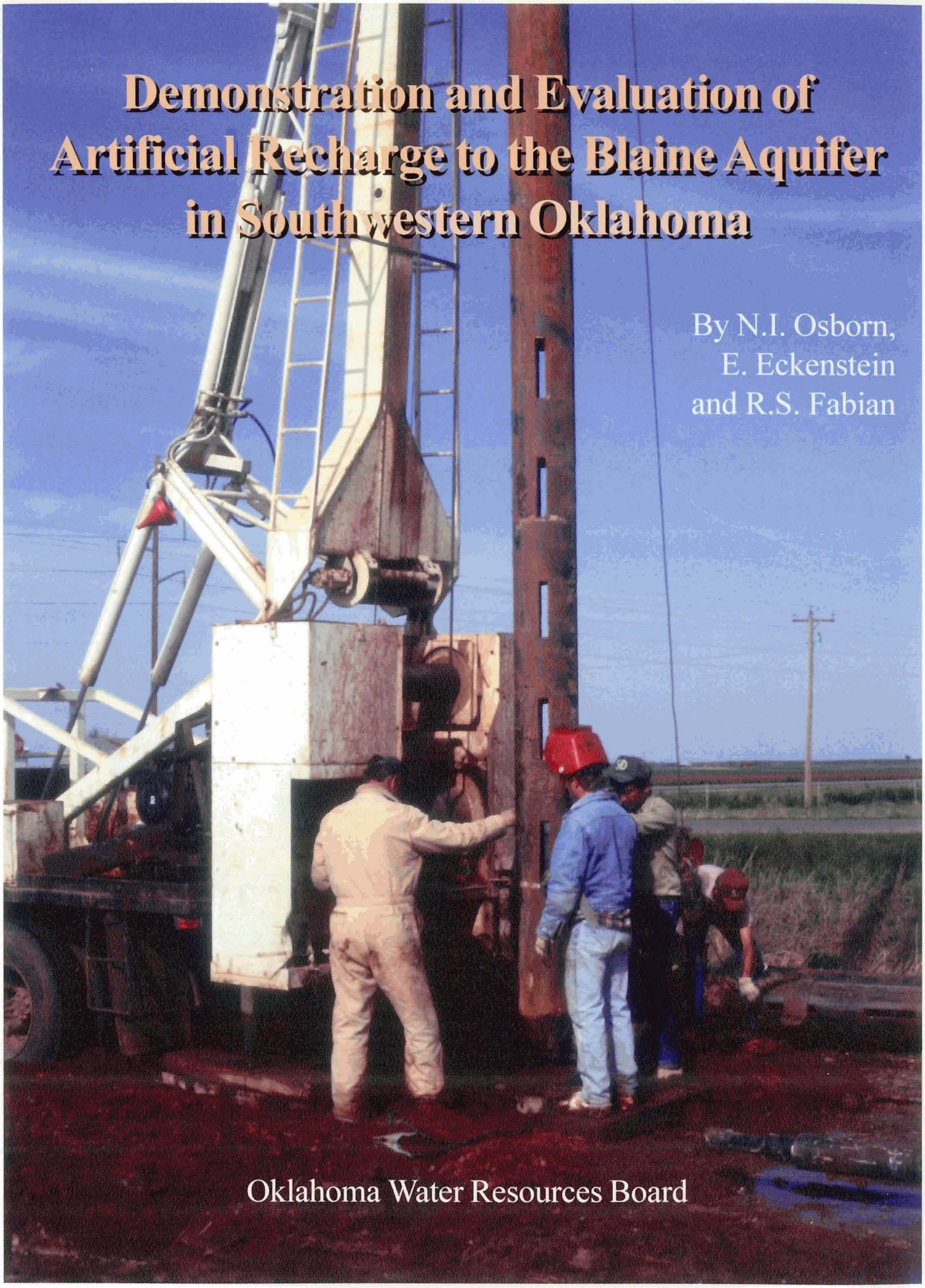


Demonstration and Evaluation of Artificial Recharge to the Blaine Aquifer in Southwestern Oklahoma

By N.I. Osborn,
E. Eckenstein
and R.S. Fabian

Oklahoma Water Resources Board

Demonstration and Evaluation of Artificial Recharge to the Blaine Aquifer in Southwestern Oklahoma

By N.I. Osborn, E. Eckenstein, and R.S. Fabian

Oklahoma Water Resources Board
Technical Report 97-5

December 1997

Acknowledgments

The authors would like to extend thanks to the Southwest Water and Soil Conservation District and to individuals in Harmon, Jackson, and Greer counties who have provided information and permitted access to their land. Particular recognition is due to Paul Horton for his support of the project and help in obtaining easements and to Gene Pierce for his watchful eye and careful maintenance of the recharge sites. Thanks are extended to the Oklahoma Department of Environment Quality Laboratory for analyzing the water quality samples. Thanks to Jamie Schlottmann Norvell with the USGS for her assistance with the statistical analysis of the water quality data. Also, thanks to Dr. Kenneth Johnson with the Oklahoma Geological Survey for his technical assistance and review regarding information on the Blaine Formation.

The authors are especially thankful for the tireless efforts of Kim Sullivan and Hank Elling, who monitored the equipment and collected monitoring data and water samples. The assistance of OWRB staff Mark Belden, Susan Birchfield, Linda Eaton, Gary Glover, Lou Klaver, James Leewright, Ira Smith, Mike Sughru, Deanne Whiteaker, and Kent Wilkins is also greatly appreciated.

This manuscript is submitted for publication with the understanding that the United States Government is authorized to reproduce and distribute reprints for governmental purposes. Research was supported by the U.S. Department of the Interior, Bureau of Reclamation, under Bureau Cooperative Agreement O-FC-60-01170. Any use of trade names in this publication is for descriptive purposes and does not imply endorsement by the State of Oklahoma or U.S. Government.

This publication is prepared, issued and printed by the Oklahoma Water Resources Board. 150 copies were prepared at a cost of $14.00. Copies have been deposited with the Publications Clearinghouse at the Oklahoma Department of Libraries.

Contents

Figures

Tables

Acronyms and Abbreviations

cfs	cubic foot per second
CN	curve number method for determining precipitation runoff
District	Southwest Water and Soil Conservation District
EPA	U.S. Environmental Protection Agency
ft	feet
ft/day	feet per day
ft^2/day	feet squared per day
FWS	U.S. Fish and Wildlife Service
GC/MS	gas chromatograph mass spectrometer
gpm	gallons per minute
HAL	health advisory level
Hollis	Town of Hollis
MCL	maximum contaminant level
meq/L	milliequivalents per liter
mg/L	milligrams per liter
MRL	Minimum reporting limit
n	Sample size
NEXRAD	Next Generation Weather Radar
NOAA	National Oceanic and Atmospheric Administration
ODEQ	Oklahoma Department of Environmental Quality
OWRB	Oklahoma Water Resources Board
PVC	polyvinyl chloride
Reclamation	U.S. Bureau of Reclamation
SCS	Soil Conservation Service Division of the USDA
TDS	total dissolved solids
TSS	total suspended solids
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VOC	volatile organic compound
μg/L	micrograms per liter

Introduction

BACKGROUND

The Blaine Gypsum Groundwater Recharge Demonstration Project was one of 13 demonstration projects implemented by the Bureau of Reclamation (Reclamation) and local sponsors in cooperation with the Environmental Protection Agency (EPA) and the U.S. Geological Survey (USGS) under the "High Plains States Groundwater Demonstration Program Act" of 1983. The primary purpose of this act was to advance state-of-the-art groundwater recharge techniques.

The purpose of the Blaine Gypsum Groundwater Recharge Demonstration Project was to demonstrate the feasibility and effectiveness of recharging the cavernous Blaine aquifer with surface runoff. Recharge to the aquifer was accomplished with recharge wells that intercepted surface runoff and channeled the water, by gravity flow, into cavities within the aquifer. The project consisted of five recharge sites near the Town of Hollis (Hollis), in southwestern Oklahoma. Recharge facilities included five recharge wells, one impoundment, and 24 monitoring wells.

This report summarizes the project activities and findings. More information can be found in the *Blaine Gypsum Groundwater Recharge Demonstration Project Final Report*. A summary of water quantity and quality data is available in a supplementary data report. Copies of these reports may be obtained by contacting Ms. Susan Birchfield, Oklahoma Water Resources Board, 3800 North Classen Boulevard, Oklahoma City, OK 73118; telephone: (405) 530-8800. Monitoring data collected after September 1996 are not included in any of the reports. These data are available from the OWRB upon request.

PARTICIPANTS

The study was sponsored by the Oklahoma Water Resources Board (OWRB), which oversaw the construction of the recharge facilities, operated and maintained the project, and conducted the monitoring program. The OWRB also analyzed and interpreted the data and wrote the final report.

The OWRB worked in cooperation with the Southwest Water and Soil Conservation District (District). The District secured permits, land, and easements; assisted with the maintenance of the recharge facilities; and served as a liaison between the OWRB and local entities.

Reclamation, USGS, and EPA participated in evaluating the project proposal, Development Plan, Quality Assurance Plan, Monitoring and Mitigation Plan, and quarterly and final reports. The USGS provided technical assistance for the water quality analysis and interpretation. The EPA reported to Congress on the impacts to surface water and groundwater quality. Reclamation worked in coordination with the U.S. Fish and Wildlife Service (FWS) to assure that any adverse impacts on fish and wildlife resources were mitigated.

LOCAL PROBLEMS AND NEEDS

The economy of the study area is based on agriculture, with land being used for crops, pasture, and rangeland. The Blaine aquifer is the primary source of irrigation water. Drinking water is supplied by wells in the alluvial and terrace deposits of the Salt Fork of the Red River, located outside the study area.

During the 1960s, southwestern Oklahoma experienced a decline in the water table of the Blaine aquifer due to increasing use of irrigation and to a series of droughts that occurred in the 1950s and 1960s. Water levels declined again in the 1980s. Some wells went dry and water quality in other wells deteriorated due to induced infiltration of salt water from underlying strata and from the Red River.

In 1968 farmers in Harmon County, primarily around Hollis, formed the District. The purpose of the District was to find ways to augment the supply of water in the Blaine aquifer to prevent irrigation wells from going dry. To date, the District has constructed about 70 recharge wells and four diversions. About 45 recharge wells are currently in operation.

PURPOSE AND OBJECTIVES

The purpose of the Blaine Gypsum Groundwater Recharge Demonstration Project was to demonstrate the feasibility and effectiveness of recharging surface runoff into the cavernous Blaine aquifer with gravity-flow wells. Specific study objectives were to determine:

1. The volume of water artificially recharged to the aquifer.
2. The impact of artificial recharge on the water quality of the aquifer.
3. The economic feasibility of this method of artificial recharge.

Site Conditions

AREA DESCRIPTION

Physical Setting

The study area is defined by the drainage basin for Sandy Creek and encompasses the recharge and discharge areas for the project's recharge wells (Figure 1). It covers 373 square miles in Harmon and Jackson counties in southwestern Oklahoma, and in Childress and Collingsworth counties in the Texas panhandle. The project area, which encompasses the five recharge sites, is located within three miles of Hollis (Figure 2).

The study area is in the Southwest Plains physiographic province. The ground surface slopes gently to the southeast, with the altitude ranging from about 1,950 feet in the northwest to about 1,290 feet in the southeast.

Soils

Two basic types of soils are present over the study area: deep to shallow, well drained, loamy and sandy soils on uplands (Grandfield-Devol and Tipton-Westview-Altus map units) and very shallow to deep, well drained to excessively drained, sandy, loamy, and clayey soils on uplands (Tillman-Vernon map unit) (USDA, 1984).

The Grandfield-Devol map unit consists of nearly level to strongly sloping soils on smooth to hummocky uplands. The Tipton-Westview-Altus map unit consists of nearly level to very gently sloping soils on smooth concave and slightly convex stream terraces. The Tillman-Vernon map unit consists of areas of soils on smooth, broad uplands (USDA, 1984).

Climate

The study area has a dry, sub-humid climate. The normal annual precipitation (1961-1990) at Hollis is 23.32 inches. Most precipitation occurs in the spring, summer, and fall as torrential rains of short duration. Figure 3 shows the monthly normal precipitation for Hollis. About 71% of the annual precipitation occurs between May and October, with the highest occurring in May and June, and the lowest in December and January (NOAA, 1992).

Figure 4 shows the historical annual precipitation at Hollis for 1923 through 1995. Annual precipitation for the period of record ranges from a minimum of 10.37 inches in 1933 to a maximum of 45.15 inches in 1941. Monthly precipitation extremes were 13.06 inches in October 1923, 11.85 inches in May 1949, and 11.83 inches in October 1983.

The normal annual temperature for Hollis is 62°F. Summer temperatures often exceed 100°F while winter temperatures can drop near zero (NOAA, 1992).

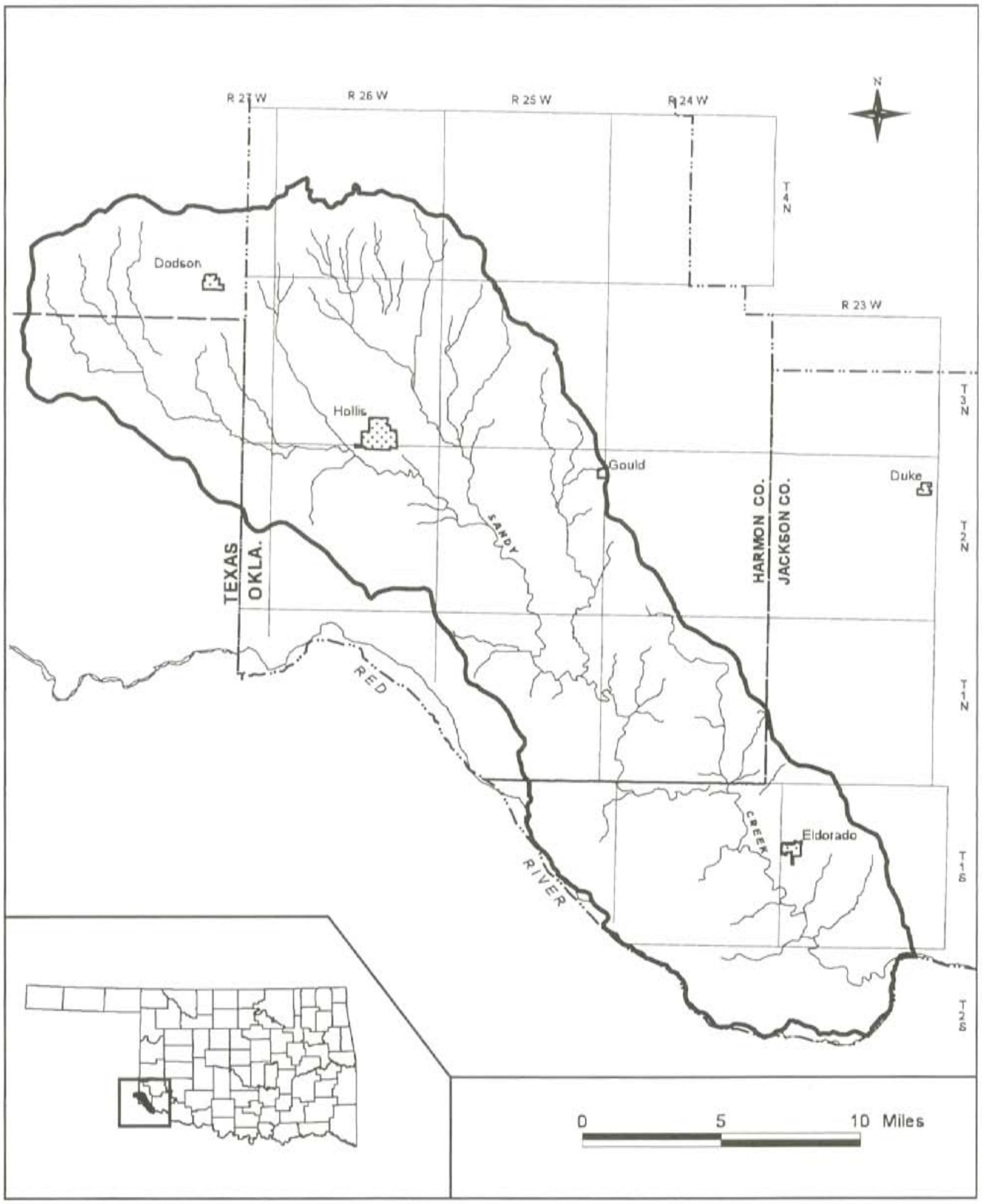


Figure 1. Study area of the Blaine Gypsum Groundwater Recharge Demonstration Project.

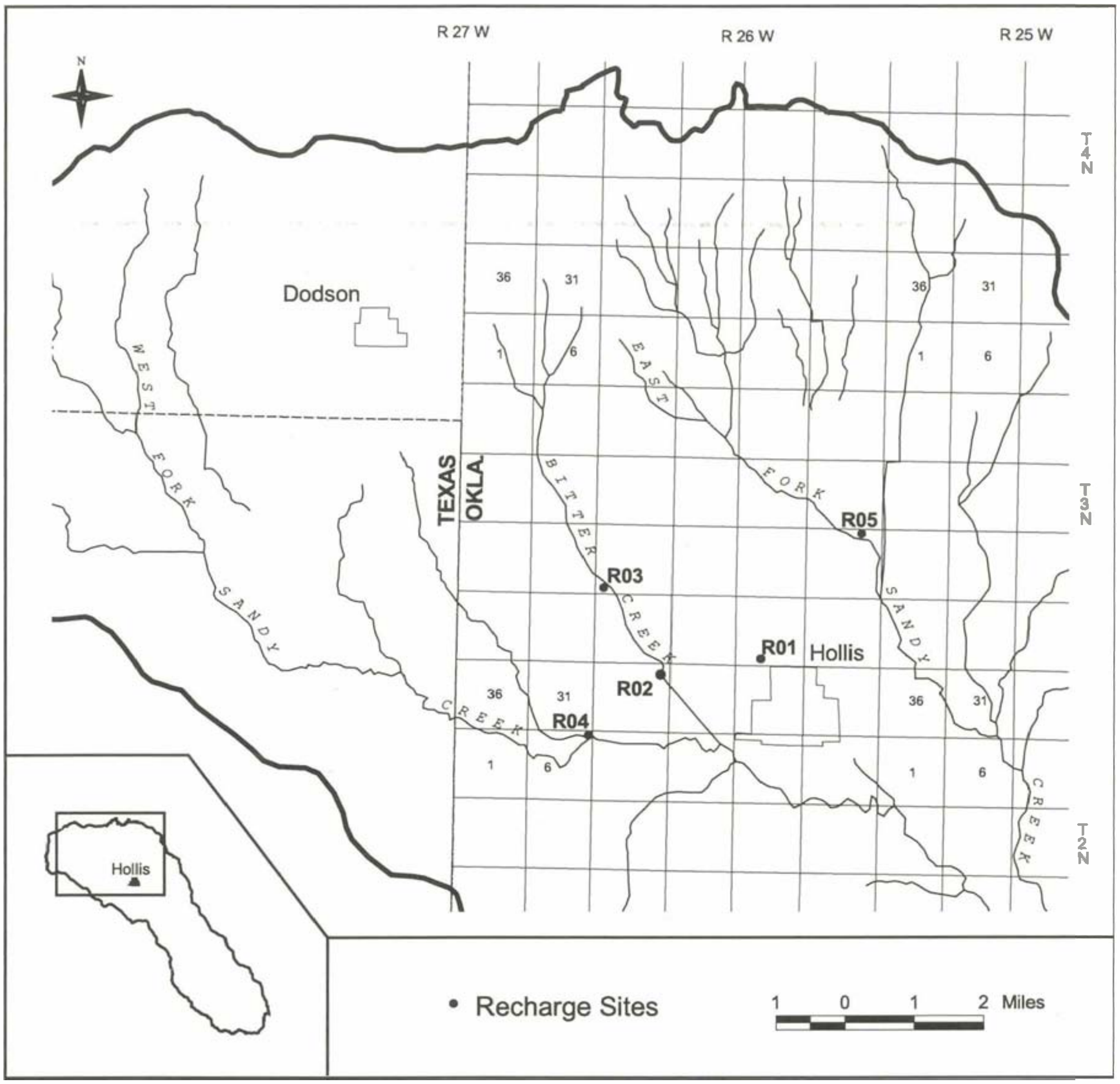


Figure 2. Project area showing recharge sites.

