
104	5087	27S.19W.32.2	55	8	4,259	4,273.30	-14.30
106	5088	27S.20W.09.1	50	3	4,226	4,237.24	-11.24
107	5089	27S.20W.16.4	52	3	4,255	4,248.31	6.69
NA	5095a	28S.19W.16.444	59	8	4,310[b]	4,308.02	1.98
Minimum residual (feet)			-79.9		**Residual mean**	-2.11 feet	
Maximum residual (feet)			27.9		**Standard deviation**	18.10 feet	
Absolute residual mean (feet)			13.14		**Sum of squares**	29,540	
Ratio of standard deviation to observed head range			0.05		**Observed head range**	350 feet	

[a]Number assigned in table 1 of Water-Supply Paper 422 (Schwennesen, 1918)
[b]Calculated from data in table 3 of Reeder (1957); well 28.19.16.444

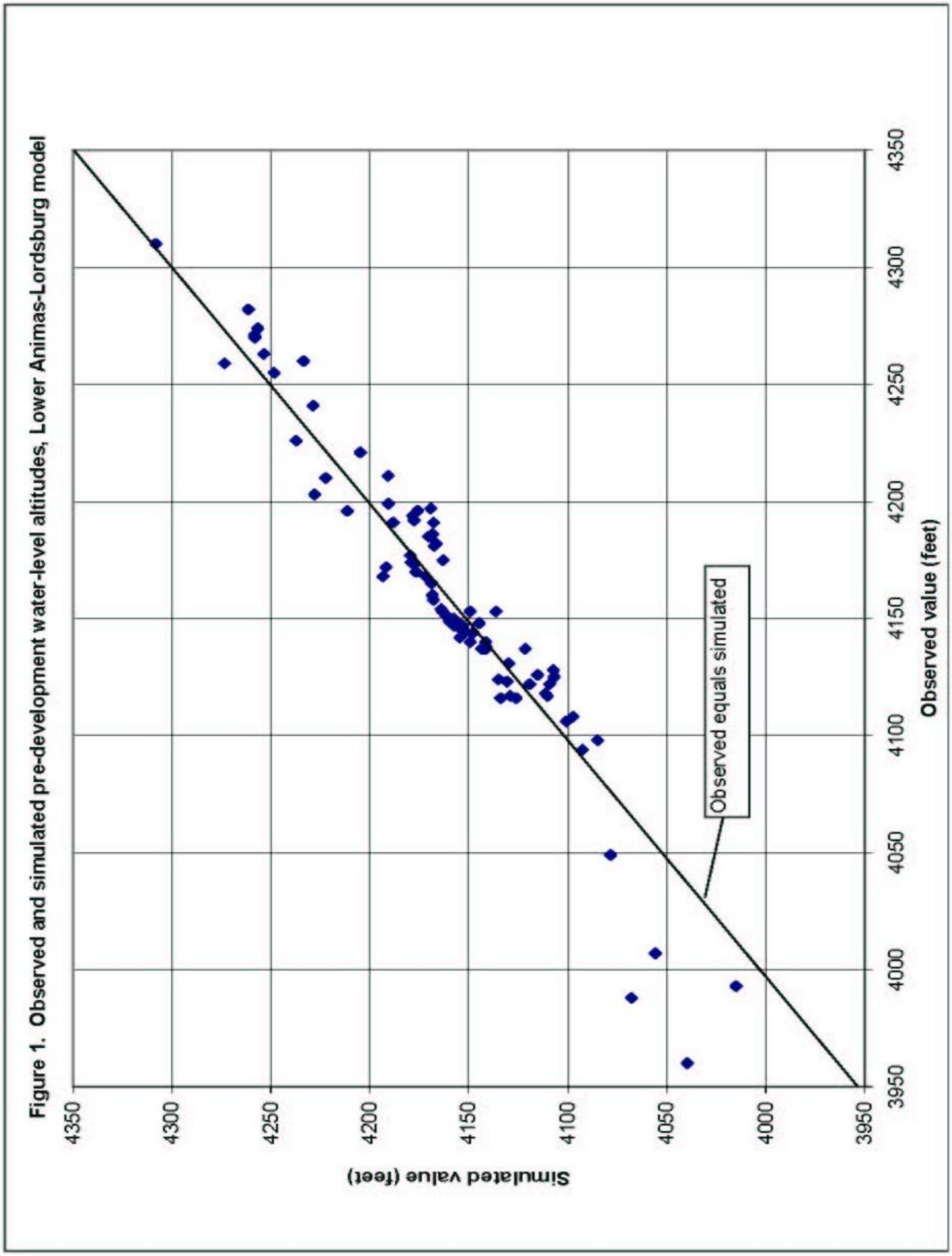
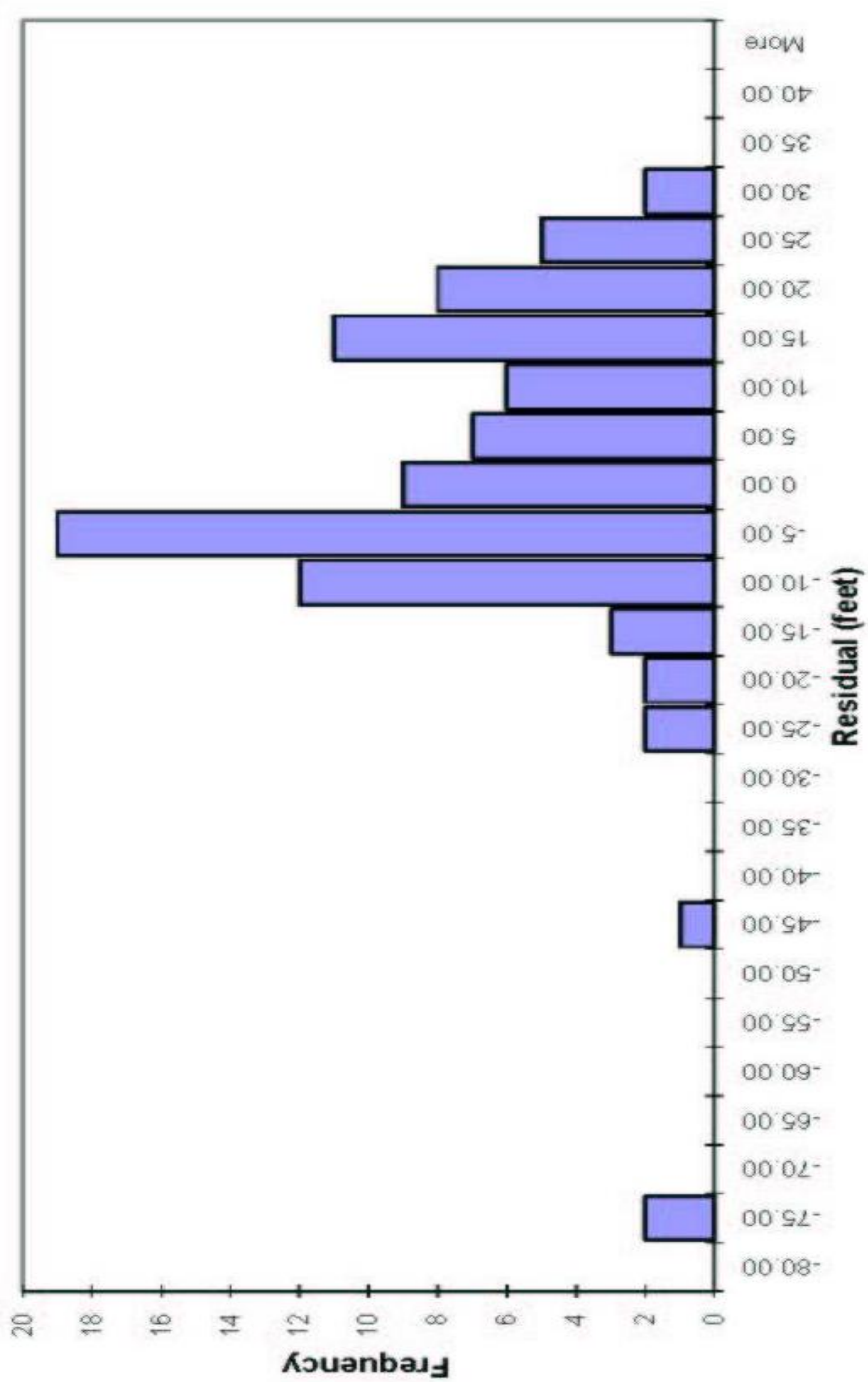


Figure 1. Observed and simulated pre-development water-level altitudes, Lower Animas-Lordsburg model

Figure 2. Histogram of residuals between observed and simulated pre-development water-level altitudes, Lower Animas-Lordsburg model



Calibration statistics for the steady-state model are summarized in table 7. Residuals range from about -80 to +28 feet, with a mean of about –2.1 feet and an absolute mean of 13.1 feet. The ratio of residual standard deviation (18.1 feet) to the observed range in head (350 feet) is about five percent, and heads at 76 of 89 targets (85 percent) are within ± 20 feet of observed values. Heads are reasonably well simulated in the irrigated areas of the Lower Animas (mean residual about –7 feet at 40 targets in Cotton City area; about 2 feet at 14 targets in Animas area) and Lordsburg Basins (mean residual 12 feet at 16 targets), and in the vicinity of Lordsburg (10 feet at 14 targets).

Simulated heads are too high in the northern Lower Animas Basin south of Summit Hills (mean residual –52 feet at five targets). Also no pre-development targets were available to compare to simulated heads in the model northeast of a line between Summit Hills and Lordsburg, an area roughly delineated by model rows 1-15, columns 1-10; and rows 1-20, columns 11-25 (plate 7), so calibration in this area is uncertain.

Sources of error in the comparison of model calculated heads with the observed heads from Schwennesen (1918) and Reeder (1957) include errors in the original reported well locations and measured depths to water. Additional error was introduced in converting well locations to projected coordinates, in overlaying these on an unprojected model grid, and in converting depth to water to water-level altitude using the DEM.

Water budget

Table 8 summarizes the estimated and simulated pre-development ground-water budget for the model area. For the model area as a whole, inflows of 12,950 ac-ft/yr from mountain-front recharge, 4,600 ac-ft/yr of underflow from the Upper Animas sub-basin, and 580 ac-ft/yr of inflow from the Gila River were simulated. Outflows consisted of discharges to the Gila River of 4,240 ac-ft/yr in reach 1, and 13,890 ac-ft/yr in reach 2.

Recharge in the Lower Animas Basin was distributed in the following manner: 2,500 ac-ft/yr evenly distributed along 40 miles of the eastern front of the Peloncillo Mountains, and 3,000 ac-ft/yr evenly distributed along 20 miles of the western front of the Pyramid Mountains (table 4). Another 4,600 ac-ft/yr was evenly distributed along the southern edge of the model area in the Lower Animas Basin to simulate the underflow from the Upper Animas sub-basin (table 5). Recharge from geothermal upflow in the Lightning Dock KGRA was not estimated or simulated explicitly.