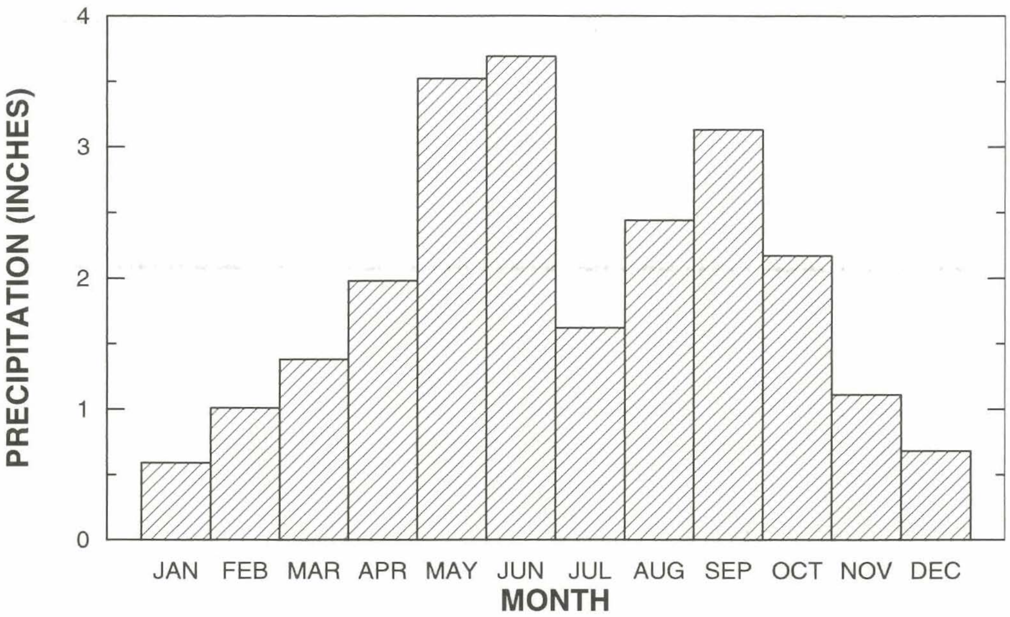


Figure 3. Monthly normal precipitation for Hollis (1961-1990).

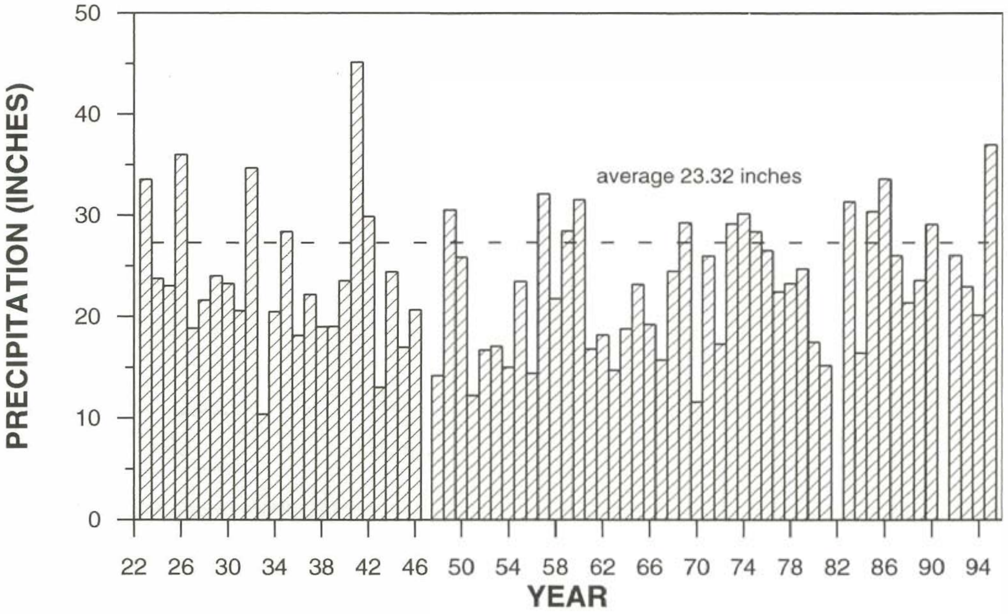


Figure 4. Annual precipitation (1923-1995) recorded at the Hollis rain gauge.

LAND AND WATER

Population

According to the 1990 census, the population of the study area is about 3,400. Hollis, Eldorado, and Gould are the only incorporated towns in the area. Hollis is the largest, with a population of about 2,580.

Land Use

The economy of the area is based on agriculture, with land being used for crops, pasture, and rangeland. The primary crops are cotton, wheat, sorghum, and alfalfa.

A land use survey was conducted in 1991 in which surveys were mailed to 79 landowners within a forty-mile radius of Hollis. The survey requested information regarding crops and chemical uses for the years 1988 to 1990. Twenty-one landowners, representing 30 farms and about 10,500 acres of land, responded.

Survey results indicate that farming practices remained the same over the three-year period. The dominant crop was cotton, followed by wheat and pasture. Cotton was irrigated during the summer, and wheat was irrigated throughout the year. Cotton was fertilized during the spring and summer, and wheat was generally fertilized in the fall.

The most commonly used pesticides for the area were trifluralin (Treflan) and pendimethalin (Prowl). Both are herbicides which are used for pre-emergent control of grass and weeds. They are applied to cotton crops during the spring. Other reported pesticides include ethephon (Prep-new), which is a defoliant applied to cotton in the fall, and methyl parathion (Penncap-M), an organophosphorus insecticide.

Water Use

Groundwater

The drinking water supply for the towns and the rural population is supplied by wells in the alluvial and terrace deposits of the Salt Fork of the Red River, located outside the study area. The Blaine aquifer is a potential source of drinking water, as defined by the EPA, but is too highly mineralized to be used as a drinking water supply.

While the Blaine aquifer is not used as a drinking water supply, it is suitable for irrigation of some crops. The Blaine aquifer is the primary source of irrigation water in the study area. Irrigation wells are typically 50 to 300 feet deep and yield 300 to 2,000 gallons per minute (gpm). The highest yielding wells are drilled within three miles of Sandy Creek, where aquifer permeability and cavern development are greatest.

The first irrigation well in the Blaine aquifer was drilled in 1946. Irrigation has increased rapidly since 1950. By 1955, more than 300 wells had been drilled in Harmon County. To date, more than 350 irrigation wells have been drilled in the study area.

When irrigation first developed, most of the water was distributed by open head ditches and furrows. In the early 1970s, many irrigators changed from furrow systems to sprinkler systems. Now almost half of the irrigated acreage is watered by sprinklers, with the center-pivot and self-propelled types being the most common (USDA, 1984).

Allocated water from the Blaine aquifer is used exclusively for irrigation. Within the study area, 86,702 acre-feet/year of water is allocated to irrigate 52,143 acres of land.

Oklahoma water law requires permitted water users to report annually how much water they pumped. Figure 5 shows the annual pumpage from the Blaine aquifer for the study area since 1967. The average annual pumpage for the time of record is 17,130 acre-feet/year. The lowest reported water use was 6,004 acre-feet in 1992, and the highest was 23,925 acre-feet in 1980.

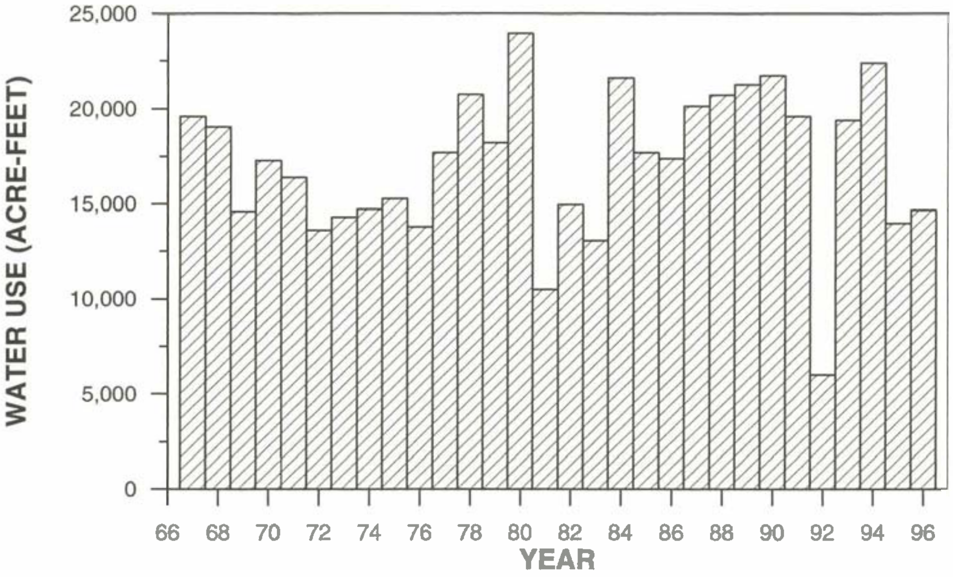


Figure 5. Reported annual pumpage from the Blaine aquifer in the study area.

In dry years, when precipitation was low and pumpage was high, irrigation wells went dry. This occurred in the mid 1960s and 1980s. Also during these years, water quality in some wells deteriorated because of induced infiltration of salt water from the Red River and from the underlying Flowerpot Shale.

Stream Water

The water quality of the Red River is poor, and is not used for drinking water or irrigation in the study area. The OWRB has determined that about 15,500 acre-feet of water is available from Sandy Creek on an annual basis. However, only a small portion (2,914 acre-feet) has been permitted for water use. Of this, 2,000 acre-feet is allocated for artificial recharge and 914 acre-feet for irrigation.

GEOLOGY

Structural Setting

The study area lies within the Hollis basin, a large structural basin located in southwestern Oklahoma and adjacent parts of Texas. The basin developed early in the Pennsylvanian Period, and contains 3,000 to 12,000 feet of sediments of Late Cambrian to Permian age. Sediments in the basin were folded and faulted during the Pennsylvanian Period. Vertical displacement across deep-seated faults is hundreds to thousands of feet, whereas displacement across the faults at the land surface ranges from 10 to 90 feet. Younger Permian strata drape across the deep-seated structures. Outcropping rocks are flat-lying, dipping less than one degree. Figure 6 shows the structure map of the base of the Blaine Formation (Johnson, 1985).

Stratigraphy

A thick sequence of Permian redbeds and evaporites was deposited in the basin, when a broad, shallow sea covered much of southwestern United States. The stratigraphic sequence of Permian units is, in ascending order, the Flowerpot Shale, Blaine Formation, Dog Creek Shale, and the Whitehorse Group (Figure 7). Figure 8 shows the surface geology of the Blaine aquifer (from Havens, 1977 and Cederstrand, 1997).

The Flowerpot Shale consists of 150 to 300 feet of red-brown shale interbedded with thin layers of gypsum, dolomite, siltstone, and green-gray shale (Johnson, 1990a). The Flowerpot yields small quantities of saline or brackish water. One water sample collected in 1987 near Eldorado had a concentration of 82,900 mg/L of sodium and 194,100 mg/L of chloride (Runkle and Johnson, 1988).

The Blaine Formation consists of a cyclic series of interbedded gypsum, shale, and dolomite (Johnson, 1990a). Each cycle consists of a thin layer of dolomite (0.5 to 5 ft thick), overlain by a layer of gypsum or anhydrite (5-30 ft thick), and topped with a layer of shale (1-50 ft thick). The formation ranges from 180 to 220 feet thick and averages 200 feet thick.

The Blaine Formation is subdivided into the Elm Fork and Van Vacter Members. Although each member is about 100 feet thick, the Elm Fork Member consists of three thick gypsum beds separated by thick shales (10-30 ft), and the Van Vacter Member consists of six gypsum beds separated by thin shales (0.5-3.0 ft).

The thin shale units of the Van Vacter Member are readily eroded when groundwater dissolves adjacent gypsum beds, thus developing a good hydraulic connection between the six gypsum and dolomite beds. Conversely, the thick shales of the Elm Fork Member impede the vertical movement of water, and the hydraulic connection between the Elm Fork gypsum and dolomite beds is less developed than in the Van Vacter Member (Johnson, 1990b).

The Dog Creek Shale overlies the Blaine Formation in much of the study area. The Dog Creek consists of up to 180 feet of red-brown shales with several gypsum-dolomite beds

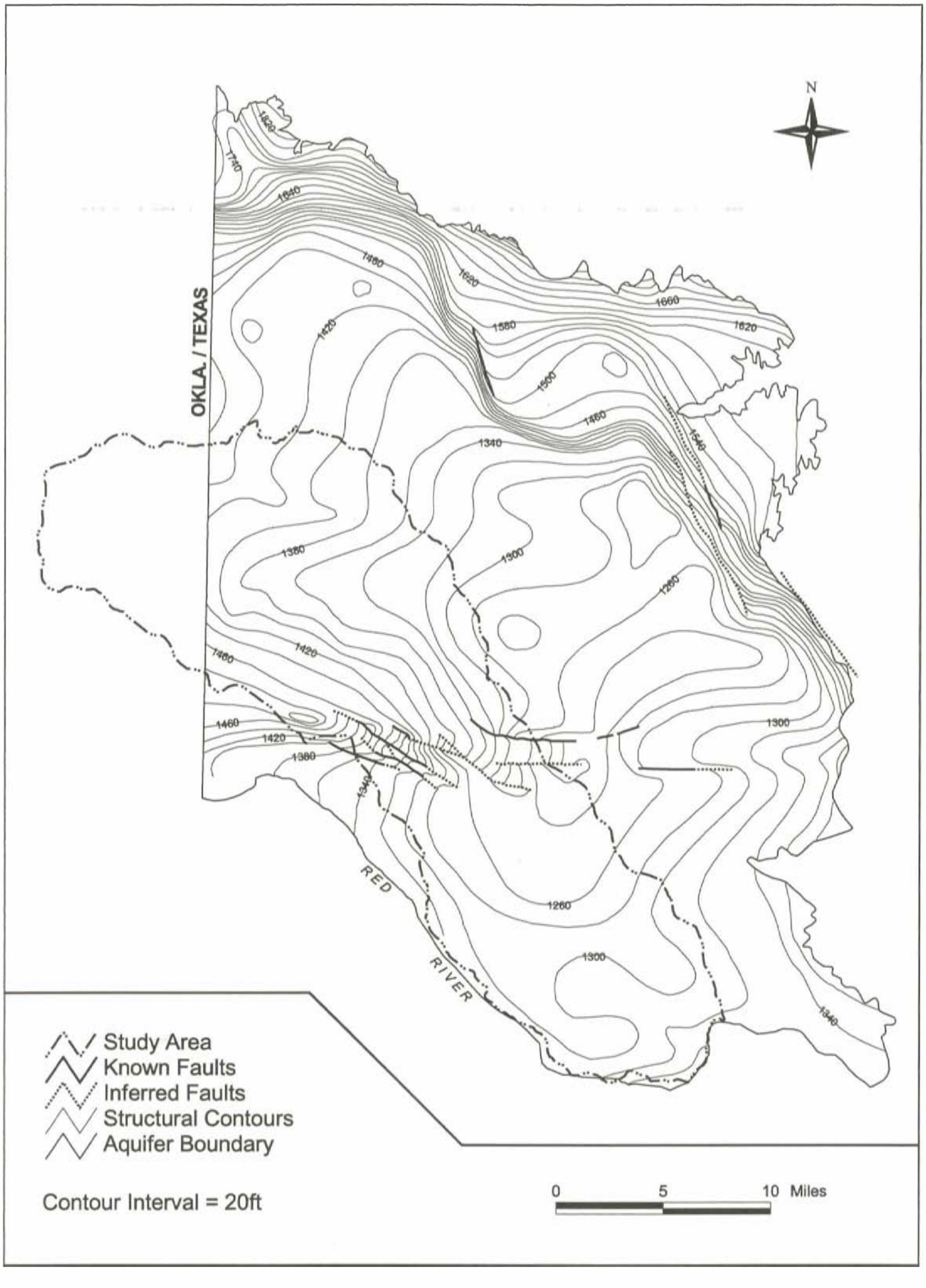


Figure 6. Structure map on the base of the Blaine Formation (from Johnson, 1985).

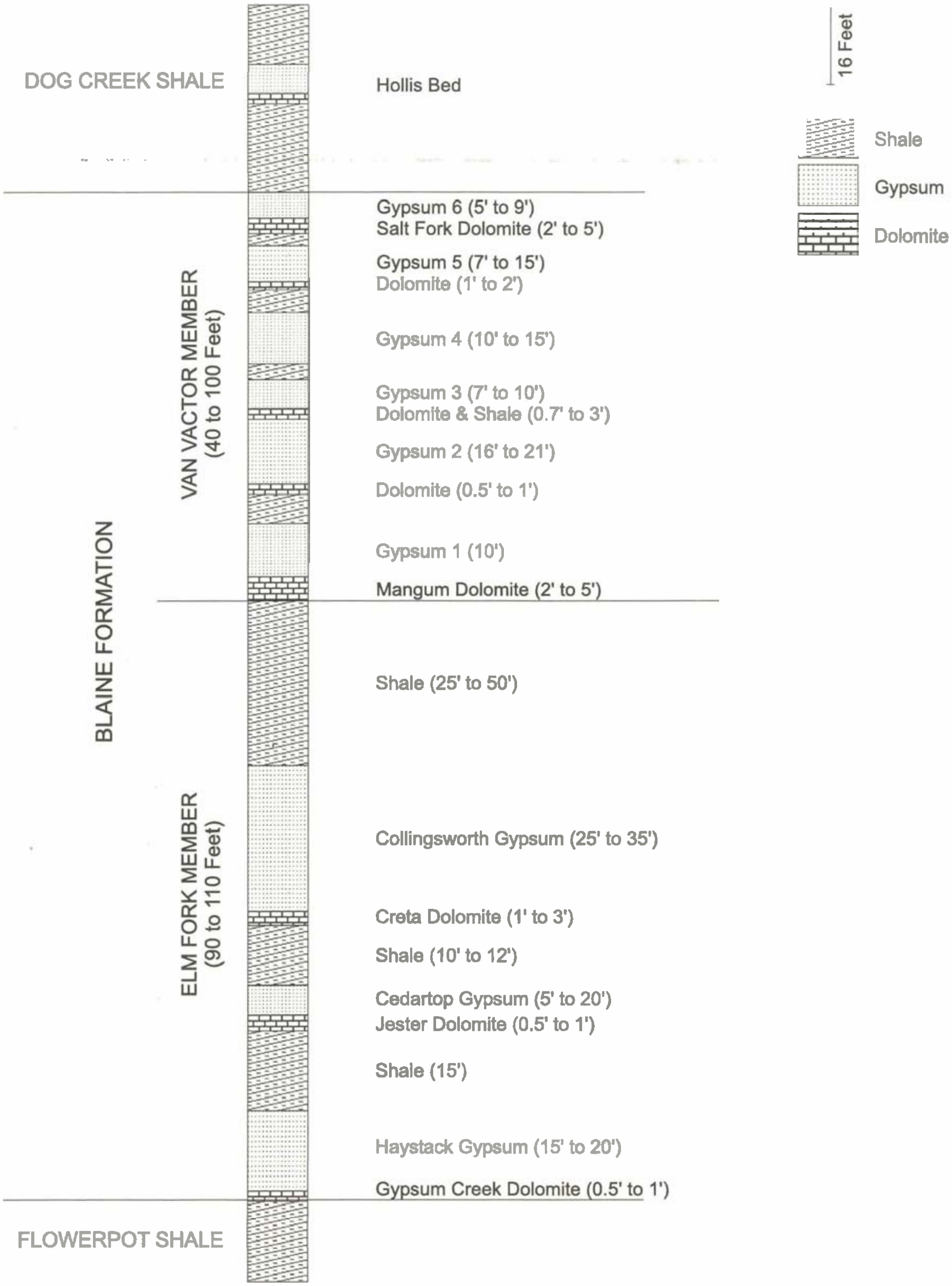


Figure 7. Stratigraphic column of the Permian units (from Johnson, 1990 a,b).