Table 8. Estimated and simulated pre-development (steady-state) water budget for the basin-fill ground-water flow system in the Lower Animas-Lordsburg model area.

Water-budget component	Estimated rate (acre-feet per year)	Simulated rate (acre-feet per year)
Lower Animas Basin Inflows		
Mountain-front recharge	5,500	5,500
Underflow from Upper Animas Basin	4,600	4,600
Underflow from Lordsburg Basin	2,600	2,600
Underflow from Redrock sub-basin	0	580
Lower Animas Basin total inflow	12,700	13,280
Lower Animas Basin Outflows		
Underflow to Gila River basin (Virden-Duncan Sub-basin)	12,700	13,280
Lower Animas Basin Total outflow	12,700	13,280
Lordsburg Basin Inflows		
Mountain-front recharge (Lordsburg Basin)	2,600	2,600
Lordsburg Basin Outflows		
Underflow to Lower Animas Basin	2,600	2,600
Redrock Sub-basin Inflows		
Mountain-front recharge	4,900 to 7,300	4,850
Redrock Sub-basin Outflows		
Discharge to Gila River between Redrock and Blue Creek gages	4,900 to 7,300	4,240
Underflow to Lower Animas Basin	0	580
Underflow to Virden-Duncan Sub-basin	0	30
Redrock Sub-basin total outflows	4,900 to 7,300	4,850
Virden-Duncan Sub-basin Inflows		
Underflow from Lower Animas Basin	12,700	13,280
Underflow from Redrock Sub-basin	0	30
Inflow from Gila River to aquifer	0	580
Virden-Duncan Sub-basin total inflow	12,700	13,890
Virden-Duncan Sub-basin Outflows		
Discharge to Gila River between Blue Creek gage and state line	12,700	13,890
Model Area Inflows		
Mountain-front recharge	13,000 to 15,400	12,950
Underflow from Upper Animas Basin	4,600	4,600
Inflow from Gila River to aquifer	0	580
Total Inflows	17,600 to 20,000	18,130
Model Area Outflows		
Discharge to Gila River between Redrock and Blue Creek gages	4,900 to 7,300	4,240
Discharge to Gila River between Blue Creek gage and state line	12,700	13,890
Total Outflows	17,600 to 20,000	18,130

In addition, 580 ac-ft/yr of inflow to the Lower Animas Basin from the Redrock sub-basin was calculated by the model. This reflects the presence of the ground-water divide in the Redrock sub-basin (plate 4) and resulting southward flow to the Lower Animas Basin, as discussed earlier. In the steady-state model all 13,280 ac-ft/yr of inflow to the Lower Animas Basin exits as underflow to the Virden-Duncan sub-basin.

In the Lordsburg Basin (table 5) a total of 2,600 ac-ft/yr of recharge was distributed along the eastern front of the Pyramid Mountains (680 ac-ft/yr, or about 40 ac-ft/mi), the southwestern front of the South Burro Mountains (1,600 ac-ft/yr, or about 57 ac-ft/mi), and the northwestern end of the Cedar Mountain Range (320 ac-ft/yr, or about 36 ac-ft/mi average). Outflow from the Lordsburg Basin of 2,600 ac-ft/yr was simulated as steady-state underflow to the Lower Animas Basin.

In the Redrock sub-basin (table 5), 4,850 ac-ft/yr (about 485 ac-ft/mi) of recharge was distributed along the southwestern front of the Big Burro Mountains (reach 7). Although this recharge rate is significantly higher than others used in the model area, it is comparable to rates of up to 440 ac-ft/mi simulated just across the divide in the Big Burro Mountains in the OSE Silver City model (Johnson, 2000; table 8). Of this inflow, 4,240 ac-ft/yr was simulated as steady-state discharge to the Gila River in the reach between the Redrock and Blue Creek gages (reach 1), 580 ac-ft/yr was simulated as steady-state underflow to the Lower Animas Basin, and the remaining 30 ac-ft/yr was simulated as underflow to the Virden-Duncan sub-basin. Some underflow to the Virden-Duncan sub-basin was expected, although no amount was estimated.

Inflow to the Virden-Duncan sub-basin consisted entirely of underflow from other basins and inflow from the Gila River; no recharge was simulated in this part of the model area. Simulated steady-state underflow from the Lower Animas Basin was 13,280 ac-ft/yr, and from the Redrock sub-basin was 30 ac-ft/yr. Another 580 ac-ft/yr of inflow to the Virden-Duncan sub-basin was simulated from the Gila River in the reach between the Blue Creek gage and the state line (reach 2). Total simulated steady-state discharge to the Gila River in reach 2 was 13,890 ac-ft/yr. Net discharge to the river in reach 2 was only 13,310 ac-ft/yr (table 5), because all of the simulated inflow to the aquifer from the river in this reach re-enters the river in that same reach. All of this inflow to the aquifer came from one constant-head cell near the head of the reach, near the mouth of the Lower Gila Box, indicating that the Lower Gila Box may be a losing reach of the Gila River.

Transient model testing

Following the steady-state calibration the model was tested against transient conditions. Estimated ground-water diversions for municipal uses at Lordsburg (table 9; figure 3) and other non-irrigation uses, and for irrigation in the Lower Animas and Lordsburg Valleys (table 10; figure 4) were applied as pumping stresses to the model. Ground-water withdrawals to supplement surface water irrigation in the Redrock and Virden Valleys were not simulated. Other pumping in the model area was assumed to have been minor, and was not included. Irrigation pumping was distributed based on OSE reports and digital coverages (Rappuhn, 2002), and municipal and industrial pumping was distributed based on information in OSE files and Gordon (1994).

Estimated municipal diversions at Lordsburg for the period 1920-2000 (table 9), industrial diversions at the Lordsburg Power Plant (1937-1994) and at a chile processing plant in the Animas Basin (1990-2000), and self-supplied commercial diversions associated with a greenhouse operation in the Animas Basin (1985-2000), were simulated in the model based on OSE reports, databases, files and other sources (Johnson, 2002). Irrigation diversions (figure 4) in the Lordsburg (1956-2000) and Lower Animas Basins (1947-2000) were simulated in the model based on various sources (Rappuhn, 2002).

A uniform storage coefficient of 0.1 was applied to the entire model area, based on values used previously for the Lordsburg Basin (0.10) by West (1961), and for the Lower Animas Basin (0.11) by Hawkins (1981) and O'Brien and Stone (1983). Simulated water levels were compared visually to maps of observed water-level declines in the Lower Animas Basin (Reeder, 1957; O'Brien and Stone, 1983), and to water-level altitudes in the Lordsburg Basin (unpublished maps in OSE files). Simulated water levels were not compared to observed water levels at specific points (wells) through time.

Simulated water-level declines by 1954 in the Lower Animas Basin are compared with observed declines mapped by Reeder (1957; fig. 35) on plate 8, and simulated declines by 1980 are compared with observed declines mapped by O'Brien and Stone (1983; fig. 15) on plate 9. In the Lordsburg Basin contours of simulated water-level altitude in 1960 (plate 10) and 1980 (plate 11) match contours on unpublished OSE maps reasonably well. The ability of the model to sufficiently reproduce historic responses to pumping in the Lower Animas and Lordsburg Basins indicates that it can be expected to predict effects of projected pumping in these areas reasonably accurately.

Table 9. Reported and estimated diversions at Lordsburg's wells and well fields, in acre-feet (ac-ft) and as a percentage of total pumping (%), as simulated in the Lower Animas-Lordsburg model (1920-2000).

Year(s)	Model stress period	East well field (LV-269,S,S-3) R28,C20		East WF (LV-269-S-2) R29,C20		North well field (LV-37 et al.) R26,C19		Well's well (LV-380) R26,C19		Total	Source[a]
		Ac-ft	%	ac-ft	%	ac-ft	%	ac-ft	%		
1920-26	1	104.09	100	--	--	--	--	--	--	104.09	BBERpop.X50 GPCD
1927-31	2	165.33	100	--	--	--	--	--	--	165.33	BBERpop.X50 GPCD
1932-36	3	243.22	100	--	--	--	--	--	--	243.22	BBERpop.X75 GPCD
1937-41	4	331.41	100	--	--	--	--	--	--	331.41	BBERpop.X75 GPCD
1942-46	5	267.19	60	--	--	178.13	40	--	--	445.32	BBERpopX100GPCD
1947	6	166.01	32	--	--	352.78	68	--	--	518.79	Linear interpolation
1948	7	173.85	32	--	--	369.43	68	--	--	543.28	Linear interpolation
1949	8	181.69	32	--	--	386.08	68	--	--	567.77	Linear interpolation
1950	9	189.53	32	--	--	402.75	68	--	--	592.28	BBERpopX150GPCD
1951	10	189.83	32	--	--	403.40	68	--	--	593.23	Linear interpolation
1952	11	190.14	32	--	--	404.05	68	--	--	594.19	Linear interpolation
1953	12	190.45	32	--	--	404.70	68	--	--	595.15	Linear interpolation
1954	13	190.75	32	--	--	405.35	68	--	--	596.10	Records in OSE file
1955	14	182.93	32	--	--	388.73	68	--	--	571.66	Records in OSE file
1956	15	208.41	32	--	--	442.87	68	--	--	651.28	Records in OSE file
1957	16	201.20	32	--	--	427.56	68	--	--	628.76	Records in OSE file
1958	17	164.34	25	--	--	493.02	75	--	--	657.36	Records in OSE file
1959	18	155.06	25	--	--	465.18	75	--	--	620.24	Records in OSE file
1960	19	194.96	25	--	--	584.87	75	--	--	779.82	Records in OSE file
1961	20	206.86	25	--	--	620.58	75	--	--	827.44	Linear interpolation
1962	21	218.76	25	--	--	656.29	75	--	--	875.06	Linear interpolation
1963	22	230.67	25	--	--	692.01	75	--	--	922.67	Linear interpolation
1964	23	242.57	25	--	--	727.72	75	--	--	970.29	Linear interpolation
1965	24	254.48	25	--	--	763.43	75	--	--	1017.91	Linear interpolation
1966	25	266.38	25	--	--	799.15	75	--	--	1065.53	Linear interpolation
1967	26	278.29	25	--	--	834.86	75	--	--	1113.15	Linear interpolation
1968	27	290.19	25	--	--	870.57	75	--	--	1160.76	Linear interpolation
1969	28	302.10	25	--	--	906.29	75	--	--	1208.38	Linear interpolation
1970	29	314.00	25	--	--	942.00	75	--	--	1256.00	NMOSE (1974)
1971	30	315.55	27	--	--	640.66	55	210.60	18	1166.82	Linear interpolation
1972	31	234.50	22	--	--	476.11	44	367.02	34	1077.63	Linear interpolation
1973	32	160.24	16	--	--	325.34	33	502.87	51	988.45	Linear interpolation
1974	33	99.52	11	--	--	196.75	22	602.99	67	899.26	Records in OSE file
1975	34	245.70	25	105.30	11	351.00	35	285.00	29	987.00	Sorensen (1977)
1976	35	395.98	42	169.71	18	377.12	40	0.59	0	943.40	Linear interpolation
1977	36	440.90	49	188.96	21	269.94	30	--	--	899.80	Linear interpolation
1978	37	479.47	56	205.49	24	171.24	20	--	--	856.20	Linear interpolation
1979	38	511.94	63	219.40	27	81.26	10	--	--	812.60	Linear interpolation
1980	39	538.30	70	230.70	30	--	--	--	--	769.00	Sorensen (1982)
1981	40	554.65	70	237.71	30	--	--	--	--	792.36	Linear interpolation
1982		571.00	70	244.72	30	--	--	--	--	815.72	Linear interpolation
1983		587.36	70	251.72	30	--	--	--	--	839.08	OSE meter records
1984		553.25	70	237.11	30	--	--	--	--	790.36	OSE meter records
1985		585.20	70	250.80	30	--	--	--	--	836.00	OSE meter records
1986	41	476.71	70	204.30	30	--	--	--	--	681.01	OSE meter records
1987		543.68	70	233.00	30	--	--	--	--	776.68	OSE meter records
1988		572.28	70	245.26	30	--	--	--	--	817.54	OSE meter records
1989		557.90	70	239.10	30	--	--	--	--	797.00	OSE meter records
1990		577.36	70	247.44	30	--	--	--	--	824.80	OSE meter records
1991	42	475.81	70	203.92	30	--	--	--	--	679.73	OSE meter records
1992		505.82	70	216.78	30	--	--	--	--	722.60	OSE meter records
1993		553.18	70	237.08	30	--	--	--	--	790.26	OSE meter records
1994		565.61	70	242.40	30	--	--	--	--	808.01	OSE meter records
1995		546.16	70	234.07	30	--	--	--	--	780.23	OSE meter records
1996	43	561.62	70	240.69	30	--	--	--	--	802.31	OSE meter records
1997		577.29	70	247.41	30	--	--	--	--	824.70	OSE meter records
1998		513.60	70	220.11	30	--	--	--	--	733.71	OSE meter records
1999		537.81	70	230.49	30	--	--	--	--	768.30	OSE meter records
2000		572.60	70	245.40	30	--	--	--	--	818.00	OSE meter records