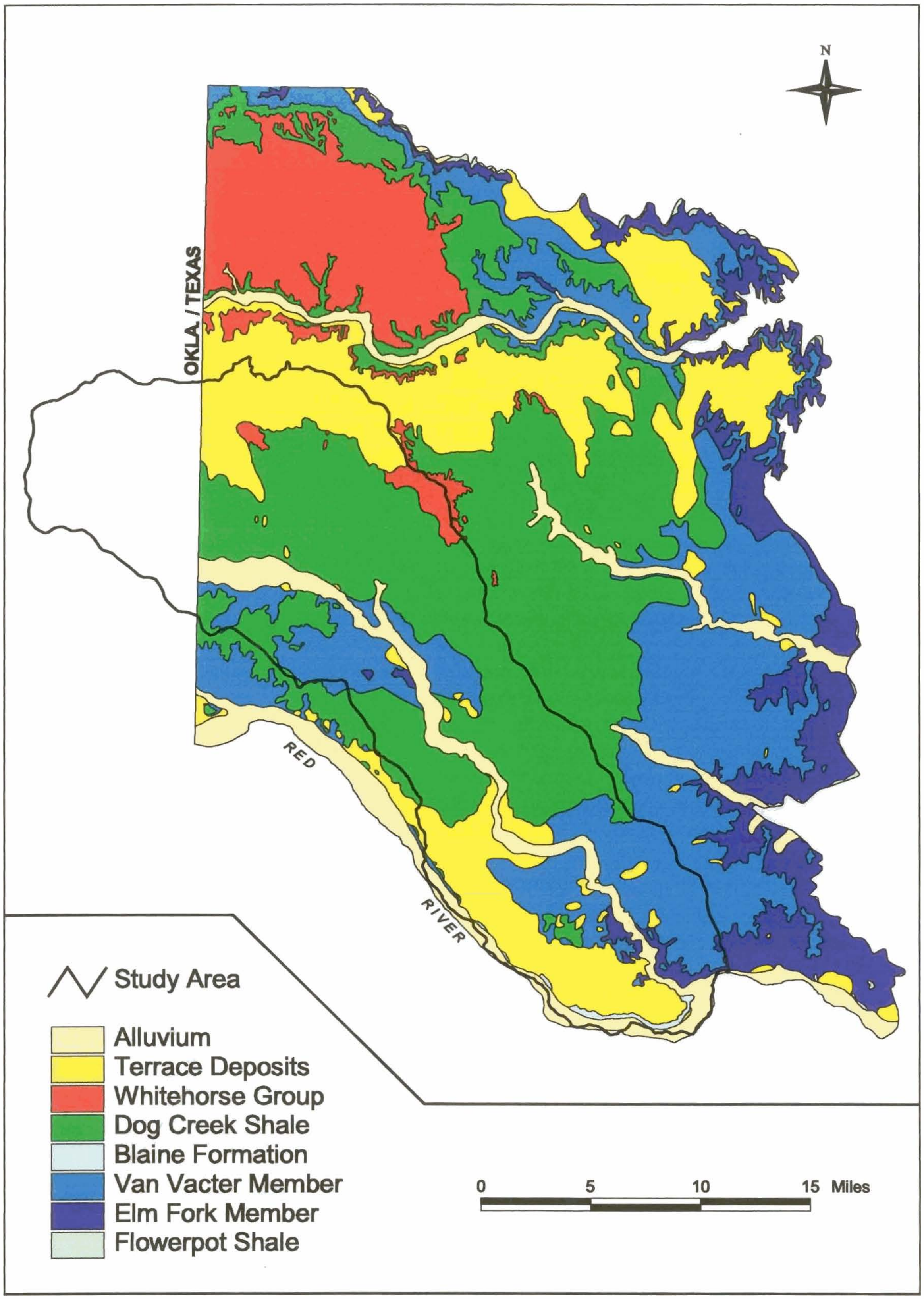


Figure 8. Surface geology of the Blaine aquifer (from Havens, 1977 and Cederstrand, 1997).

in the lower 50 feet of the formation. The dolomite beds range from 0.2 to 2.0 feet thick, and the gypsum beds from two to 10 feet thick. The gypsum and dolomite beds, primarily present in the southern half of Harmon County, yield small quantities of irrigation water (Johnson, 1985).

The Dog Creek Shale is disconformably overlain by the Whitehorse Group in the northwestern part of the study area. The Whitehorse Group consists of orange-brown, quartzose sandstone and siltstone, and contains several thin shale and gypsum beds. The sandstone yields small to moderate amounts of water. However, it is hydrologically separated from the Blaine aquifer by the thick shales of the Dog Creek Shale.

Overlying the Permian strata in parts of the basin are Quaternary alluvial and terrace deposits derived from modern rivers and streams. These deposits range from 10 to 130 feet thick, and consist of unconsolidated sand, gravel, silt, and clay. The alluvial and terrace deposits along Sandy Creek are in hydraulic connection with the Blaine aquifer (Johnson, 1990b).

HYDROGEOLOGY

Karst Development and Features

The Blaine aquifer is a major aquifer in southwestern Oklahoma. Water is obtained from cavities, solution channels, and fractures present in the gypsum and dolomite beds of the Blaine Formation.

Solution openings are formed when percolating rain water and circulating groundwater dissolve beds of soluble gypsum ($CaSO_4*2H_2O$) and dolomite ($CaMg(CO_3)_2$). Porosity appears to develop first in the dolomite layers (Johnson, 1990b). Flow of water through conduits in the dolomite beds causes gypsum dissolution, which leads to cavern development along, and just above, the gypsum-dolomite contact.

Enlargement of the individual cavities and caverns is due to dissolution of the soluble rock, as well as abrasion of the rock by gravel, sand, and silt carried by through-flowing waters (Johnson, 1990b). Caverns generally have a height and width that range from several inches to about 10 feet. Underground caverns sometimes become so wide that their roofs collapse. The resulting structures and fractured strata enable vertical movement of water in many parts of the aquifer. The enhanced vertical flow of water accelerates dissolution, and increases the amount of karst features.

Karst features such as caves, sinkholes, disappearing streams, and springs occur within the study area. An example of a sinkhole, located south of Hollis, is shown in Figure 9. Karst features are most abundant near streams, where fresh water percolates into the gypsum. Areas where the Blaine Formation crops out, or is in the shallow subsurface beneath the Dog Creek Shale, correspond to areas where the Blaine aquifer consistently yields large quantities of water to irrigation wells (Johnson, 1990b).

Figure 9. Sinkhole south of Hollis.

Karst development is generally highest in areas where the overlying Dog Creek Shale is less than 60 feet thick and lowest where the formation is greater than 100 feet. In areas where the Dog Creek Shale is thick, fresh water is not in contact with the Blaine Formation. Anhydrite ($CaSO_4$) is typically present instead of gypsum (Johnson, 1990b; Runkle and McClean, 1995).

Aquifer Characteristics

Aquifer Parameters

Hydraulic conductivity varies considerably in the aquifer. It is greatest where dissolution of gypsum and dolomite occurs, in areas of high recharge. Using a groundwater flow model of the aquifer, Runkle and McLean (1995) estimated the average hydraulic conductivity for areas of low recharge to be 4 ft/day, and the average value for areas of high recharge to be 71 ft/day. Hydraulic conductivity is suspected to be much higher in local areas where cavern development is extensive. Transmissivity ranges from 800 to 45,000 ft^2/day.

Steele and Barclay (1965) estimated transmissivity and storage coefficient by applying the Theis nonequilibrium equation to regional pumping centers. They estimated the storage coefficient in high-yield areas to range from 0.0004 to 0.03, and average 0.016. They estimated the average storage coefficient for the entire aquifer to be 0.001.

In much of the study area, the Blaine aquifer is overlain by the Dog Creek Shale. Where more than 100 feet thick the Dog Creek Shale is considered a confining unit. However, where it is less than 100 feet thick, karst features in its three gypsum-dolomite units make the Dog Creek Shale a leaky confining unit. The aquifer is unconfined where the Blaine outcrops or where it is in communication with alluvial and terrace aquifers (Johnson, 1990b).

Recharge

Natural recharge to the aquifer occurs from infiltration of precipitation and from streams that flow across sinkholes. Artificial recharge occurs from return flow of irrigation water and from direct injection of surface water into recharge wells.

Recharge is greatest where less than 60 feet of Dog Creek Shale overlies the aquifer. Average recharge to the aquifer is estimated to be 1.5 inches per year, or 6 percent of the normal annual precipitation of 24 inches (Runkle and McLean, 1995).

Artificial recharge of the Blaine aquifer began in 1968, with the creation of the District. Many of the recharge projects consist of diverting surface drainage to sinkholes, caves, or other natural openings into the ground, while others involve the construction of injection wells or impoundments. To date, the District has constructed four impoundments and about 70 injection wells. Approximately 45 recharge wells are currently operating in the study area. Figure 10 shows the locations of active recharge wells.

Discharge

Groundwater that is not discharged to wells is discharged to streams and rivers. Discharge from the Blaine aquifer to Sandy Creek occurs in the southern portion of the study area, primarily in Jackson County. The USGS used base flow measurements taken in 1988 to determine that the Blaine aquifer discharged 15.9 cubic feet per second (cfs) to Sandy Creek and 6.9 cfs to the Red River (Runkle and McLean, 1995). This is about 11,500 and 5,000 acre-feet/year, respectively.

Groundwater Flow

Figure 11 is a potentiometric map of the Blaine aquifer based on water level measurements taken from wells in February 1994 and on the altitudes of perennial streams that are in hydraulic connection with the aquifer. Groundwater flows southeast, where it discharges into Sandy Creek and the Red River. The regional slope of the potentiometric surface is about 10 ft/mile, or 0.002. Depth to water ranges from just below land surface to greater than 100 feet below land surface.

Assuming a regional hydraulic gradient of 0.002, an average hydraulic conductivity of 71 ft/day, and an average porosity of 0.016 (storage coefficient), regional groundwater velocity is about 9 feet/day.

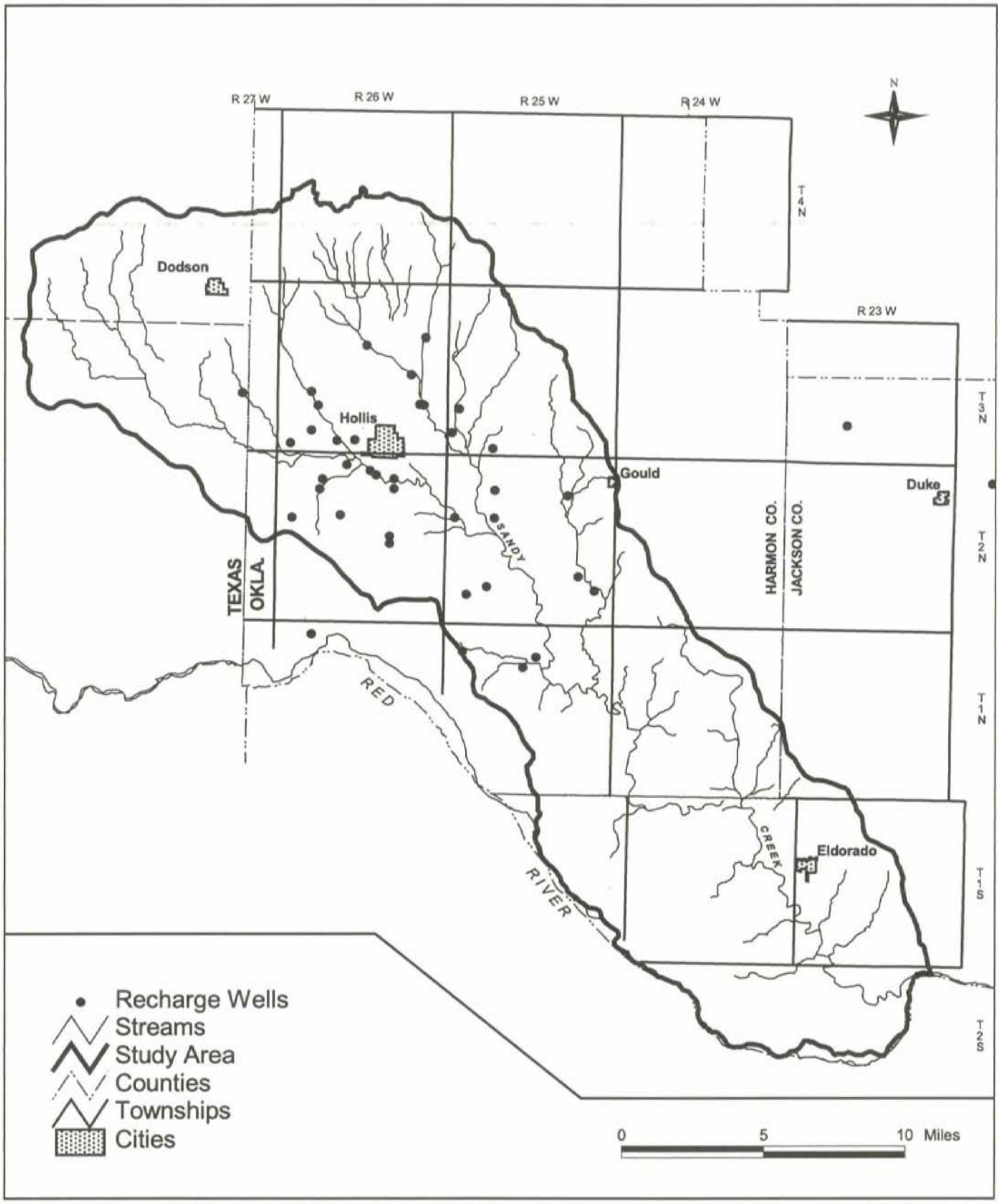


Figure 10. Map showing locations of active recharge wells.

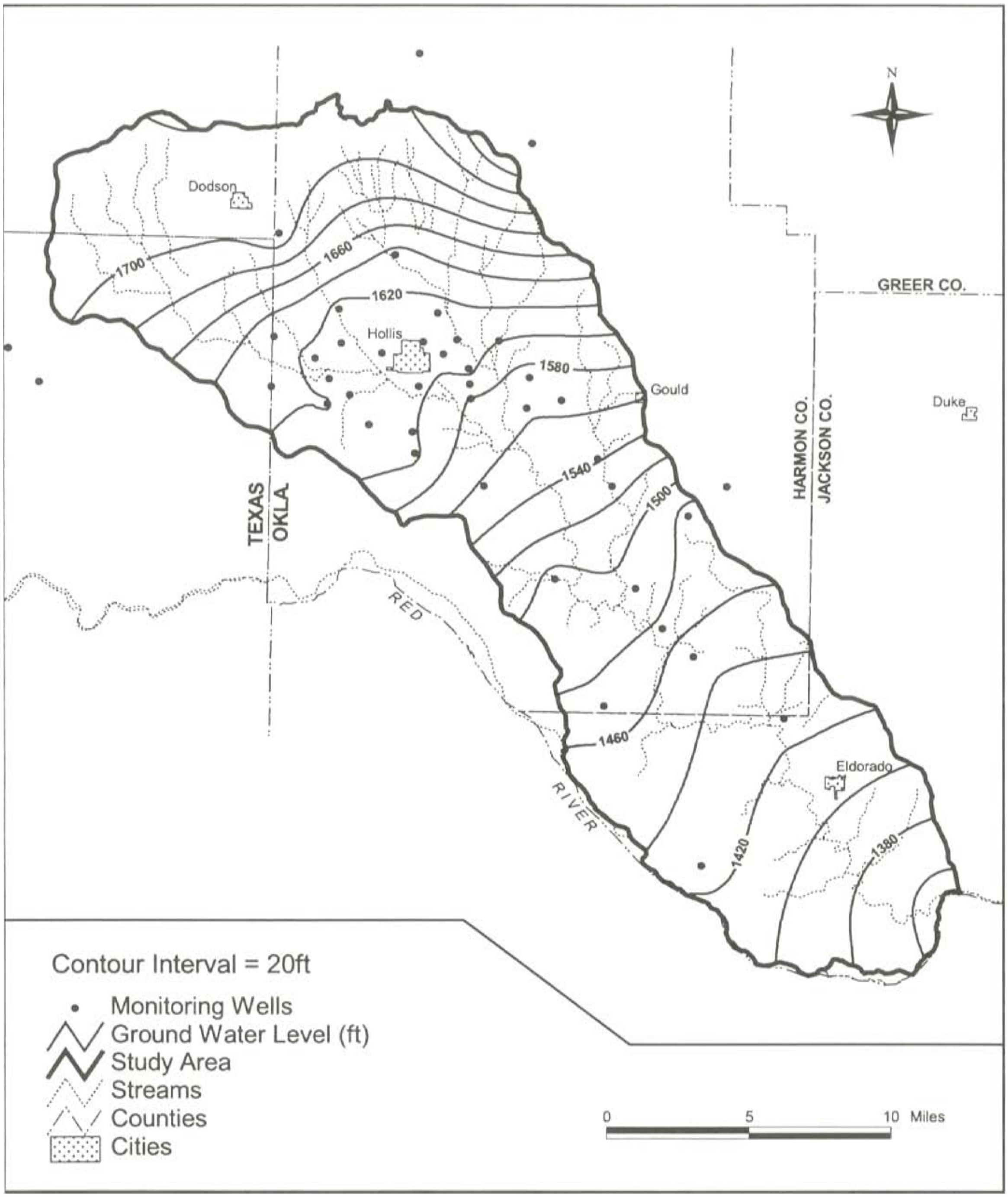


Figure 11. Potentiometric map of the Blaine aquifer from wells measured in February 1994.

Water Level Fluctuations

Figure 12 is a hydrograph of an irrigation well in the Hollis area showing annual water level measurements since 1950. Typical of other wells in the area, the hydrograph shows a gradual decline in the water level from 1950 to 1960. After a slight incline in 1961, it continued to decline to historically low levels between 1965 and 1968. The water level then increased to a high period between 1976 and 1978, followed by a decrease in the early 1980s. Water levels increased between 1985 and 1996.

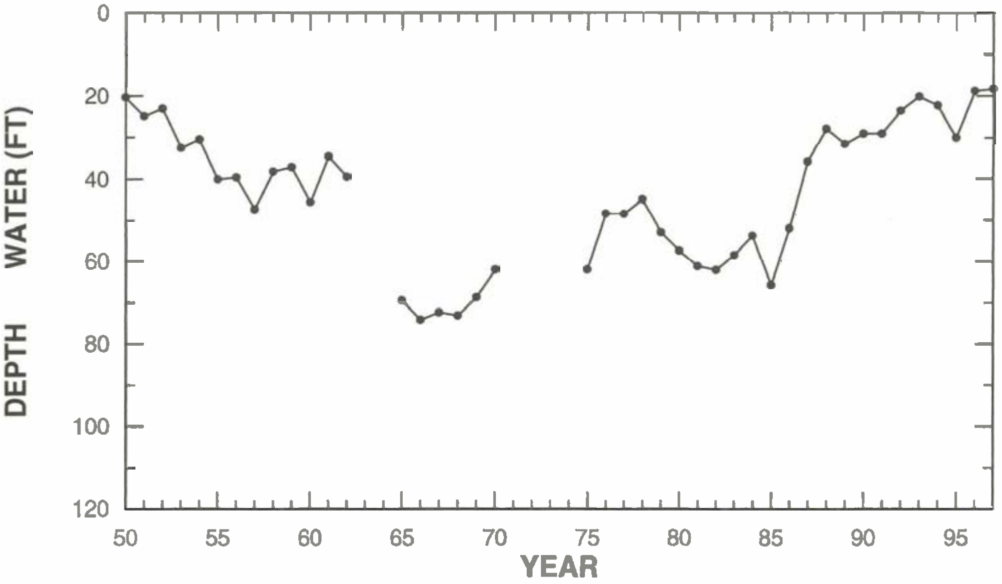


Figure 12. Hydrograph of an irrigation well in the Hollis area (05-2N-26W).

Water Quality

Table 1 summarizes the general water quality of the groundwater and surface water in the study area. Groundwater samples from the Blaine aquifer were collected by the USGS and OWRB in 1987. Surface water samples from Sandy Creek and the Red River were collected by the USGS during low-flow periods between 1986 and 1988 (Runkle, et. al., 1997).

The ambient quality of the Blaine aquifer is very poor. The aquifer is highly mineralized, reflecting dissolution of gypsum and dolomite in the Blaine Formation. Total dissolved solids (TDS) from the groundwater samples ranged from 2,941 to 35,630 mg/L, and sulfate from 1,470 to 2,037 mg/L, well above the secondary maximum contaminant levels (MCLs) of 500 and 250 mg/L, respectively. Water from the Flowerpot Shale, which underlies the Blaine aquifer, is high in TDS and leakage from this formation to the Blaine Formation may increase the TDS of the aquifer in some areas.

Table 1. General water quality of groundwater and surface water in the study area

	BLAINE AQUIFER		SANDY CREEK		RED RIVER	
	n=10		*n=7*		*n=4*	
PARAMETER	**RANGE**	**MEDIAN**	**RANGE**	**MEDIAN**	**RANGE**	**MEDIAN**
Ca	470-728	580	160-800	690	710-1,000	810
Mg	<1-185	141	150-1,300	170	170-250	215
SO_4	1,470-2,037	1,817	2,000-2,400	2,000	2,500-3,600	2,900
Cl	110-2,625	306	2,400-3,800	2,600	7,800-12,000	8,550
TDS	2,941-35,630	3,636	7,250-9,450	7,740	1,640-22,900	19,675

The Blaine aquifer is generally a calcium-sulfate to sodium-sulfate type water as illustrated in the piper diagram in Figure 13. Within the cation portion of the plot the proportions of calcium to magnesium to sodium vary quite a bit as do the sulfate to chloride proportions in the anion portion.

The waters of Sandy Creek and the Red River are also highly mineralized, reflecting discharge of the mineralized groundwater. TDS concentrations from Sandy Creek samples ranged from 7,250 to 9,450 mg/L, and concentrations from the Red River ranged from 1,640 to 22,900 mg/L.

The Red River is higher in chloride than the Blaine aquifer and Sandy Creek. Chloride concentrations from the Red River ranged from 7,800 to 12,000 mg/L. Saline water is derived from natural-brine springs located upstream in Texas. The source of the brine is dissolution of salt beds in the Flowerpot Shale (Johnson, 1990b).