[a]BBERpop = Population from UNM Bureau of Business and Economic Research; GPCD = gallons per capita per day

Figure 3. Estimated municipal ground-water withdrawals by the City of Lordsburg (1920-2000)

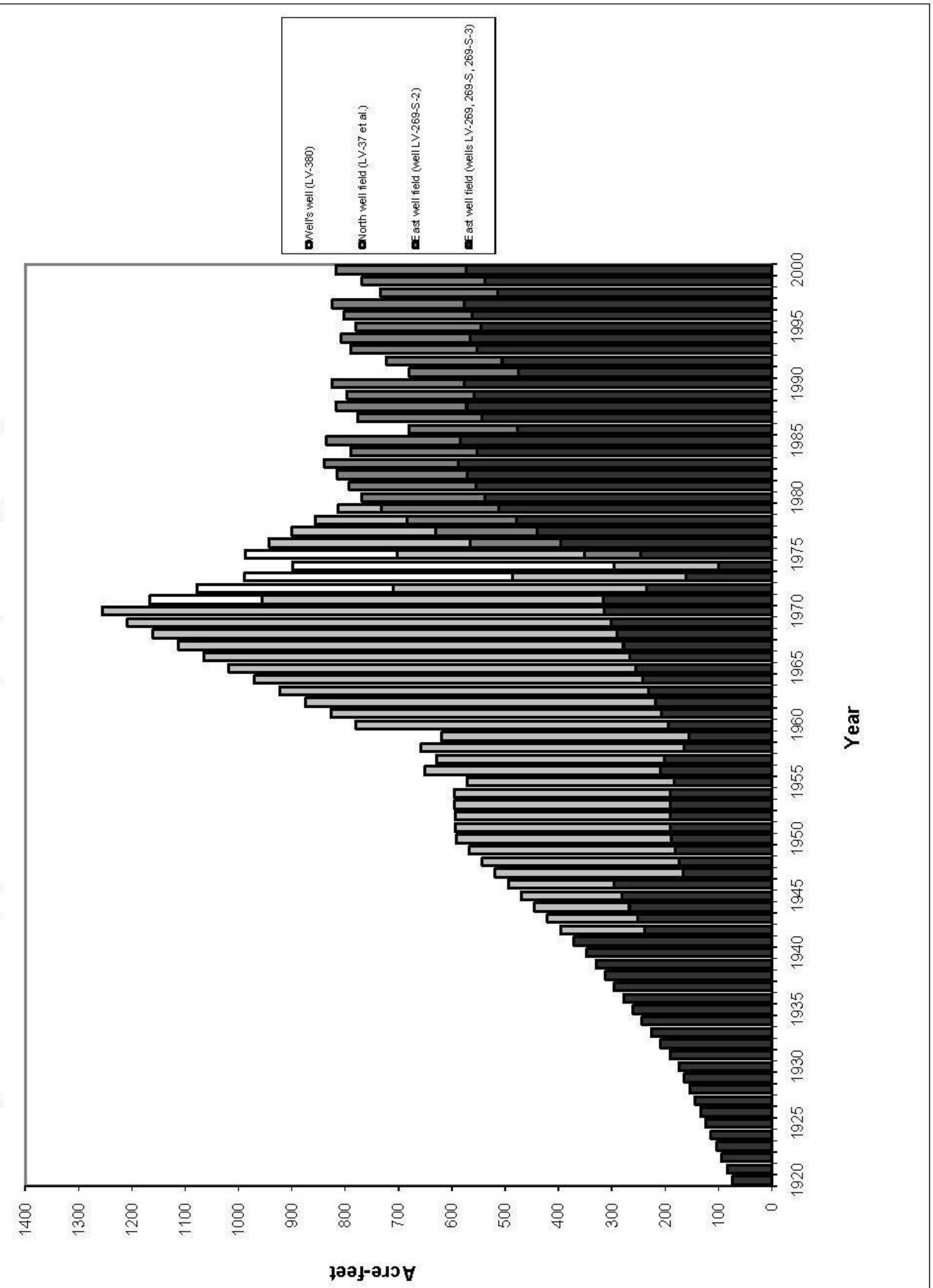
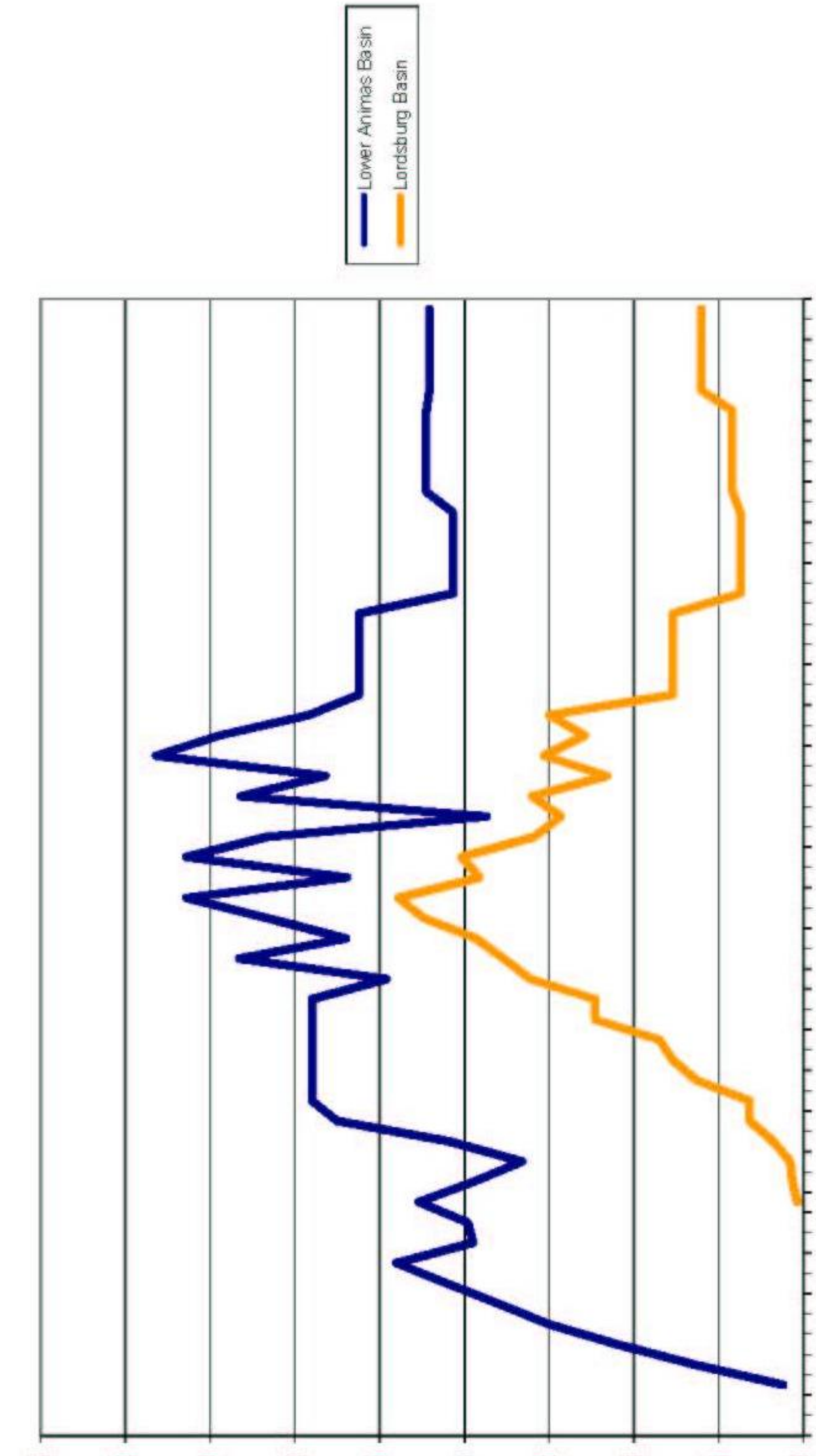


Table 10. Irrigated acreage and ground-water withdrawals in acre-feet, Lower Animas and Lordsburg Sub-basins, as simulated in the Lower Animas-Lordsburg model (1947-2000).

Year(s)	Model stress period	Lower Animas Basin		Lordsburg Basin	
		Estimated irrigated acreage	Ground-water withdrawals	Estimated irrigated acreage	Ground-water withdrawals
1947	6	800	1,200	--	--
1948	7	4,000	6,400	--	--
1949	8	6,800	11,000	--	--
1950	9	7,900	15,000	--	--
1951	10	9,000	18,000	--	--
1952	11	10,900	21,000	--	--
1953	12	11,000	24,000	--	--
1954	13	11,400	19,500	--	--
1955	14	11,400	19,800	--	--
1956	15	12,500	22,700	200	370
1957	16	12,800	19,500	435	660
1958	17	12,800	16,600	600	780
1959	18	12,800	20,900	1,090	1,780
1960	19	12,800	27,500	1,480	3,180
1961	20	12,800	29,000	1,480	3,180
1962	21	12,800	29,000	2,535	6,300
1963	22	12,800	29,000	3,590	7,700
1964	23	12,800	29,000	4,645	8,500
1965	24	12,800	29,000	5,700	12,300
1966	25	12,800	29,000	6,408	12,300
1967	26	12,800	24,600	7,116	16,100
1968	27	12,800	33,300	7,824	17,700
1969	28	11,940	27,000	8,530	19,300
1970	29	14,000	31,640	9,890	22,400
1971	30	14,000	36,400	9,176	23,900
1972	31	14,000	26,900	8,462	19,100
1973	32	14,000	36,400	7,748	20,200
1974	33	14,000	31,640	7,034	15,900
1975	34	8,250	18,700	6,320	14,300
1976	35	14,680	33,200	6,168	16,000
1977	36	14,680	28,200	6,016	11,600
1978	37	14,680	38,200	5,864	15,300
1979	38	12,745	34,400	5,712	12,900
1980	39	10,810	29,190	5,560	15,010
1981-1985	40	[a] 8,566	26,220	[a] 3,289	7,720
1986-1990	41	[a] 6,269	20,690	[a] 1,321	3,730
1991-1995	42	[a] 6,687	22,250	[a] 1,176	4,190
1996-2000	43	[a] 6,813	22,060	[a] 1,645	6,040

Data sources and conventions from Rappuhn (2002).
[a] 5-year value derived from approximate average of end-members

Figure 4. Estimated irrigation groundwater withdrawals in Lower Animas and Lordsburg Basins (1947-2000)



MODEL USES AND LIMITATIONS

The Lower Animas-Lordsburg model described in this report should be considered a preliminary effort to simulate the ground-water system in the study area. The model was designed to predict effects of ground-water pumping based on projected demands for the area, and so can be used to make similar predictive calculations, such as estimating drawdowns and surface water depletions from water rights applications in the Lordsburg UWB, and that portion of the Animas Valley UWB located in the model area. The model was not designed for, and should not be used for evaluations in those portions of the Virden Valley and Gila-San Francisco UWBs located in the model area (plate 3).

The single storage coefficient used in the model matches that used in analytical methods used by OSE such as the Theis equation and the model of West (1961). As a result of model calibration the distribution of aquifer thickness and hydraulic conductivity varies spatially, and should provide a more realistic representation of the response of the ground-water system to stresses than the single transmissivity value used in analytical methods. Likewise, the boundary conditions are somewhat more realistic, and allow for estimating depletions to the Gila River, should such calculations be needed. However, local drawdowns (within one mile of the pumping well) are not well simulated by the model due to discretization effects. It is recommended that the Theis equation or other suitable methods such as a local finely gridded numerical model be used to estimate drawdowns within one mile of the pumping well.

Better control on the spatial distribution of heads and aquifer properties could improve model calibration. The data set used for the steady-state calibration contained no values northeast of a line between the Summit Hills and Lordsburg. Supplementing this data set could improve the calibration for the northern part of the model area. Aquifer hydraulic conductivity values were varied during calibration within wide published ranges of values for particular HSUs, and have not been rigorously verified against field data. Also, only one value of storage coefficient was used in the model, while storage coefficient in the aquifer may vary significantly by location. For a regional model of an area with limited field data such as this one, and given the time constraints on this project, this approach was not an unreasonable one. However, it is recommended that available field data for these aquifer parameters be compiled and compared to model values, and adjustments to the model made as necessary.

The Lower Animas-Lordsburg model may be used as a source of hydrogeologic information, including values for aquifer parameters such as hydraulic conductivity (K), transmissivity (T) and storage coefficient (S), for use in analytical equations for drawdown (Theis) and stream depletion (Glover-Balmer). However, care must be exercised in using values from a regional model such as this in determining local impacts when other site-specific data may be more appropriate.

Boundary conditions at the gaps between the Lower Animas and Lordsburg Basins and adjacent basins such as the Playas and Hachita Basins were represented simply as no-flow boundaries in the model. However, some interpretations of water-level data indicate that inter-basin underflow may have occurred at these divides under pre-development conditions, and may still be occurring. Other methods should be explored to represent conditions at these divides, to better simulate the effects of pumping on possible inter-basin flows. Alternative simulations of the Gila River boundary condition, simulated simply in this model as a constant-head boundary, should also be explored.

Because only one layer was used to simulate the flow system, vertical head differences and flows in the basin-fill flow system, including possible deep geothermal recharge to the system in the Lightning Dock KGRA, are not simulated. Multi-layer simulation of the entire basin-fill thickness should be considered to better represent these aspects of the flow system. The hydrogeologic framework of Hawley and others (2000) could be used to readily adapt the current model for such multi-layer simulation.

The model was not rigorously calibrated to transient conditions, and formal sensitivity analysis was not performed. Estimates of historical ground-water withdrawals for irrigation, municipal, and other uses in the Lower Animas and Lordsburg Basins made for this investigation could be used in a transient calibration of the model. These estimates are considered improvements over previous efforts, but still have a considerable amount of uncertainty associated with them. If possible other ground-water withdrawals in the model area not considered in this investigation should be estimated and included in any transient calibration as well. While transient calibration and sensitivity analysis would improve any final version of the Lower Animas-Lordsburg model, the model in its present form is believed suitable for simulating ground-water flow and estimating the effects of ground-water pumping in the Lower Animas and Lordsburg Basins.

REFERENCES

Anderson, M. P., and Woessner, W. W., 1992, Applied ground-water modeling: simulation of flow and advective transport: Academic Press, San Diego, California.