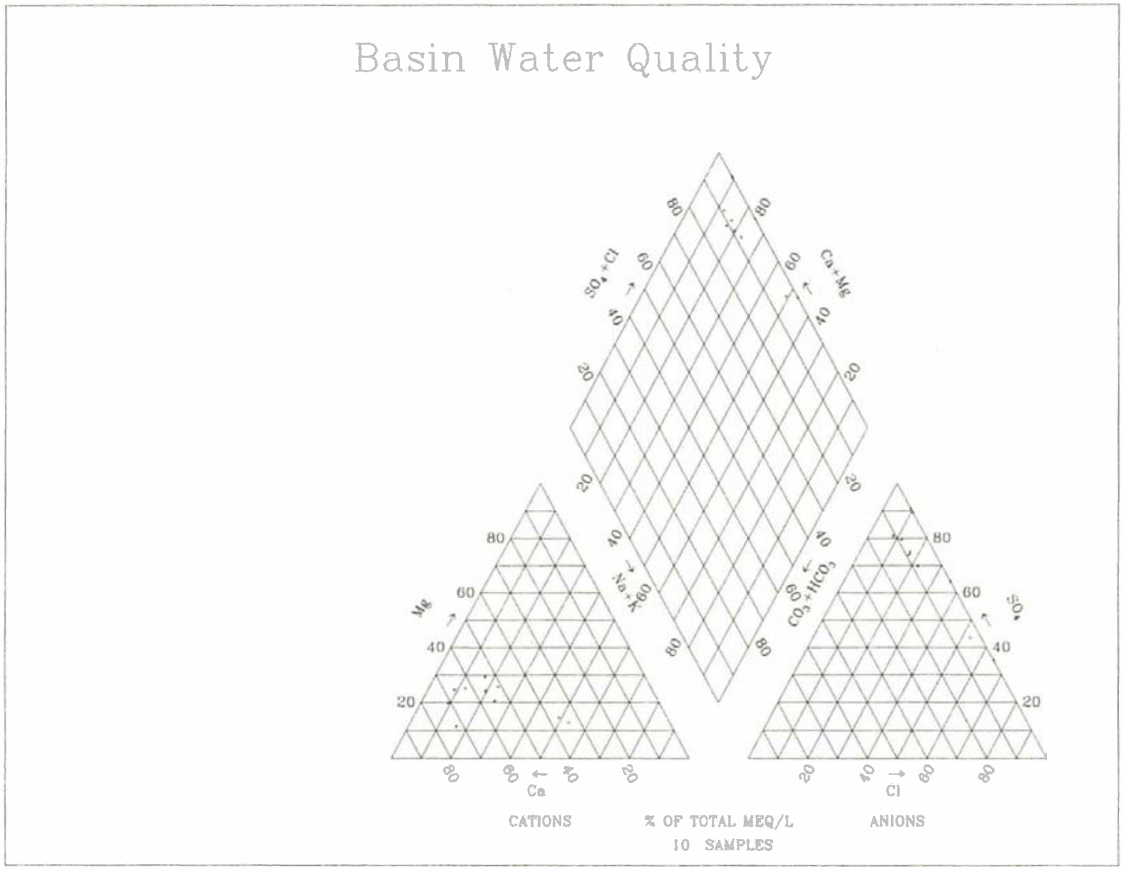


Figure 13. Piper plot of water quality samples collected in 1987.

Development and Construction

REGULATORY ISSUES

Water Rights

Under Oklahoma's water law, stream water is considered public water. A stream water use permit is required to use stream water for artificial recharge. The applicant must show a present and future need for the water, as well other factors, to obtain a permit. Because stream water belongs to the public, a permittee does not have to own the land where the diversion will take place, but must have an easement or other means of access to the point of diversion. At least once during any continuous seven year period the entire amount of water must be put to use or the permit may be reduced or canceled.

Unlike stream water, groundwater is considered a private property right. The amount of water a permit holder may use is determined by the amount of land the individual owns or leases that overlies the groundwater basin, and by the maximum annual yield of that basin as determined by a study. To obtain a groundwater permit the applicant must show that the groundwater will be used beneficially and will not be wasted, but does not have to show a *need* for the groundwater. The taking of groundwater must be from wells on lands dedicated to the permit.

To use the stored water from artificial recharge, the applicant should hold both stream water and groundwater permits for the area where the water is injected and stored. The District obtained a stream water use permit to divert stream water into injection wells for artificial recharge of the Blaine aquifer. Individual landowners within the study area have the groundwater use permits for irrigation.

Other Regulatory Issues

The five project recharge wells were registered with the Oklahoma Department of Environmental Quality (ODEQ), which has statutory authority for the regulation of Class V injection wells. In Oklahoma, water quality monitoring is not required for Class V injection wells.

The project's Monitoring and Mitigation Plan addressed the environmental concerns regarding the potential impact of the recharge demonstration project on the groundwater and surface water in the study area. The Fish and Wildlife plan addressed wildlife and environmental aspects of the project and includes information and suggestions provided by the U.S. Fish and Wildlife Service and the Oklahoma Department of Wildlife Conservation.

Before undertaking ground-disturbing activities, a Class III cultural resources ground survey was conducted in compliance with the National Historic Preservation Act. No significant cultural or historic sites were discovered at any of the construction sites.

FACILITIES DESIGN AND CONSTRUCTION

Source Water Supply

Surface water used for recharge is taken from Sandy Creek, Bitter Creek, an unnamed tributary to Sandy Creek, and drainage ditches, all located in Harmon County, Oklahoma. The headwaters of Sandy Creek and its tributaries are in the Texas Panhandle, but the major portion of the drainage basin is in Oklahoma. Sandy Creek is an intermittent stream except in the lower portion of the study area where it becomes perennial. Irrigation tailwater is also a source of water for recharge.

Facilities

Five recharge wells were constructed at locations described in Table 2. Each of the five recharge sites had one monitoring well located upgradient from the recharge well and a minimum of two downgradient monitoring wells. An impoundment was built at the R01 site to divert runoff into the recharge well.

Table 2. Recharge well location information

SITE NAME	WELL ID	LEGAL LOCATION	LATITUDE	LONGITUDE	SURFACE ELEVATION (FEET)
Conservation Dam	R1	SW SW SW 27-03N-26W	34°41'47.91" N	99°55'34.14" W	1642.0
Motley/Jones	R2	SE NE NE 32-03N-26W	34°41'35.23" N	99°56'51.67" W	1638.6
Paul Horton	R3	SE SW SW 20-03N-26W	34°42'43.76" N	99°57'40.15" W	1675.0
Kelly Horton	R4	SE NE NE 06-02N-26W	34°40'52.74" N	99°57'55.38" W	1642.0
Warren/Dill	R5	NW NW NE 23-33N-26W	34°43'26.16" N	99°54'06.26" W	1642.8

Recharge Wells

The recharge wells intercept surface runoff and channel the water into cavities and fractures within the Blaine Formation. Surface runoff is diverted to an inlet structure, where the untreated water flows, by gravity, into the recharge well. Wells are cased with 12-inch diameter casing to depths ranging from 155 to 270 feet. Slotted casing allows recharge water to enter the cavernous and fractured zones.

Rotary drilling rigs were used for construction of the wells, with fresh water used as the drilling fluid. All recharge wells, except well R5, were constructed using the same basic design (Figures 14 through 18). A 22-inch hole was drilled to a minimum depth of 89 feet. Steel surface casing, 16 inches in diameter and with a wall thickness of 0.375 inches, was placed into the drilled hole (Figure 19). Centralizers were attached to the casing at 20-foot intervals to keep the casing centered in the drill hole.

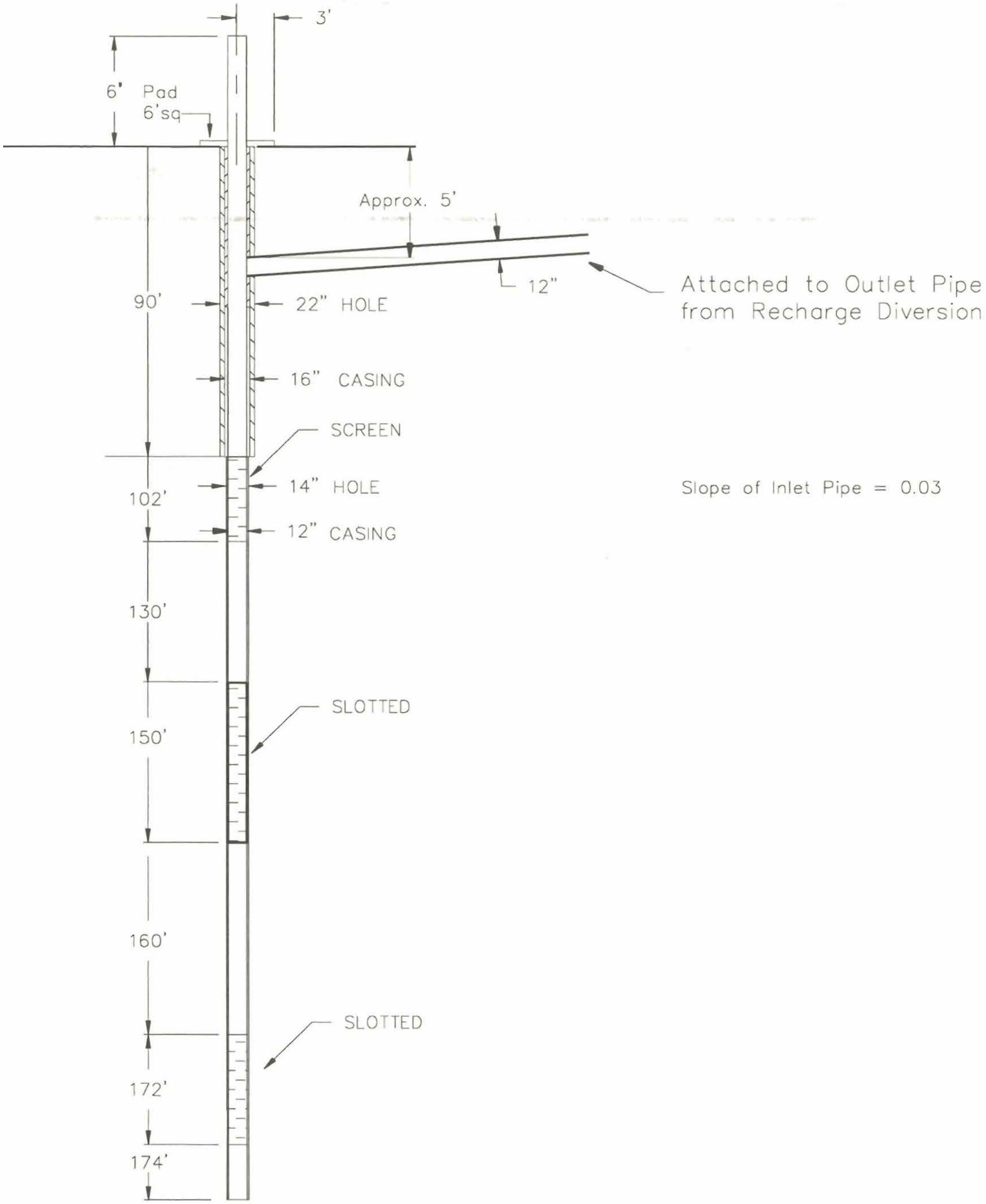


Figure 14. Schematic of recharge well R1 (Conservation Dam site).

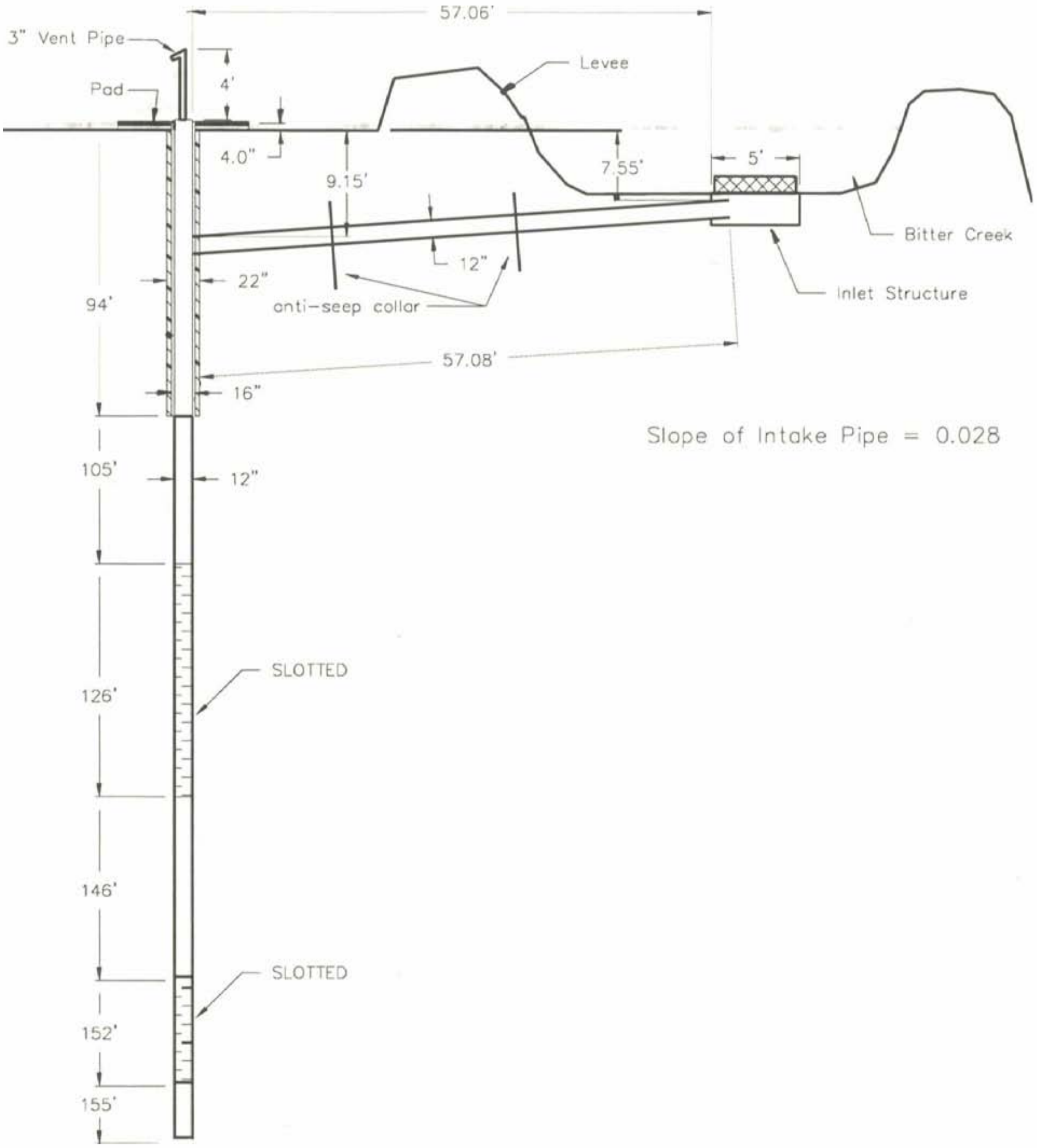


Figure 15. Schematic of recharge well R2 (Motley/Jones site).

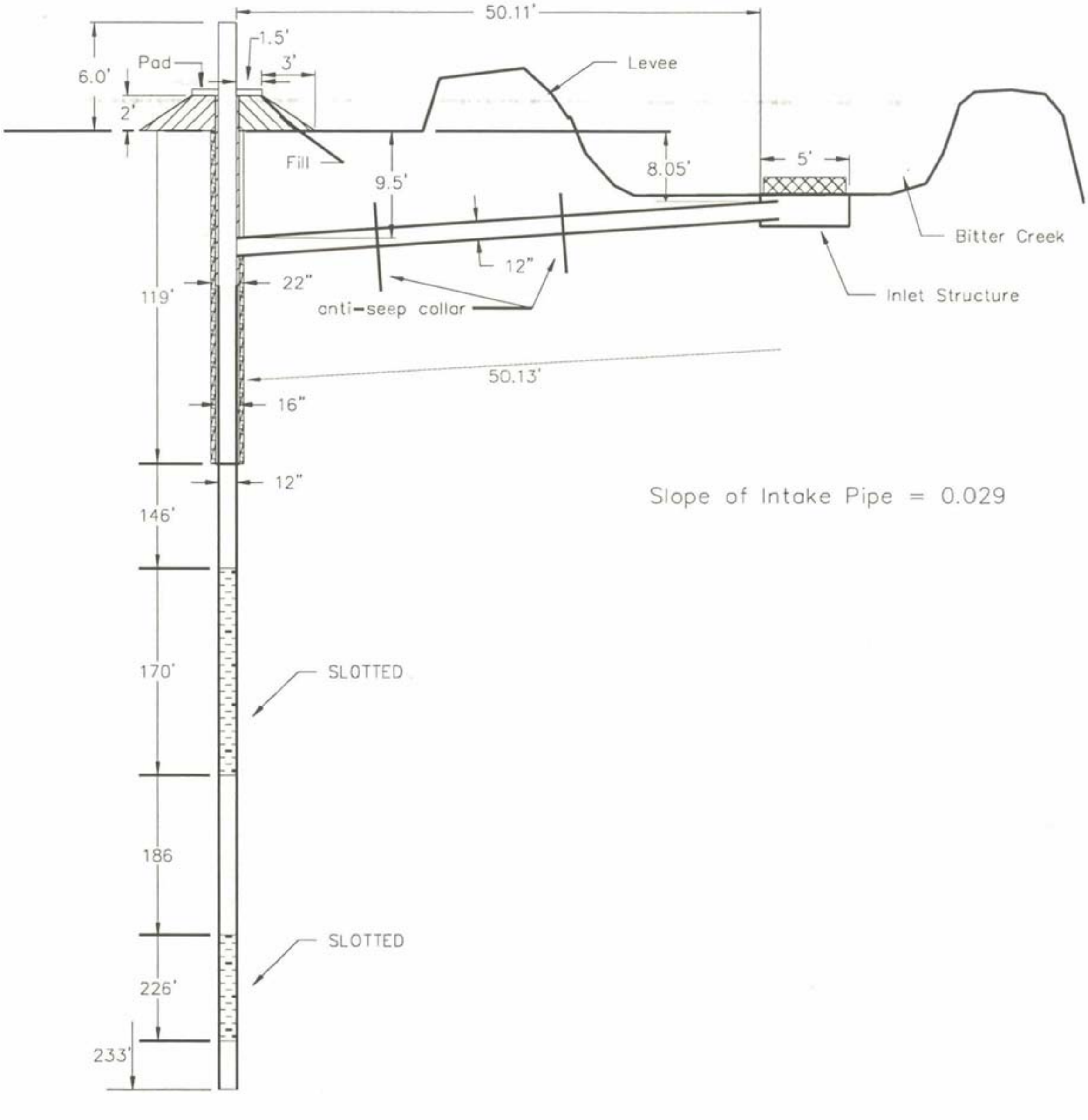


Figure 16. Schematic of recharge well R3 (Paul Horton site).

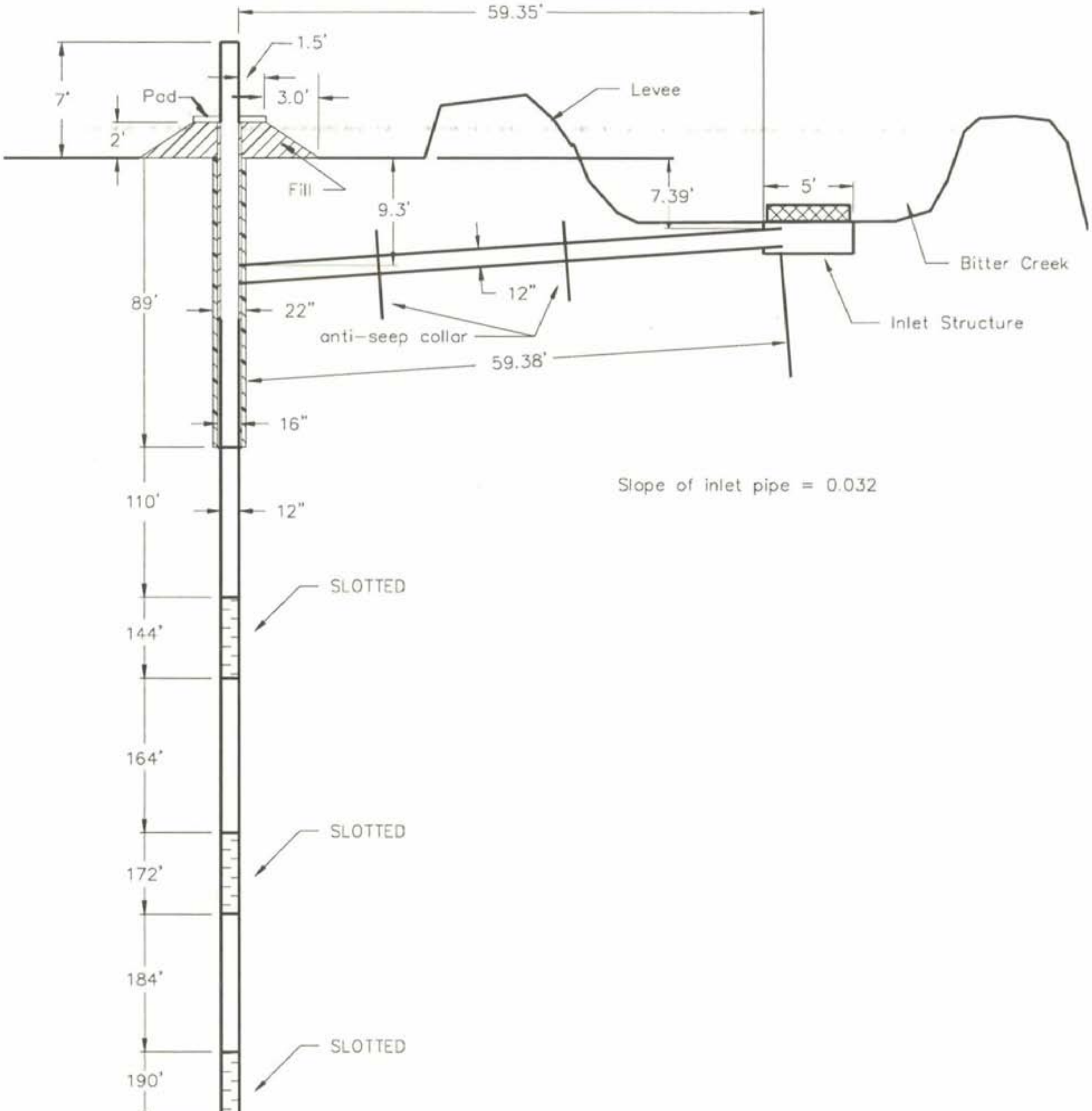


Figure 17. Schematic of recharge well R4 (Kelly Horton site).

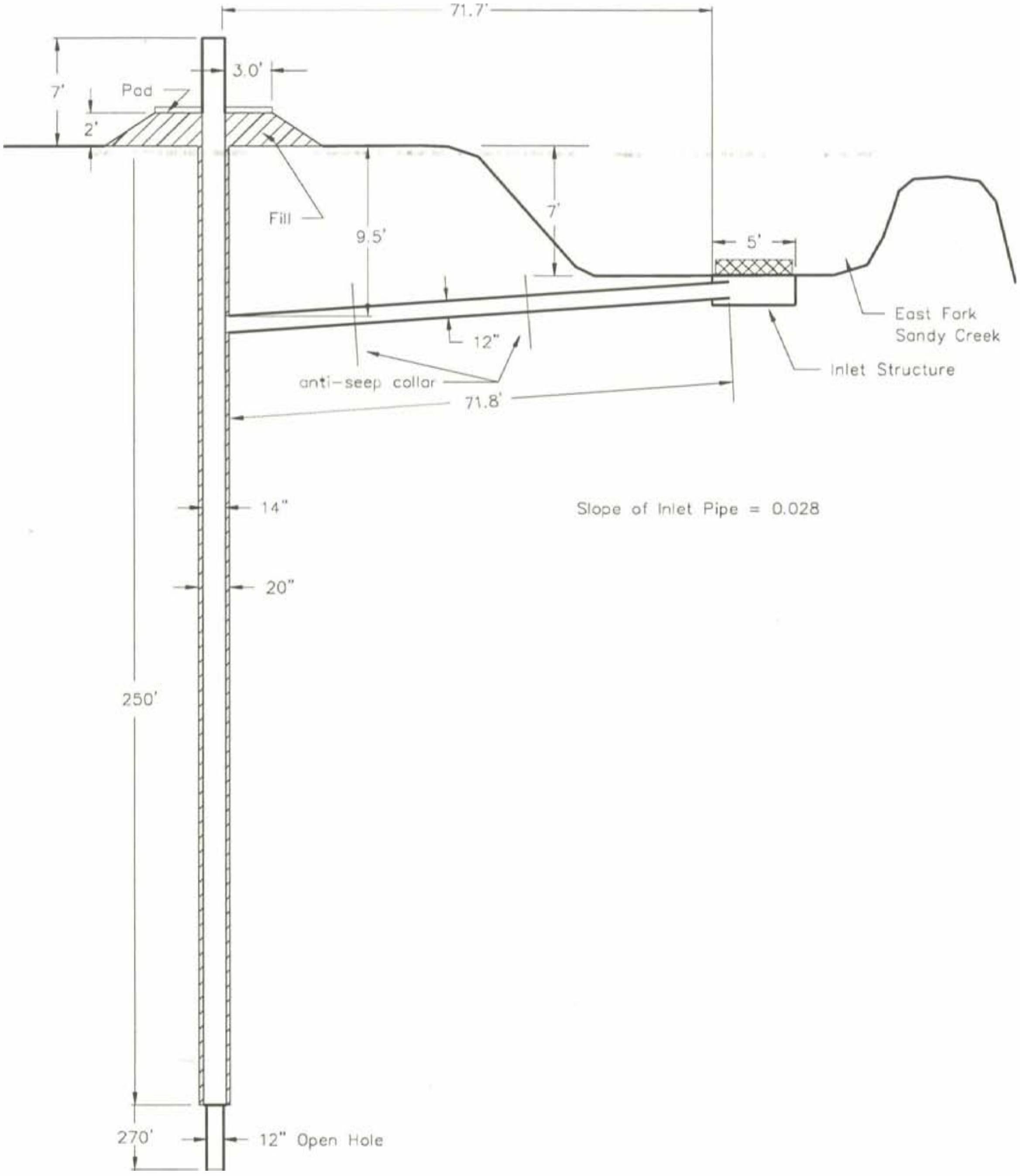


Figure 18. Schematic of recharge well R5 (Warren/Dill site).

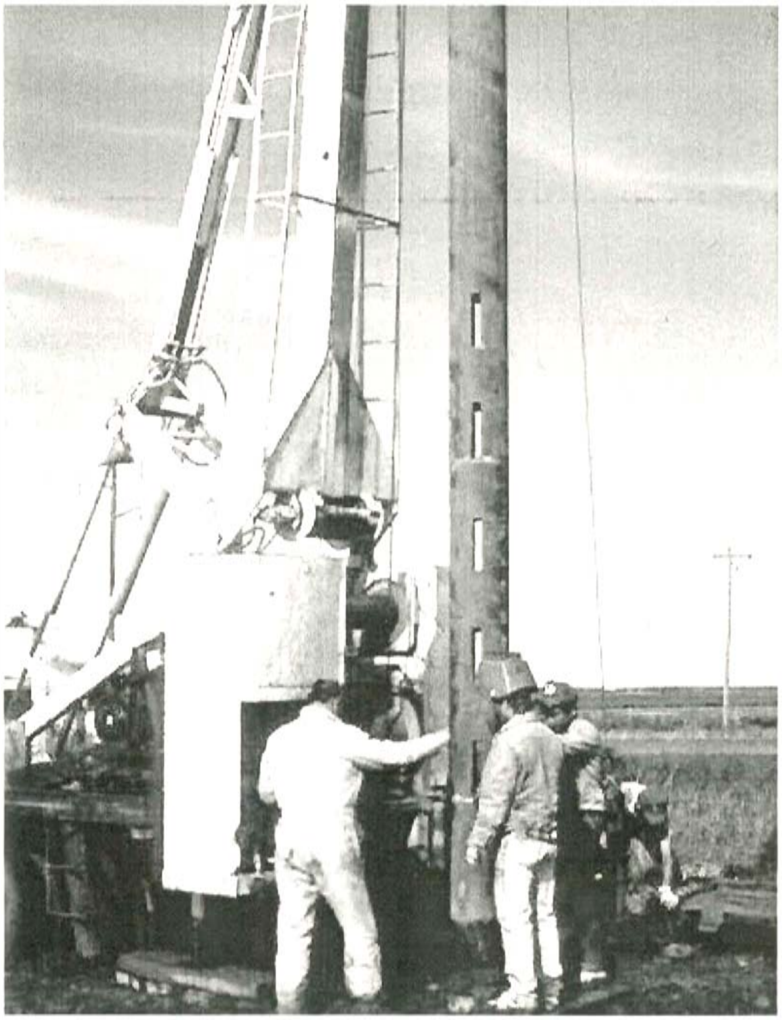


Figure 19. Photograph showing installation of 12-inch steel inner casing for the recharge well at the R02 (Motley) site.

A 15-inch hole was drilled through the bottom of the cement plug within the 16-inch steel casing to the total depth of the well at each site. Steel pipe, 12 inches in diameter and 0.375 inches thick, was placed within the 16-inch outer pipe. The inner casing extended from five feet above land surface down to the total depth of the well. All pipe joints were welded. A cementing collar was attached to the inner casing approximately 20 feet below the attachment point of the inlet pipe with the casing.

Slots were cut at the appropriate intervals in the 12-inch steel inner casing (Figure 19). These slots were cut in the casing at intervals that were to be adjacent to the fractured or cavernous zones of the formation. Slots were approximately two inches wide and 12 inches long and spaced at six-inch intervals around the circumference of the casing. Several rows of slots were cut in the casing to span the thickness of the particular zone to be recharged. Most recharge wells were slotted across multiple intervals (Table 3).

Table 3. Recharge well completion information

WELL ID	TOTAL DEPTH (FEET)	SURFACE CASING (FEET)	SLOTTED INTERVAL 1 (FEET)	SLOTTED INTERVAL 2 (FEET)	SLOTTED INTERVAL 3 (FEET)
R1	174	90	90-102	130-150	160-172
R2	155	94	105-126	146-152	
R3	233	119	146-170	186-226	
R4	193	89	110-144	164-172	184-190
R5	270	250			

In contrast to the other recharge wells, well R5 (Figure 18) was constructed using a single steel casing. A 22-inch hole was drilled to a depth of 250 feet. Steel casing, 12 inches in diameter with a wall thickness of 0.375 inches, was placed into the drilled hole. Centralizers were attached to the casing at 20-foot intervals to keep the casing centered in the hole. Following pressure cement grouting of the annular space, a hole was drilled through the cement plug to a depth of 20 feet below the casing. The 20-foot interval below the casing was left open for recharge.

Recharge Well Vent Pipe

All recharge wells have the inner, 12-inch steel casing extending approximately five feet above ground surface. The top of the casing is covered by a slotted steel plate welded to the casing. This feature acts as a vent for the recharge well and allows air to enter the well.

The vent pipe for the R2 recharge well was constructed differently to allow a central pivot irrigation system to move past the well without the irrigation pipe striking the well. For this well, a steel plate with an attached four-inch diameter steel pipe, three feet long, was welded to the recharge well casing at ground level. What appears to be an inverted tin can is actually a piece of steel pipe that caps the top of the vent pipe. This design allows air to flow up under the steel cap and down the vent pipe into the well while preventing precipitation and irrigation water from entering the vent pipe.

Cement Grouting Methodology

The outer casing annular spaces of the recharge wells were pressure grouted. Grouting was pumped, under pressure, from the bottom of the hole of the outer casing to within five feet of where the inlet pipe would attach to the casing. Four slots, four inches in diameter, were cut into the lower two feet of the casing. Approximately two well volumes of Portland cement grout were poured into the casing.

Next, a pig was inserted into the casing above the cement grout. The pig consisted of a cylinder, 15 inches in diameter and two feet long, constructed of plywood and two-by-four boards. Cord reinforced rubber matting, 16 inches in diameter, was attached to the pig to act as a seal with the inside of the casing and to prevent cement from leaking upward past the pig. The pig was inserted into the 16-inch casing, then a metal cap was welded to the top of the casing. Air was pumped through an attachment in the cap forcing the pig down the inside of the casing. This then caused the cement grout to be forced through the openings in the bottom of the casing up the annular space of the well. After allowing the cement grout adequate time to harden, a hole was drilled through the pig and cement plug in the bottom of the casing then into the formation to the designated depth for each recharge well.

After the inlet pipe was welded to the well casing, final grouting of the annular space between the outer casing and wall of the hole was completed. Cement was poured into the outer annular space from below the inlet pipe up to land surface. Portland cement grout was also used to seal the annular space between the inner and outer casing from the cementing collar to land surface. This resulted in a very strong and stable attachment of the inlet pipe to the recharge well.

Impoundment

The Conservation Dam (R01) site is different from the other four recharge sites of this project because of the presence of a small dam and impoundment associated with the recharge well (Figure 20). The dam temporarily stores the runoff as the recharge well injects the water into the formation. Storage of the water in the pond allows more of the water generated within the watershed to be injected. The dam serves an additional function by providing flood control for Hollis. The area-capacity curve in Figure 20 shows maximum storage behind the dam to be 25 acre-feet.

The upstream side of the dam is approximately six feet from the bottom of the borrow area to the dam crest. The downstream side of the dam is approximately three feet from the base of the dam to its crest. The dam is low enough that should water overtop the dam and it fails, significant downstream flooding would not occur. Two discharge pipes run through the dam (Figure 21): one connecting to the recharge well and the other, acting as an emergency bypass, discharging water into the ditch by the county road.

Inlet Structures

The recharge wells capture surface water as it passes over an inlet structure. Water is captured by a drop inlet structure, then flows through an inlet pipe into the well. Water flows down the well casing, exiting through large slots in the casing and out into the cavernous gypsum formation. The inlet pipe extends from the bottom of a creek bed, ditch or impoundment and slopes down to connect with the recharge well (Figures 22 and 23). The inlet pipe is 12-inch steel with a wall thickness of 0.219 inches. A slope of approximately 0.03 was maintained at each recharge site with a distance between the drop inlet and the recharge well ranging from 50 to 132 feet. The top of the drop inlet structure extends two to three inches above the bottom of the creek bed, ditch or impoundment.

Each inlet pipe has two to three anti-seep collars attached to the pipe and spaced at equal intervals along the pipe (Figure 23). The anti-seep collars are constructed of 0.219-inch thick steel plate, approximately three feet on a side and welded to the inlet pipe. The purposes of these collars are to prevent water from flowing along the outside of the inlet pipe and to prevent burrowing animals from creating tunnels along the length of the pipe.

The drop inlet structure is constructed with a section of 24-inch diameter steel pipe welded to the 12-inch inlet pipe. A steel plate is welded to the bottom of the drop inlet. The length of the drop inlet is dependent on the characteristics of each individual site, but varies from two to three feet in length at the five sites. The drop inlet structure and approximately one foot of the inlet pipe are encased in cement. The cement provides support for the drop inlet and also serves as an anchor in the stream.

Treatment

Coarse filtration is accomplished by using a debris screen around the entrance to the drop inlet structure. The debris screen is constructed of 16-gauge chain link fence material attached to a box frame that sits directly over the drop inlet (Figure 24). The fencing material has openings of two inches on a side to prevent large objects from entering the well. No other filtration or treatment is done on the injected water. Formation clogging does not appear to be a problem.

Monitoring Wells

Twenty-four wells were installed to monitor both water levels and water quality. Each recharge site had one monitoring well located upgradient, in relation to regional groundwater flow, from the recharge well and a minimum of two downgradient monitoring

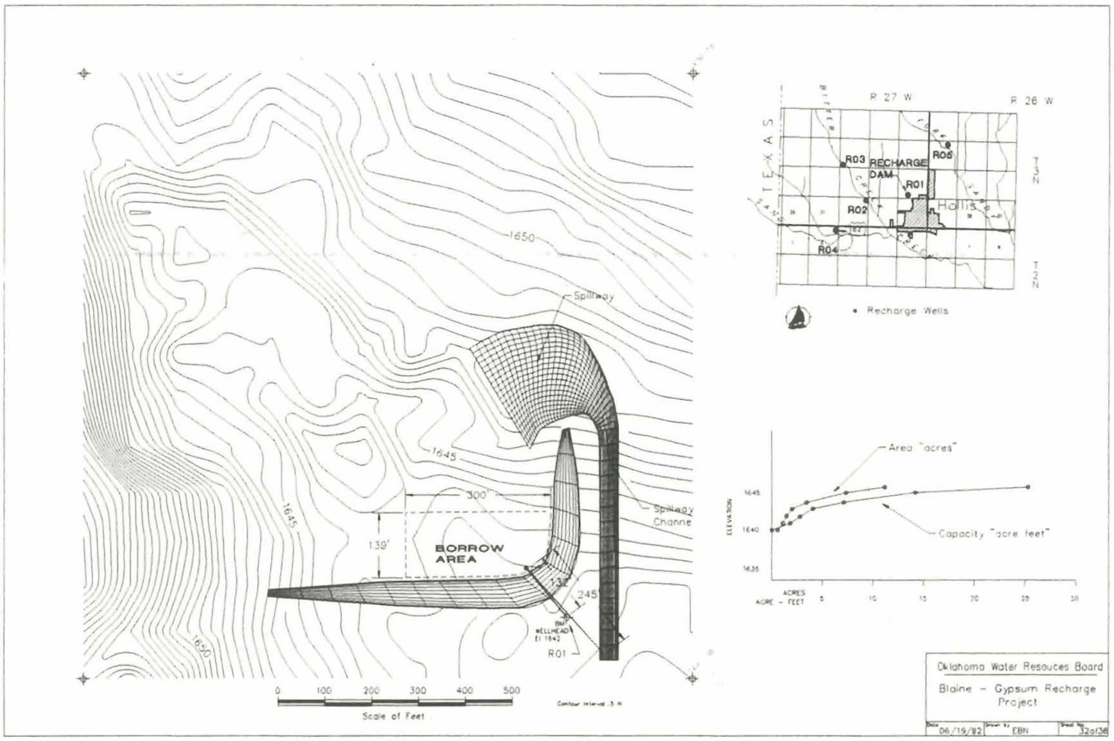


Figure 20. Schematic of the dam and impoundment for recharge well R1, Conservation Dam Site, showing site map and area capacity curve.

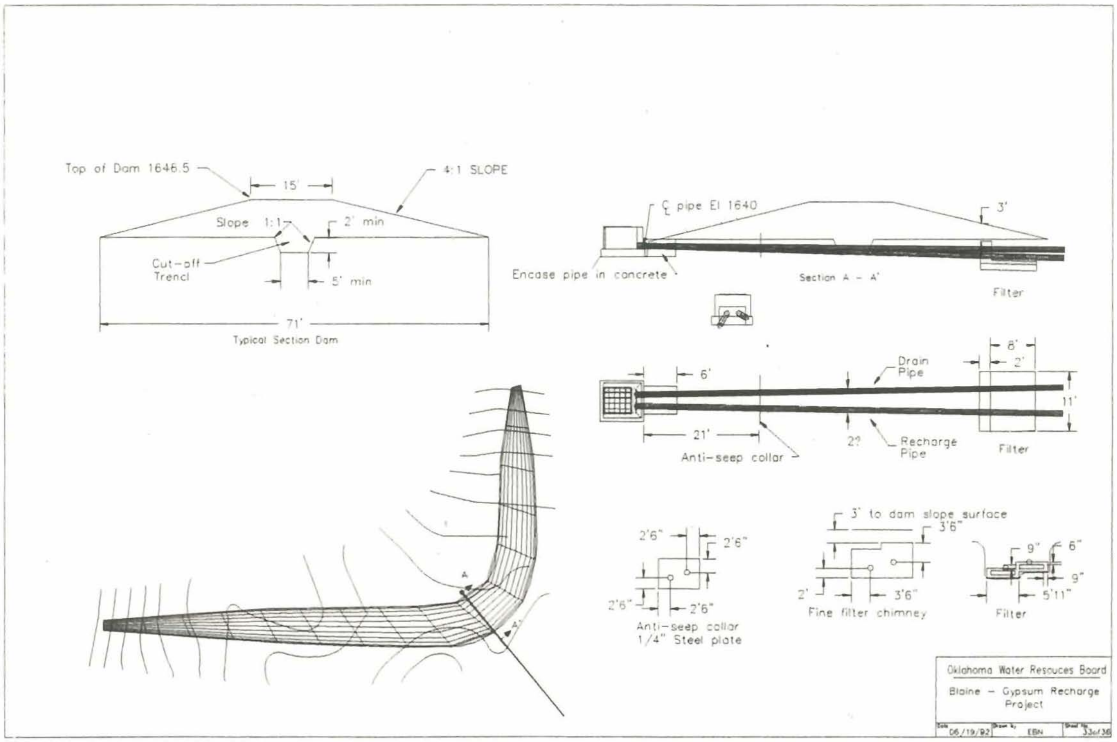


Figure 21. Schematic cross-section of dam at the Conservation Dam Site showing discharge pipes.