Elston, W. E., Deal, E. G., and Logsdon, M. J., 1983, Geology and geothermal waters of Lightning Dock region, Animas Valley and Pyramid Mountains, Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 177.

Environmental Simulations, Inc. (ESI), 1998, Guide to using Groundwater Vistas, stochastic version 2.0: computer software and manual, ESI, Herndon, Virginia.

Gordon, N., 1994, A 40-year water plan for the City of Lordsburg, New Mexico: Final report prepared for the City of Lordsburg by Engineers, Inc., December 1994.

Harbaugh, A. W., and McDonald, M. G., 1996, User's documentation for MODFLOW-96, an update to the U. S. Geological Survey Modular Finite-Difference Ground-Water Flow Model: U. S. Geological Survey Open-File Report 96-485.

Hawkins, D. B., 1981, Geohydrology of the Animas Valley, Hidalgo County, New Mexico: A computer simulation study, New Mexico Institute of Mining and Technology independent study project, July 1981.

Hawley, J. W., Hibbs, B. J., Kennedy, J. F., Creel, B. J., Remmenga, M. D., Johnson, M., Lee, M. M., and Dinterman, P., 2000, Trans-international boundary aquifers in southwestern New Mexico: prepared for the U. S. Environmental Protection Agency and the International Boundary and Water Commission, March 2000.

Johnson, M. S., 2000, Hydrologic evaluation of application GSF-1745 into GSF-1014 for permit to change location of well and place or purpose of use in the Gila-San Francisco Underground Water Basin, Grant County, New Mexico: New Mexico Office of the State Engineer Technical Division Hydrology Report 00-3, December 2000.

Johnson, M. S., 2002, Simulation of non-irrigation ground-water withdrawals in the preliminary OSE Lower Animas-Lordsburg ground-water flow model: New Mexico Office of the State Engineer memorandum to the file, May 24, 2002.

Johnson, M. S., Logan, L. M., and Rappuhn, D. H., 2002, Analysis of effects of ground-water development to meet projected demands in regional planning district 4, southwest New Mexico: New Mexico Office of the State Engineer Technical Division Hydrology Report 02-X (DRAFT), March 2002.

Lazarus, J., and Morgan, P., 1989, Geohydrologic survey, Hidalgo County, New Mexico: prepared by Glorieta Geoscience, Inc., October 1989.

Loeltz, O. J., and Murray, C. R., 1942, Report on testing of water supply for Lordsburg Airfield, Lordsburg, New Mexico, July 1942: U. S. Geological Survey report.

Morgan, A. M., Murray, C. R., Loeltz, O. J., and Theis, C. V., 1942, Ground water studies near Lordsburg, New Mexico: U. S. Geological Survey report prepared in cooperation with the State Engineer of New Mexico.

Murray, C. R., 1942, Report on pumping tests conducted for the U. S. Corps of Engineers on Lordsburg Army Camp Well No. 1, in New Mexico, April 1942: U. S. Geological Survey report.

[NMSEO/ISC] New Mexico State Engineer Office/Interstate Stream Commission, 1974, County profile, Hidalgo County, New Mexico: Water Resources Assessment for Planning Purposes.

O’Brien, K. M., and Stone, W. J., 1981, Water-level data compiled for hydrogeologic study of Animas Valley, Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-File Report 130.

O’Brien, K. M., and Stone, W. J., 1982a, Water-quality data compiled for hydrogeologic study of Animas Valley, Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-File Report 131, February 1982.

O’Brien, K. M., and Stone, W. J., 1982b, Drill hole and testing data compiled for hydrogeologic study of Animas Valley, Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-File Report 132, March 1982.

O’Brien, K. M., and Stone, W. J., 1983, A two-dimensional hydrologic model of the Animas Valley, Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-File Report 133, January 1983.

Rappuhn, D. H., 2002, New Mexico Office of the State Engineer memorandum to the file, 2002.

Reeder, H. O., 1957, Ground water in Animas Valley, Hidalgo County, New Mexico: New Mexico Office of the State Engineer Technical Report 11, prepared in cooperation with the U. S. Geological Survey.

Schwennesen, A. T., 1918, Ground water in the Animas, Playas, Hachita, and San Luis Basins, New Mexico: U. S. Geological Survey Water-Supply Paper 422.

Stone, W. J., and O’Brien, K. M., 1990, Preliminary work for a hydrologic report on Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-File Report 372.

Trauger, F. D., 1972, Water resources and general geology of Grant County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Hydrologic Report 2.

TSGTA (Tri-State Generation and Transmission Association, Inc.), 2001, Applicant’s plan for water conservation (file nos. LV-8, LV-9, LV-40, LV-40-S, and LV-282 combined): submitted to Office of the State Engineer, June 29, 2001.

Turner, S. F., 1960, Ground-water resources of the valley southeast of Lordsburg, Hidalgo County, New Mexico: report by Turner and Associates, August 1960.

Turner, S. F., and Manera, P. A., 1965, Geology and hydrology of the Lordsburg Mesa drainage area, Hidalgo County, New Mexico: report by Turner and Associates and E. R. Geophysical Company.

West, F. G., 1961, Technical basis for the administration of the Lordsburg Valley Underground Water Basin: New Mexico Office of the State Engineer inter-office memorandum, March 16, 1961.

Wilson, B., 1986, Water use in New Mexico in 1985: New Mexico Office of the State Engineer Technical Report 46, November 1986.

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

Wilson, B. C., 2001, Projected water demands in Grant, Hidalgo, and Luna Counties, New Mexico, 2000 to 2040: New Mexico Office of the State Engineer report, December 16, 2001.

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 Office of the State Engineer Technical Report 49, September 1997.

PLATES