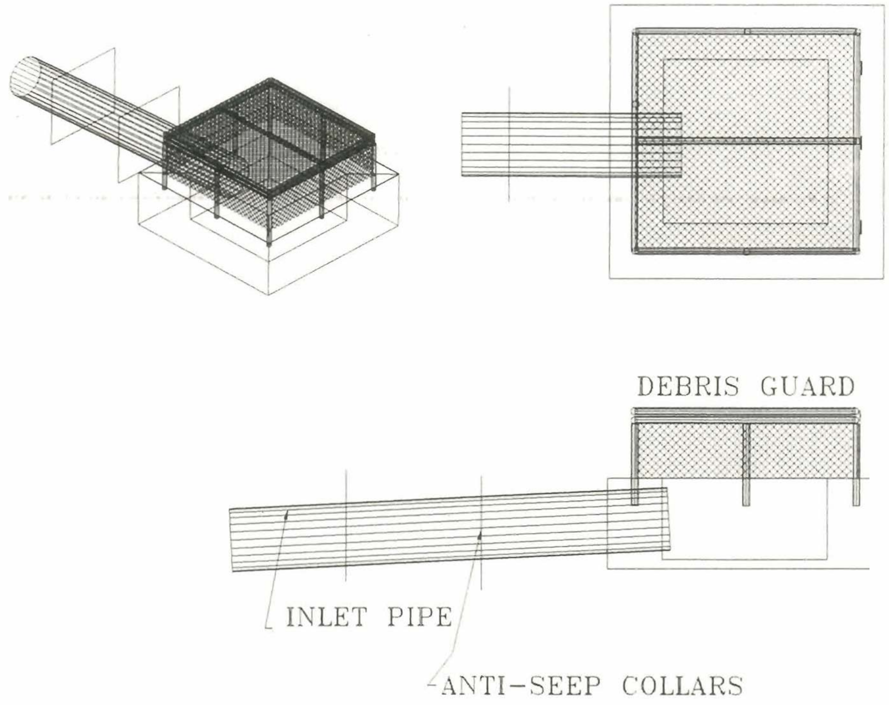


Figure 22. Schematic of typical inlet structure for recharge wells.

Figure 23. Photograph showing the inlet pipe and anti-seep collars for the recharge well at the R05 (Warren/Dill) site.

Figure 24. Photograph of the debris screen covering the drop inlet structure of a recharge well.

wells. Figures 25 through 29 show the distribution of the monitoring wells around each of the recharge wells.

The naming convention for the monitoring wells is a combination of the recharge well number (such as R1) and the monitoring well number (such as M2) to form the name (R1M2). All background monitoring wells are numbered "M1". Monitoring well numbering is shown in Table 4.

Each monitoring well was drilled to the same depth as the associated recharge well. Schedule 80 or ASDR 21 PVC casing material was used for all wells. Wells designated for water quality monitoring were constructed with four-inch PVC, and wells for monitoring water levels were constructed with two-inch PVC. Factory-slotted screen was used. Slots were 0.035 inches wide with 0.375-inch spaces between the slots. All wells were screened across the same intervals as the associated recharge wells.

A cementing collar was attached approximately two feet above the uppermost screened interval. Bentonite grout was tremied into the annular space to within 10 feet of land surface. Cement grout was then poured from the top of the bentonite to the land surface.

Each monitoring well was completed with a pad, four steel corner posts and a steel casing guard. The purpose of the casing guard was to protect the casing and to hold the water

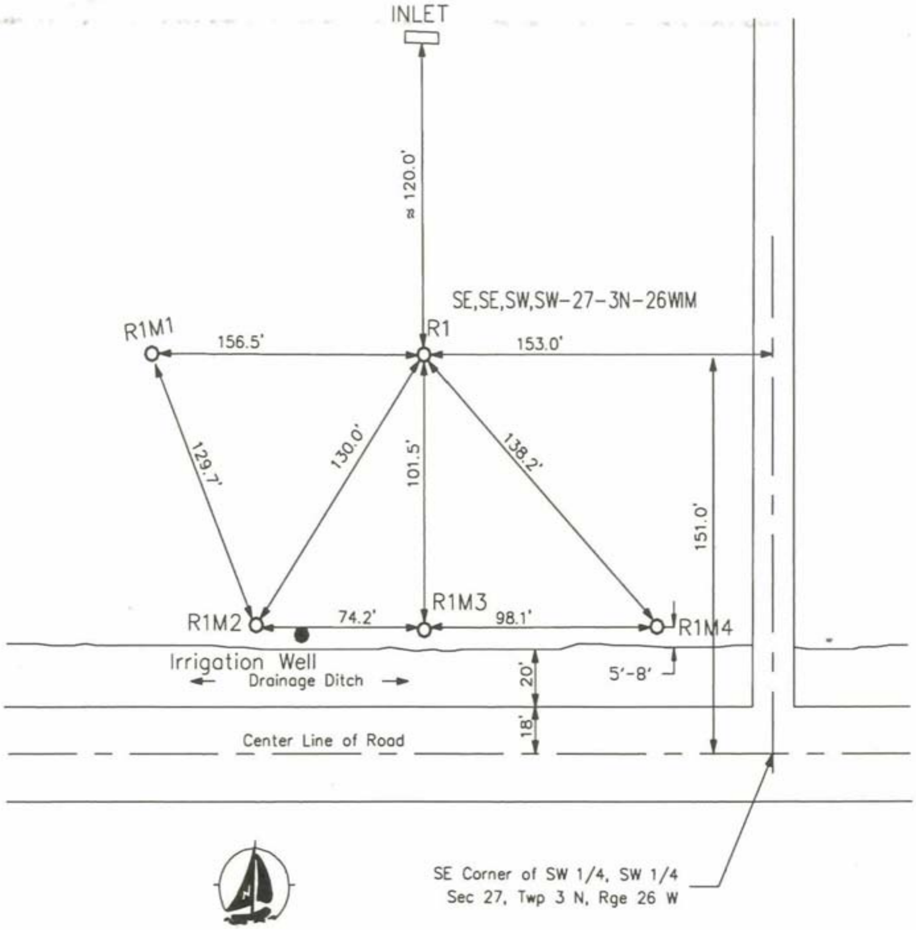


Figure 25. Map showing monitoring well identification numbers, distribution and positions for monitoring wells at the R01 site.

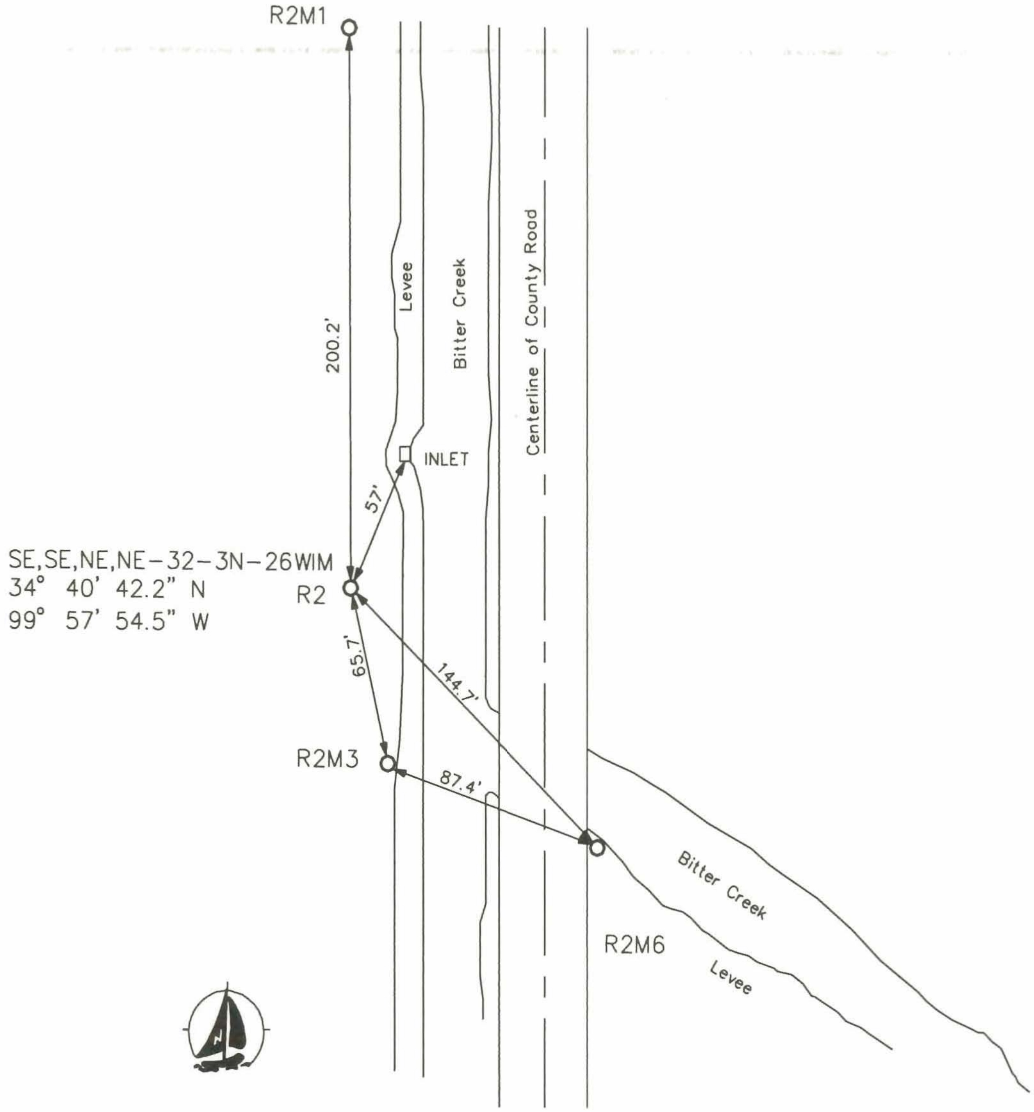


Figure 26. Map showing monitoring well identification numbers, distribution and positions for monitoring wells at the R02 site.

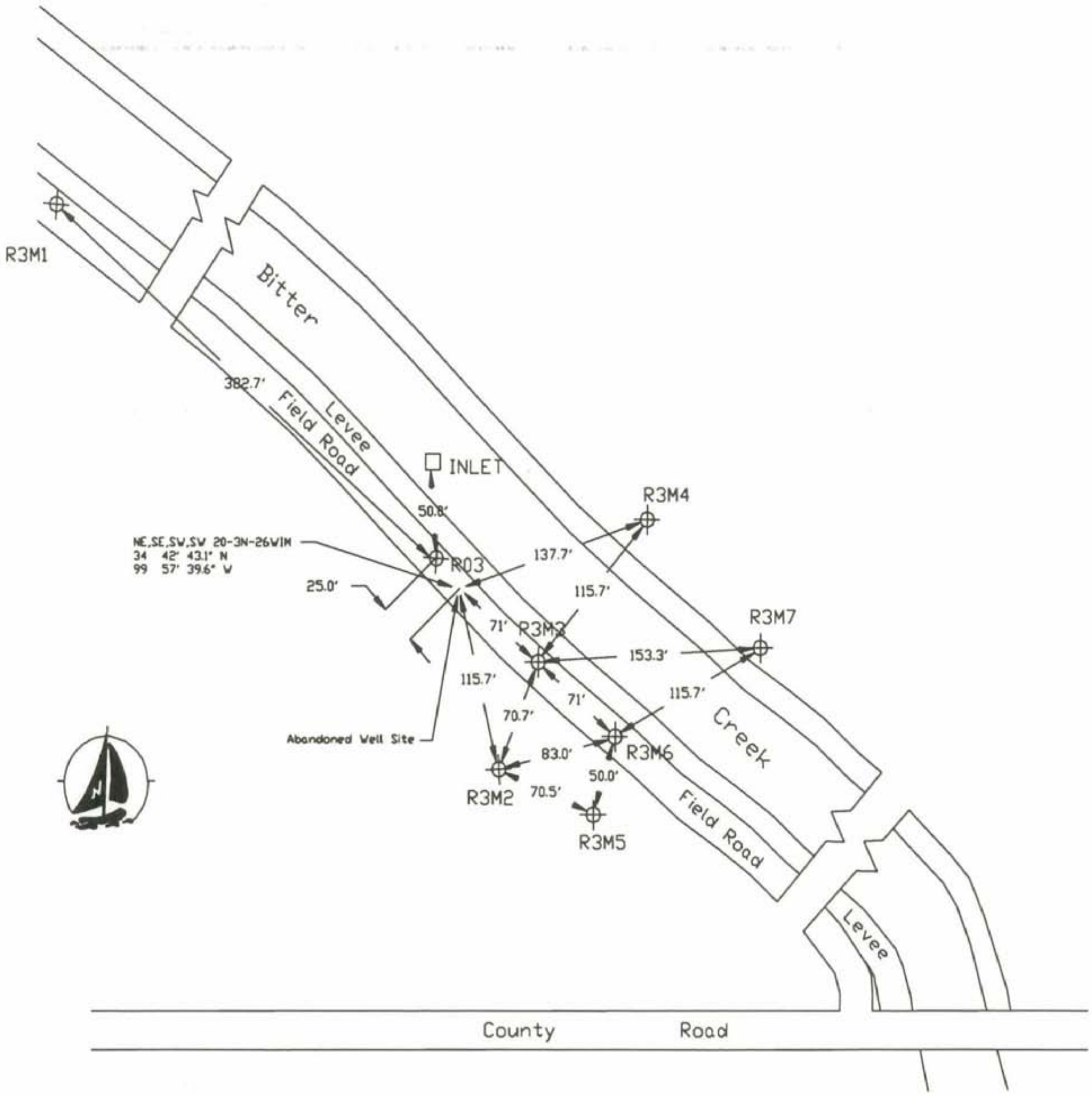


Figure 27. Map showing monitoring well identification numbers, distribution and positions for monitoring wells at the R03 site.

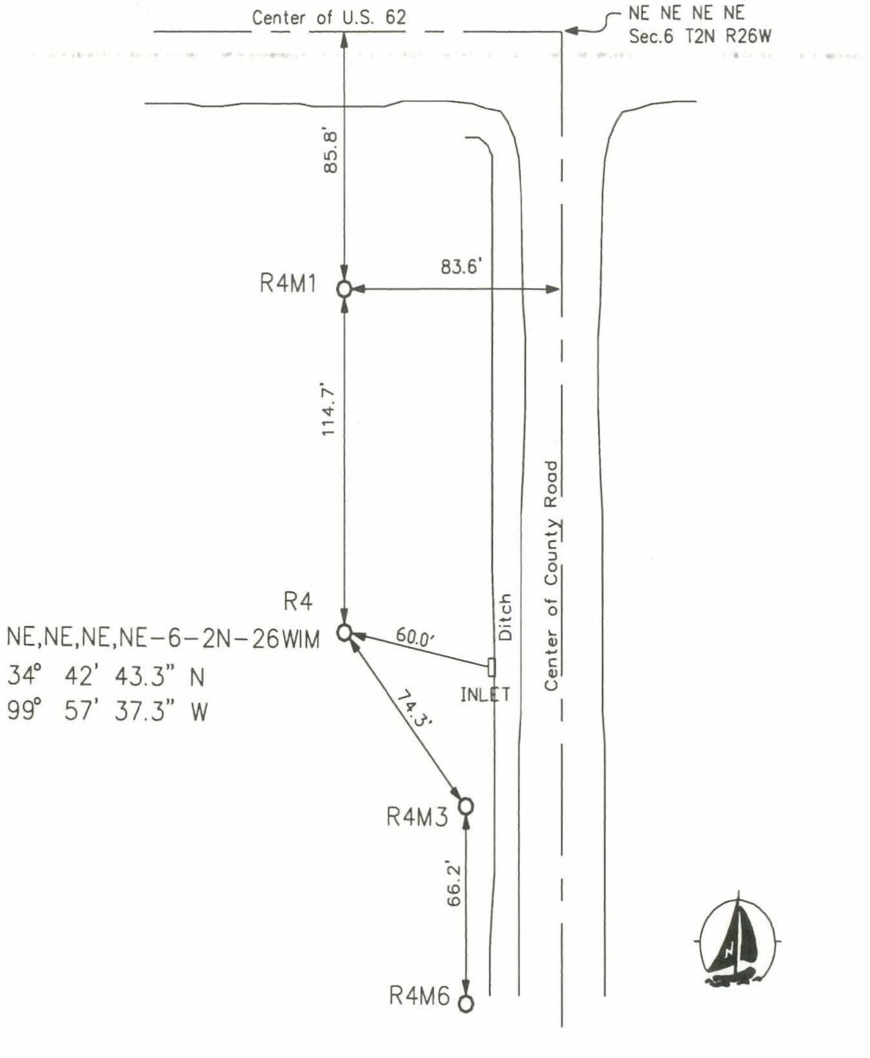


Figure 28. Map showing monitoring well identification numbers, distribution and positions for monitoring wells at the R04 site.

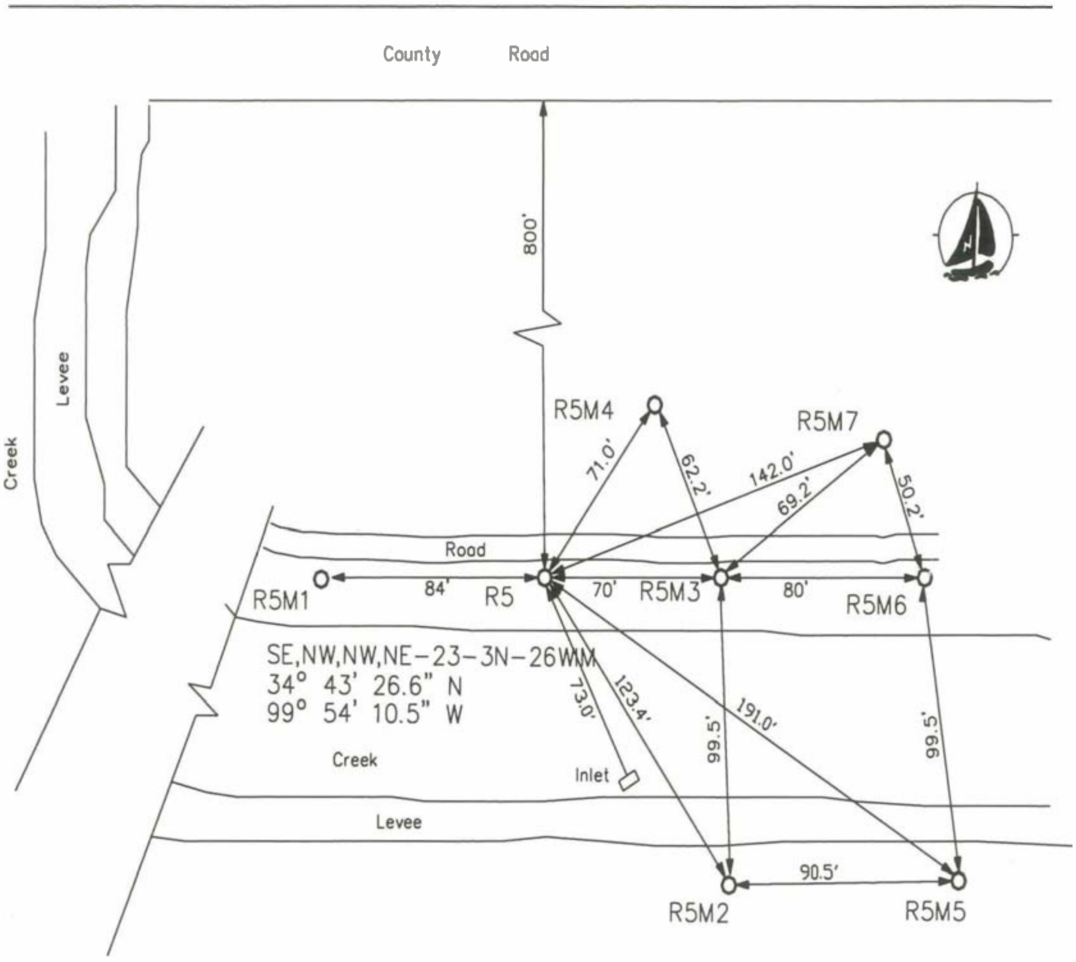


Figure 29. Map showing monitoring well identification numbers, distribution and positions for monitoring wells at the R05 site.

level monitoring instruments. The four corner posts were installed to protect the well from vehicles and cattle.

Table 4. Monitoring well numbering system

SITE NAME	SITE ID	RECHARGE WELL ID	MONITORING WELLS
Conservation Dam	R01	R1	R1M1*, R1M2, R1M3, R1M4
Motley/Jones	R02	R2	R2M1*, R2M3, R2M6
Paul Horton	R03	R3	R3M1*, R3M2, R3M3, R3M4, R3M5, R3M6, R3M7
Kelly Horton	R04	R4	R4M1*, R4M3, R4M6
Warren/Dill	R05	R5	R5M1*, R5M2, R5M3, R5M4, R5M5, R5M6, R5M7

* Upgradient monitoring well

Special Design Features

Existing Recharge Wells

Existing recharge wells constructed by the District have steel casing to a depth of 80 to 100 feet and are open hole construction below the casing. The recharge wells constructed within the last 10 years have cement poured into the bottom of the hole and then the steel casing was set into the hole and cemented. Once the cement hardened, another hole was drilled through the cement to the final depth of the well.

The District has determined from experience that the well casing must be cemented into a thick gypsum bed to prevent collapse of the well due to dissolution of the gypsum during recharge. Another point of failure of the older recharge wells occurred in the shallow subsurface. Well failure was probably caused by water leaking from the joint where the inlet pipe enters the well casing. Leakage from the inlet pipe could cause dissolution of shallow gypsum beds and eventually failure of the well. To prevent dissolution and loss of the recharge wells, the cement was poured into the upper portion of the annular space of each well so the area where the inlet pipe is welded to the casing is encased in cement.

New Design Features

The OWRB worked with the District to improve its existing well design. Three new design features were incorporated into the recharge wells:

- Pressure cement grouting the entire annular space between the outer casing and wall of the hole.

- Adding an inner string of casing.

- Cement grouting the annular space between the inner and outer well casing.

These changes should prevent dissolution in the shallow zones and subsequent well collapse. This is important, as the recharge wells are essentially *hanging* from the upper 80 to 100 feet of the formation.

Operations and Monitoring

OPERATION AND MAINTENANCE

Operation of the recharge wells began in June 1993. The recharge wells were not operated on a schedule; they depended on runoff from precipitation in the normally dry creeks and ditches. Operation and maintenance costs of the five recharge wells and impoundment were very low ($53 per month), largely because water treatment was not required. The only maintenance required was weed and brush control around the inlet structures, control of burrowing animals around the well and inlet pipe, and clearing debris off the debris screens that cover the inlet structures.

MONITORING

Both water quantity and water quality were monitored to assess the impact of the recharge to the aquifer and the environment. Monitoring data collected after September 1996 are not included in this report.

Water Quantity Monitoring

Water quantity was monitored to determine the volume of water artificially recharged to the aquifer and the aquifer's response to recharge. Water quantity monitoring included recharge flow rates, groundwater levels, stream discharge, and precipitation amounts. Baseline monitoring began in April 1988 with monthly water level measurements of existing wells. Post-recharge monitoring began in June 1993, when the recharge wells were opened, and continued to June 1997, when the monitoring wells were plugged.

In order to determine the amount of surface water entering the recharge wells, a pressure transducer was installed within the inlet pipe of each recharge well. The pressure transducer measured the overlying depth of water from which the volumetric flow rate and recharge volume were calculated.

Aquifer response to the recharge was monitored with water level measurements. Hourly water levels were recorded on electronic water level recorders installed in 24 monitoring wells located near the recharge wells. Monthly and periodic water levels were measured in 71 irrigation, recharge, stock, and observation wells located throughout the study area (Figure 30). A stream gauge measured stream flows on Sandy Creek, and two tipping bucket rain gauges recorded rainfall (Figure 31).

Water Quality Monitoring

Water quality was monitored to determine effects of the recharge on the quality of the aquifer. Water quality was monitored for one year before recharge to determine baseline conditions. Post-recharge monitoring was conducted from June 1993 to May 1997.

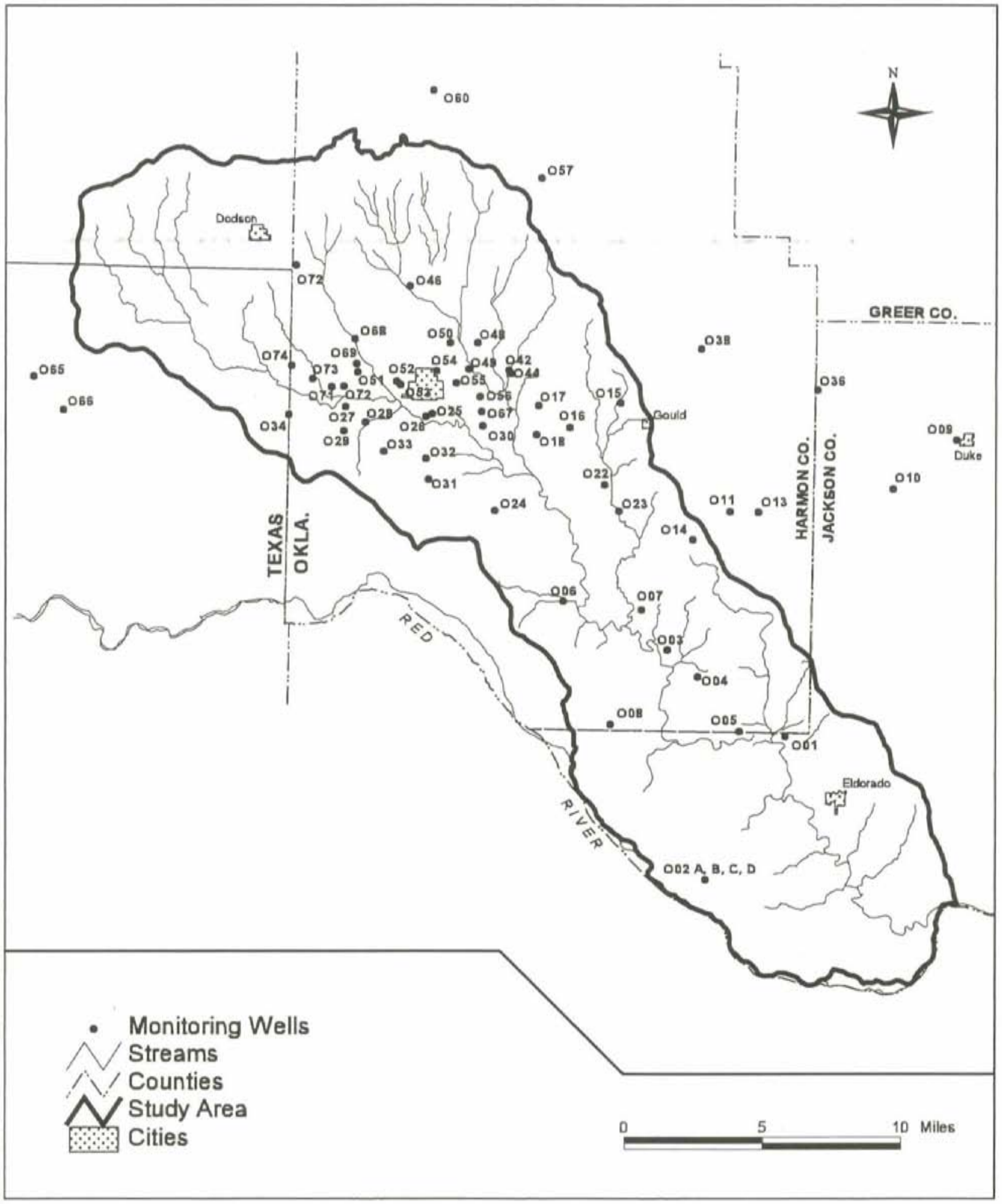


Figure 30. Locations of wells measured monthly and periodically for water level.

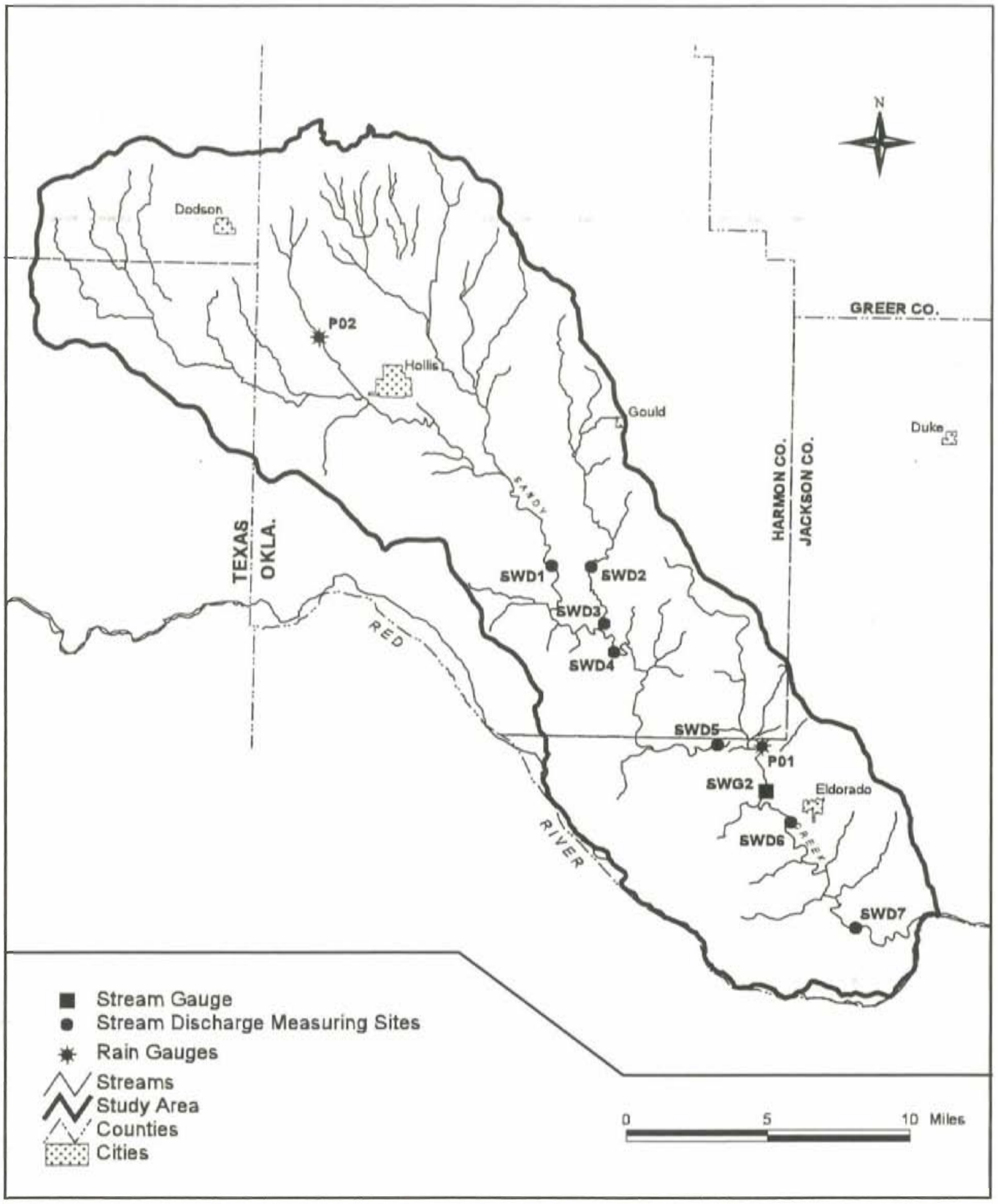


Figure 31. Location map of water quantity measurement sites.

The following sampling schedule was used for collecting water quality samples:

Sample Period I - April 1 through June 15

Sample Period II - June 16 through August 31

Sample Period III - September 1 through November 15

These periods were selected because precipitation is greatest from April through October, the growing season for cotton is April to September and pesticides are applied between April and September. Because little agricultural activity or recharge occurs from mid November through April 1, sampling during the winter months was not considered necessary.

Samples were collected during each sampling period from the inlet of each recharge well and from three monitoring wells at each site. At each site, a flowmeter/sampler unit was programmed to collect an injectate (recharge water) sample during each sampling period. Within seven days of collecting an injectate sample, groundwater samples were collected from the monitoring wells.

All water quality samples were analyzed for common ions, trace elements, organic compounds, and pesticides (Table 5). Injectate samples were also analyzed for cyanide and specific pesticides used in the study area: trifluralin (Treflan), pendimethalin (Prowl), ethephon (Prep-new), aldicarb (Temik), and methyl parathion (Penncap-M).

Soil Samples

Soil samples were collected at sites R01, R03 and R05 in April 1993 and in January 1995 to assess the impacts of soil chemistry on the injectate and groundwater. These samples were analyzed for metals and cations only.

Table 5. Water quality parameters sampled

PARAMETERS	GROUNDWATER	INJECTATE
Aldicarb (insecticide)		X
Alkalinity, total	X	X
Alkalinity, Bicarbonate	X	X
Alkalinity, Carbonate	X	X
Aluminum-total	X	X
Antimony-total	X	X
Arsenic-total	X	X
Barium-total	X	X
Beryllium-total	X	X
Boron-total	X	X
Cadmium-total	X	X
Calcium-total	X	X
Chloride	X	X
Chromium-total	X	X
Copper-total	X	X
Cyanide		X
Ethephon (defoliant)		X
Fluoride-total	X	X
Herbicide scan	X	X
Iron-total	X	X
Lead-total	X	X
Magnesium-total	X	X
Manganese-total	X	X
Mercury-total	X	X
Nickel-total	X	X
Nitrite-nitrate as n	X	X
pH, field	X	X
Parathion (insecticide)		X
Pendimethalin (herbicide)		X
Pesticide scan	X	X
Phosphorous-total p	X	X
Potassium-total	X	X
Selenium-total	X	X
Silver-total	X	X
Sodium-total	X	X
Solids, Total Dissolved	X	X
Solids, Total Suspended	X	X
Sulfate	X	X
Thallium-total	X	X
Trifluralin (herbicide)		X
VOC scan	X	X
Zinc-total	X	X

Water Quantity Findings and Results

PRECIPITATION

During the period of study, precipitation was generally higher than average. Figure 32 shows the annual precipitation recorded at the Hollis rain gauge from 1992 to 1996. The driest year was 1994, with 3.71 inches below Hollis's average annual precipitation of 23.32 inches, and the wettest year was 1995, with 12.98 inches above average.

Monthly precipitation totals are shown in Figure 33, along with the average monthly precipitation. The spring and summer months of 1994 were especially dry, resulting in high irrigation pumpage. In 1995, heavy rains caused flooding in Hollis in early June, and more flooding in August and September. As much as 3.60 inches fell on June 4, and 4.36 inches fell on August 3.

Weather conditions in 1996 were extreme. Oklahoma experienced a drought during the first half of the year. October through June precipitation was the third lowest ever recorded in the state. In June and July triple digit temperatures up to 108° and winds up to 121 miles per hour were recorded in Hollis. Rainfall in July ended the nine-month drought and made July one of the wettest on record. The second half of the year was wetter than normal, resulting in an annual precipitation total of 31.62 inches, 8.30 inches above average (NOAA, 1992-1996).

GROUNDWATER

Study Area

Water level in the Blaine aquifer fluctuates in response to recharge from precipitation and discharge from well pumping. The hydrograph of well O55 (Figure 34), located just east of Hollis, is typical of most wells in the study area. As illustrated in the hydrograph, water levels declined slightly between July 1993 and September 1995 when precipitation decreased and pumpage increased. Water levels then rose between 1995 and 1996.

Generally, water levels decline suddenly between July and September, in response to irrigation pumping, and then recover during the fall when irrigation pumping ceases. Water levels are most stable in the winter when both pumpage and recharge are least. A slight decline usually occurs around March, when winter wheat is irrigated. This is followed by a rise in May or June when spring recharge occurs.

While water levels of most wells in the study area have responses similar to well O55, a few wells deviate. Figure 35 shows hydrographs of three wells representing different flow regimes. Well O32, which is located in a recharge area south of Hollis, responds most to recharge and least to pumpage. Well O01, located in the discharge area in the

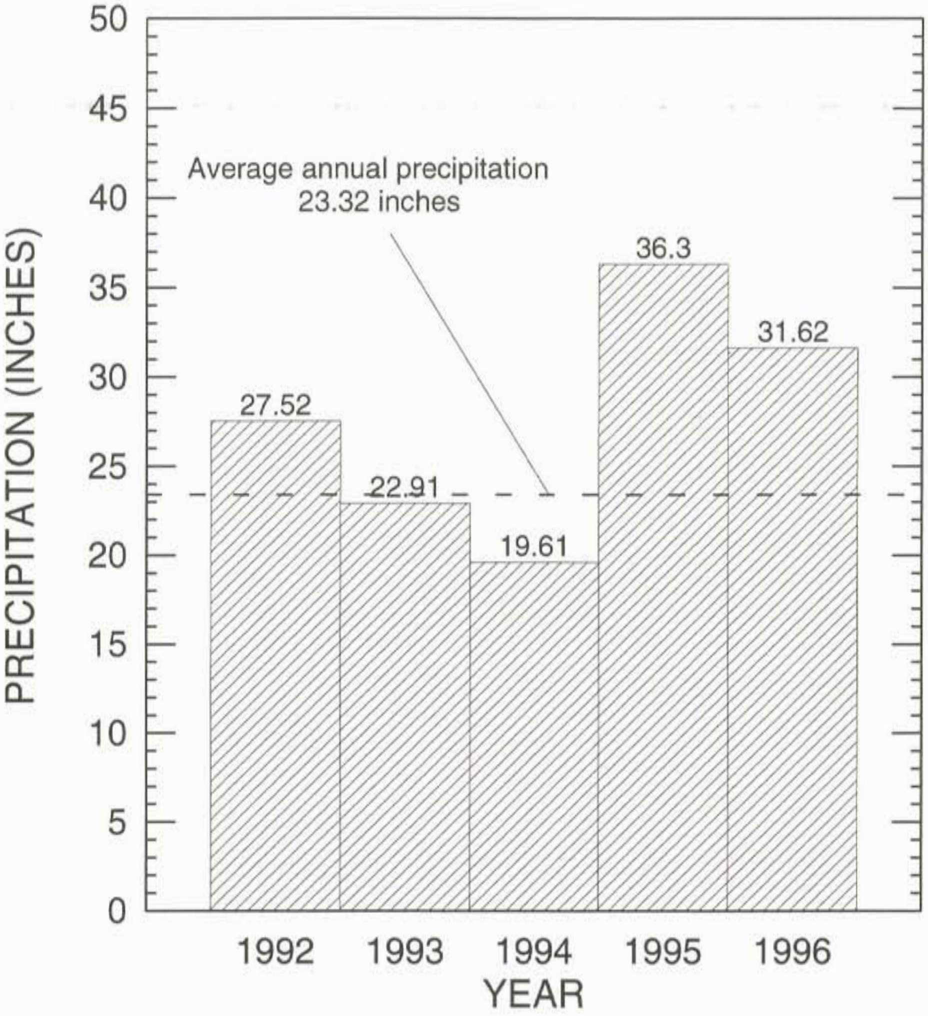


Figure 32. Annual precipitation from 1992-1996 recorded at the Hollis rain gauge.

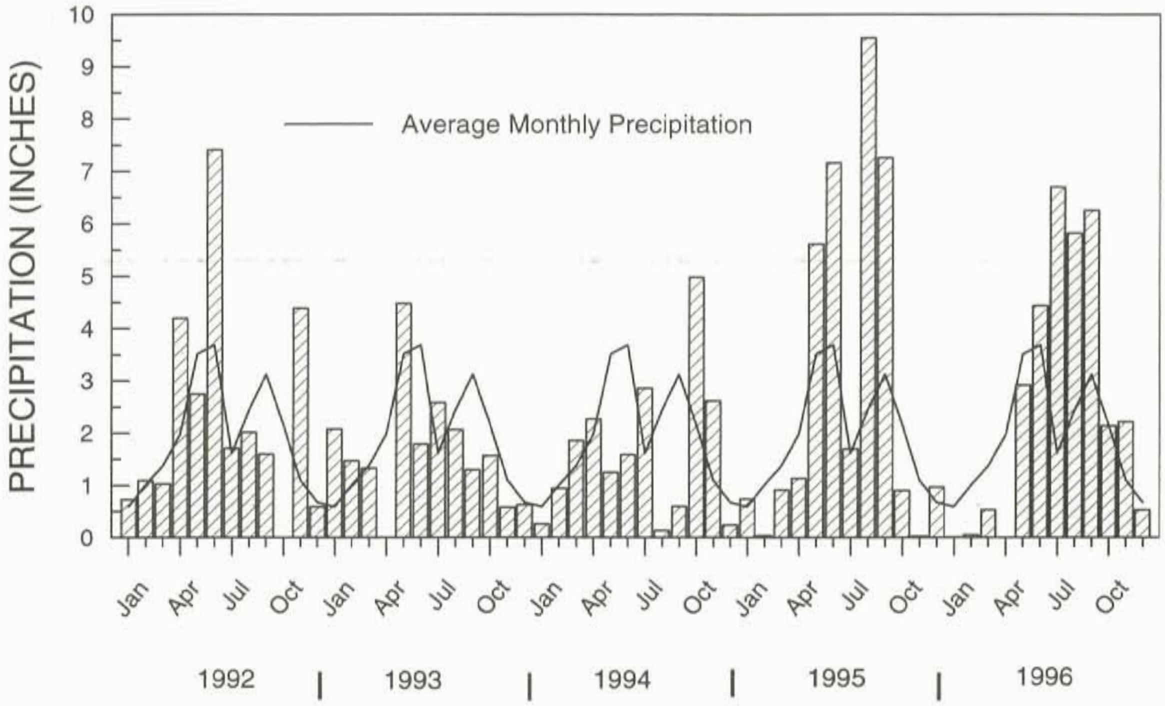


Figure 33. Monthly precipitation from 1992-1996 and average monthly precipitation for the Hollis rain gauge.

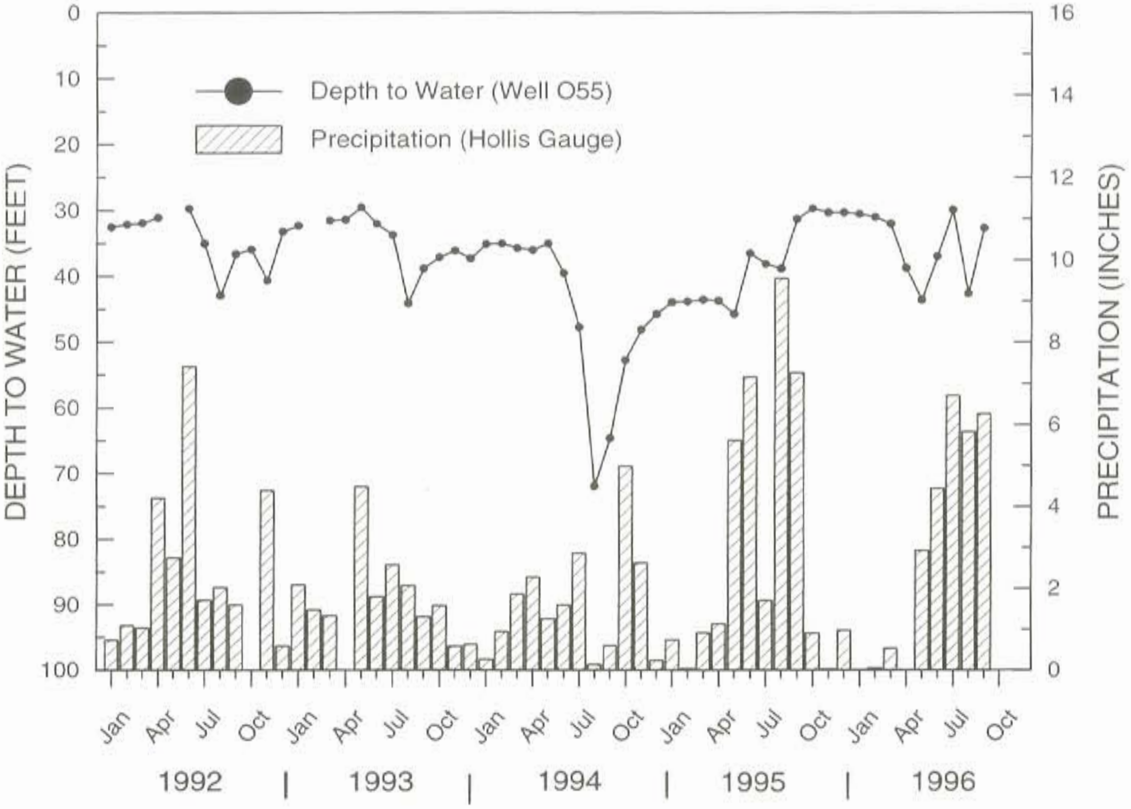


Figure 34. Monthly hydrograph of well 055 and precipitation graph of Hollis rain gauge.

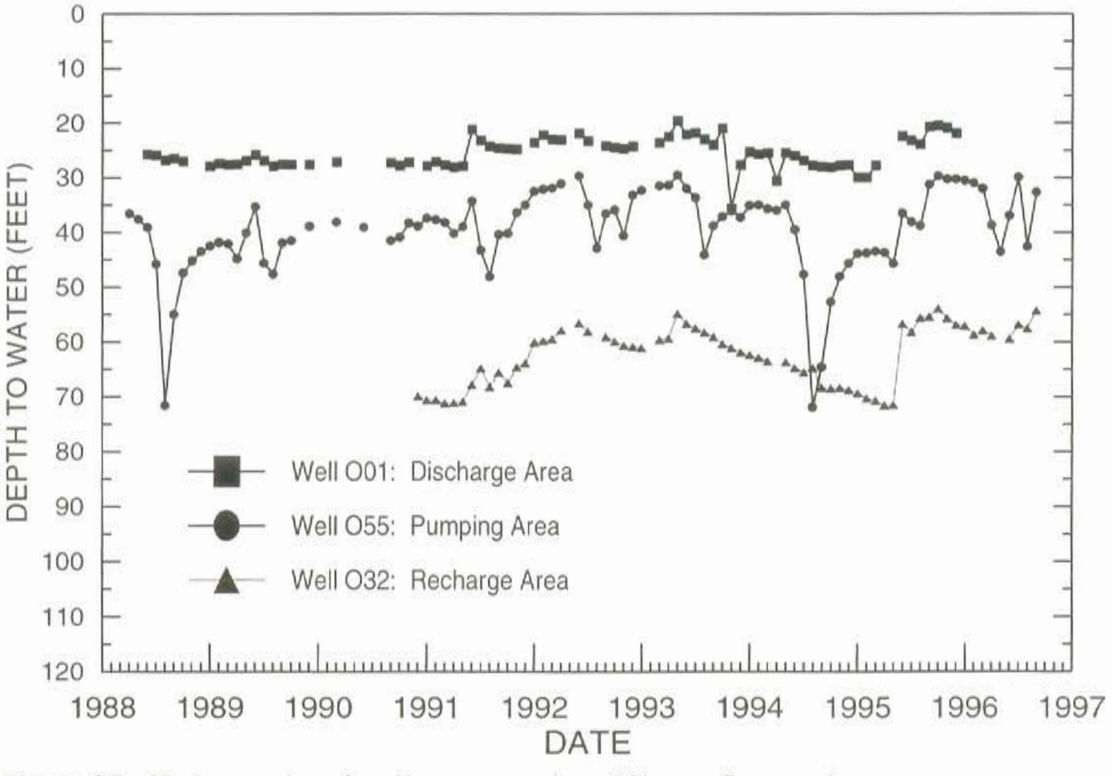


Figure 35. Hydrographs of wells representing different flow regimes.

southern portion of the study area, has a subdued response to both recharge and pumping. Well O55 is typical of wells located in areas of high irrigation pumpage.

Figure 36 displays potentiometric maps of the Blaine aquifer in the study area for 1994. The maps were constructed with a contouring package of the ARC/INFO geographic information system software (ESRI, 1997), and are based on water level measurements from wells and on altitudes of perennial streams that are in hydraulic connection with the aquifer.

The maps were constructed for four months representing different seasons. February represents winter months, when water levels are most stable; May represents spring, when recharge occurs; August represents summer, when effects of irrigation pumping are greatest; and November autumn when water levels recover from pumping. All four maps show an anomalous region near Hollis where the gradient decreases.

Areal changes in water level from season to season are best illustrated with water level change maps (Figures 37, 38, and 39). Blues represent water level declines, and yellows and reds represent water level increases.

Figure 37 shows the seasonal changes in water levels in 1994. Between February and May, the water level rose slightly in the north and central portions of the study area, and declined slightly over the rest. An extreme drop in water level occurred between May and August due to low precipitation and heavy irrigation pumping. Drawdown due to pumping created a regional cone of depression in the northern portion of the study area. The greatest decline was 60 feet in a well north of Hollis. The least change was in the southern portion of the study area and in a small area south of Hollis.

The water level change map of August to November is almost an inverse image of the May to August map, showing a significant rise in water level instead of a decline. Because little precipitation occurred during this time and pumping ceased, the rise in water level is attributed to recovery of the regional cone of depression. The greatest increase was in the northern portion of the study area, where drawdown was greatest. The least change was in the southern portion of the study area and in the small area south of Hollis.

While 1994 was characterized by dry weather and heavy irrigation pumping, 1995 was characterized by wet weather and low irrigation pumping. Figure 38 shows the seasonal changes in water level in 1995. Between February and May, the water level declined slightly over most of the study area due to dry weather and irrigation pumping for winter wheat in March. In late May and early June, the region experienced unusually high precipitation that resulted in an increase in water level over the entire study area. The greatest change was measured south of Hollis in well O31, with an increase of 27.3 feet.

Between June and August, the water level rose slightly in the central portion of the basin and declined in the northern portion. A couple of rain events occurred during this period. The decline is due to irrigation pumpage, but is subdued in comparison to other years.

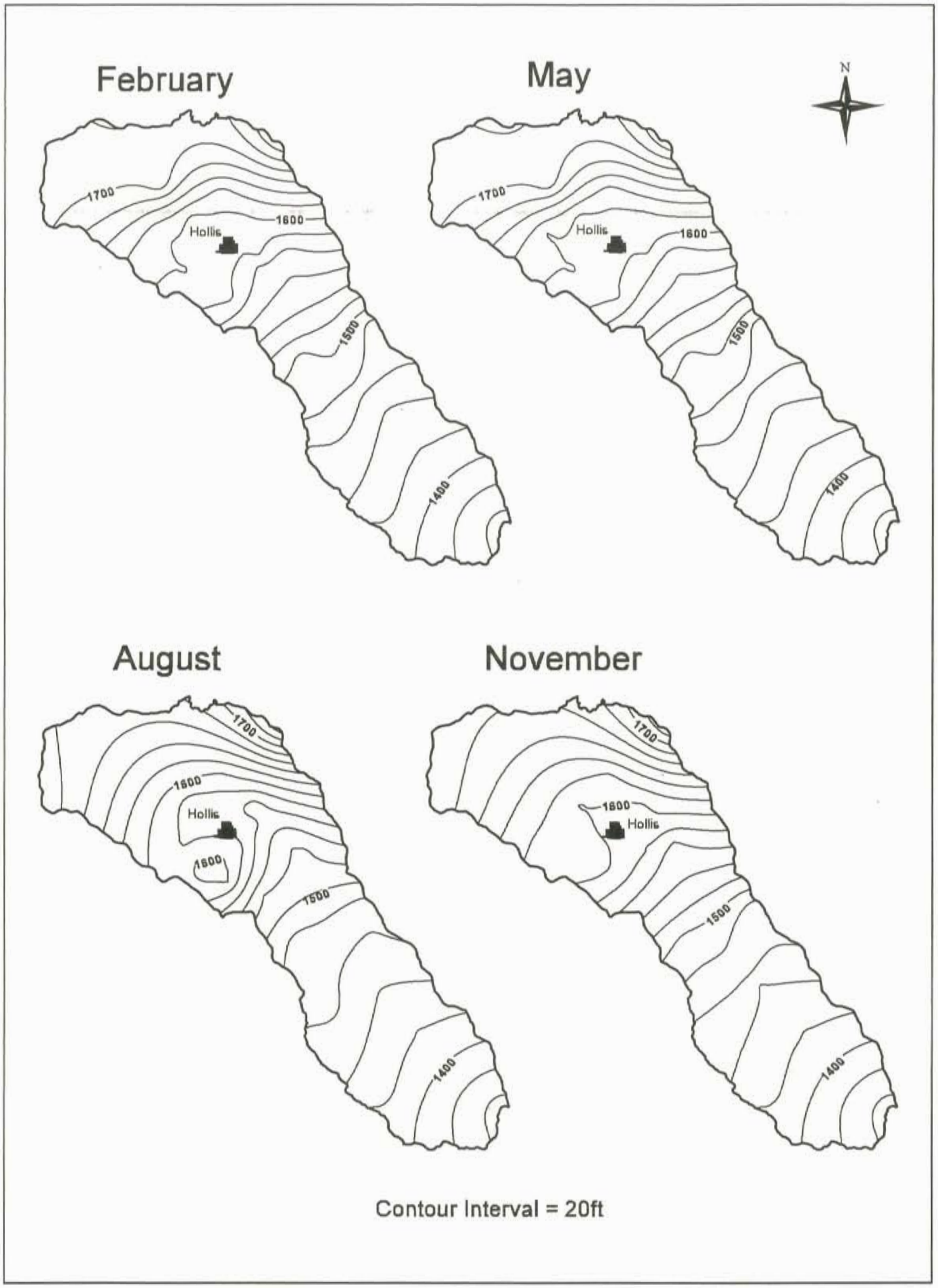
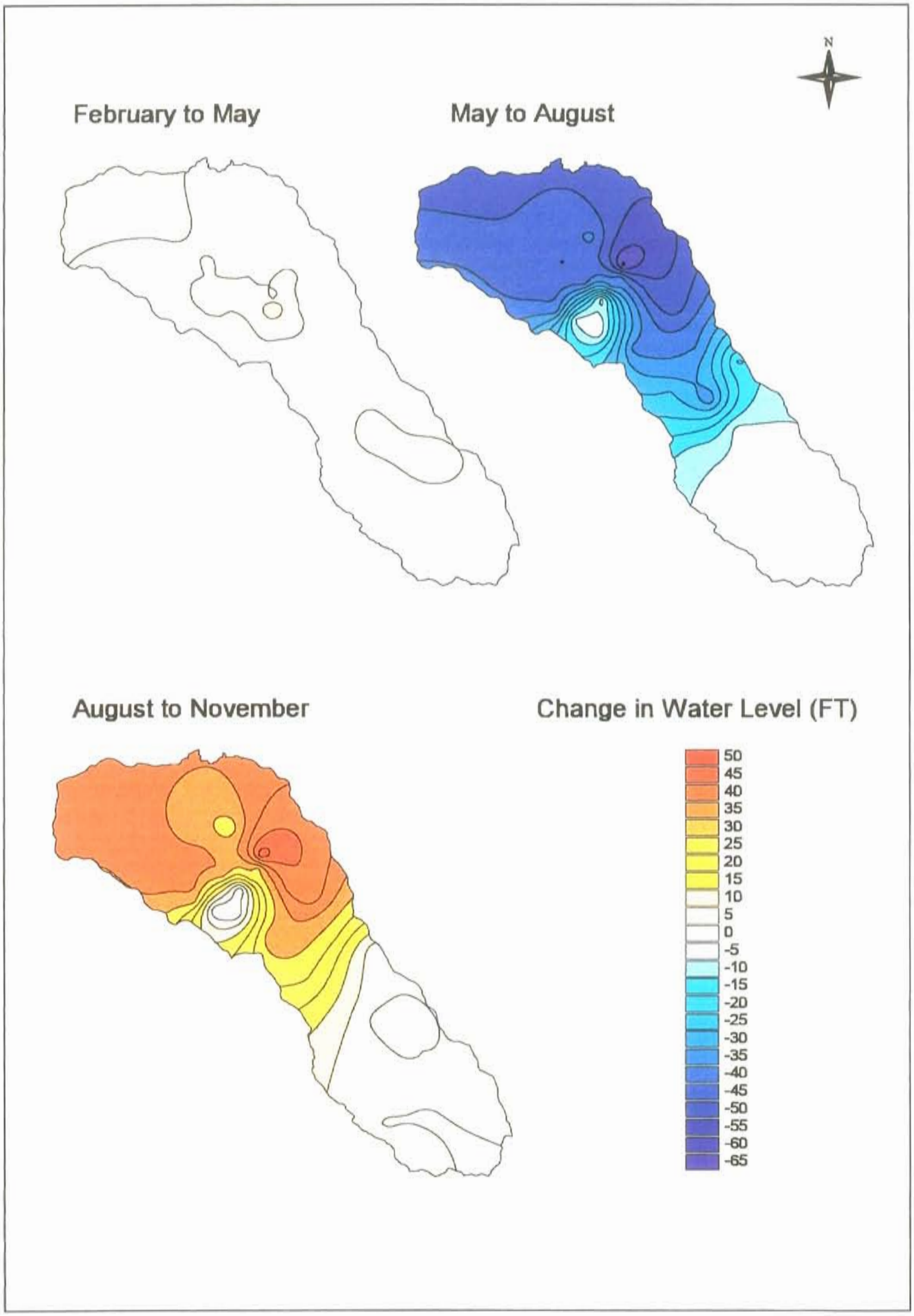


Figure 36. Potentiometric maps of the study area for four months in 1994.


February to May

May to August

August to November

Change in Water Level (FT)

Figure 37. Water level change maps showing seasonal changes in 1994.

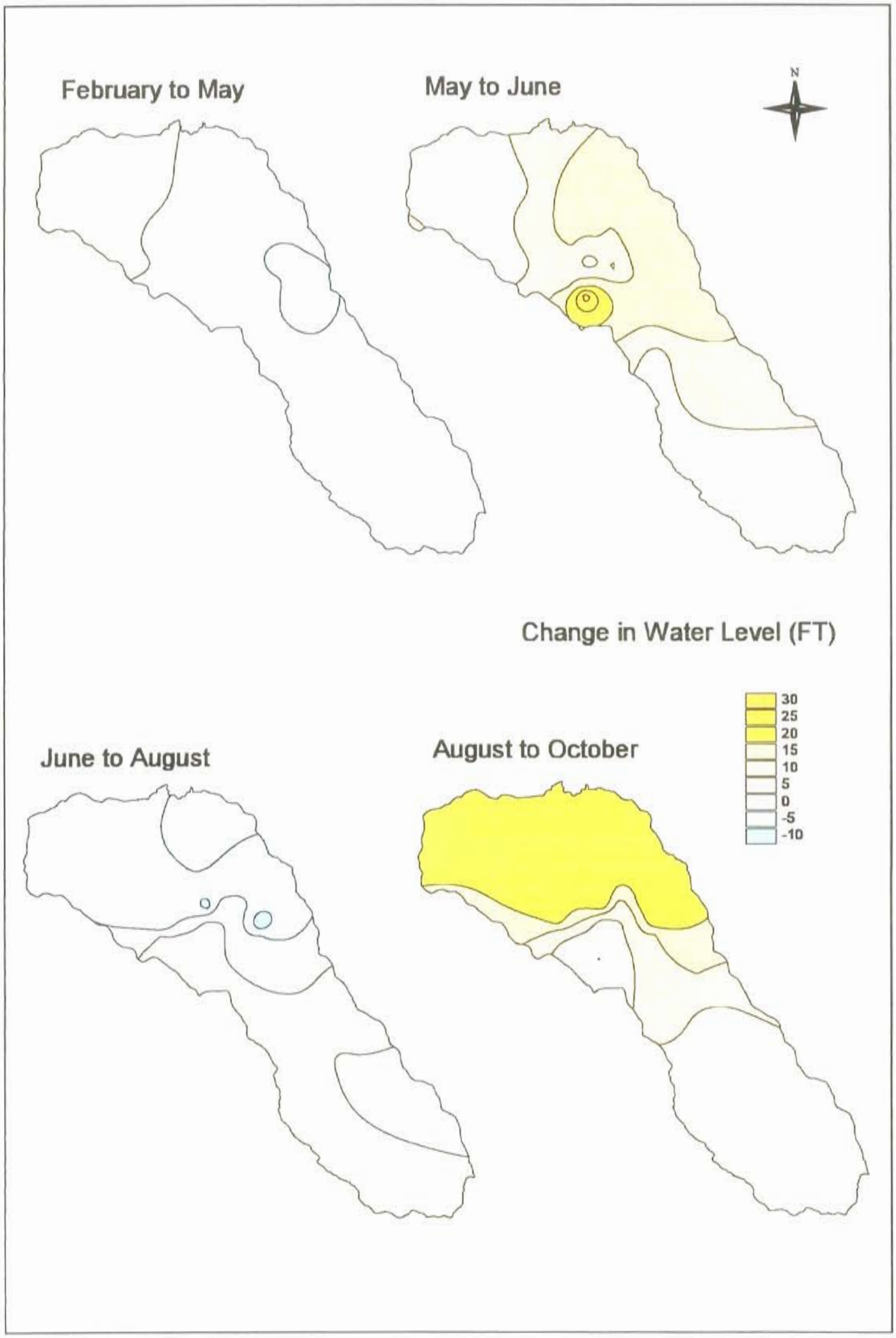


Figure 38. Water level change maps showing seasonal changes in 1995.

Between August and October, the water level rose over the entire study area. The greatest increase was in the northern portion, and the least increase was in the area south of Hollis and the southern portion of the study area. Part of the increase in water level is attributed to recovery from irrigation pumping and part is due to higher than normal precipitation in September.

Spatial patterns of recharge vary from year to year as well as seasonally. Figure 39 illustrates the water level change between February, when water levels are most stable, and either May or June, when spring rainfall occurs. The water level rises in response to the spring recharge. In 1991, most of the change in water level occurred in the north central portion of the study area. In 1994, it occurred in the central portion, and in 1995 it was highest in the area south of Hollis.

The cone of depression, indicated in the May-August and August-November 1994 maps, occurred in an area where irrigation pumpage tends to be high. It also corresponds to the confined portion of the study area, where the Blaine Formation is overlain by the Dog Creek Shale. Permeability is lowest where the Dog Creek Shale is greater than 100 feet thick. In these areas, where fresh water is not in contact with the Blaine Formation, anhydrite is present instead of gypsum (Johnson, 1990b). Drawdown is greater in confined situations than unconfined, and in low-permeability formations.

The anomalous area south of Hollis that does not respond to pumping is suspected to be a natural recharge area. The area is characterized by sinkholes and disappearing streams. The Dog Creek Shale is either absent or very thin, making this portion of the aquifer unconfined. Because of the rough land surface, this area is not as heavily pumped as the area north of Hollis. Much of this area is part of the Conservation Reserve Program and is used as non-irrigated pasture land. The fact that wells in this area do not respond to nearby pumping suggests that the formation is extremely permeable.

The southern portion of the study area shows little response to recharge or pumping. This is largely because this is a discharge area, where water from the Blaine aquifer discharges into Sandy Creek. It is also an area where the aquifer is unconfined, sinkholes are abundant, and pumpage is low.

Project Area

All 24 monitoring wells were equipped to record hourly water level measurements. Figure 40 shows a hydrograph of monitoring well R3M6, at the R03 site, and a precipitation graph of the P02 rain gauge, located next to the monitoring well. The hydrograph is based on daily averages, and the precipitation graph on daily totals.

The hydrograph shows a water level response similar to other wells in the pumping area, such as well O55 (see Figure 34). Prominent features are the drawdown that occurred in August 1994 in response to pumping and the sudden increase that occurred in 1995 in response to heavy rains.

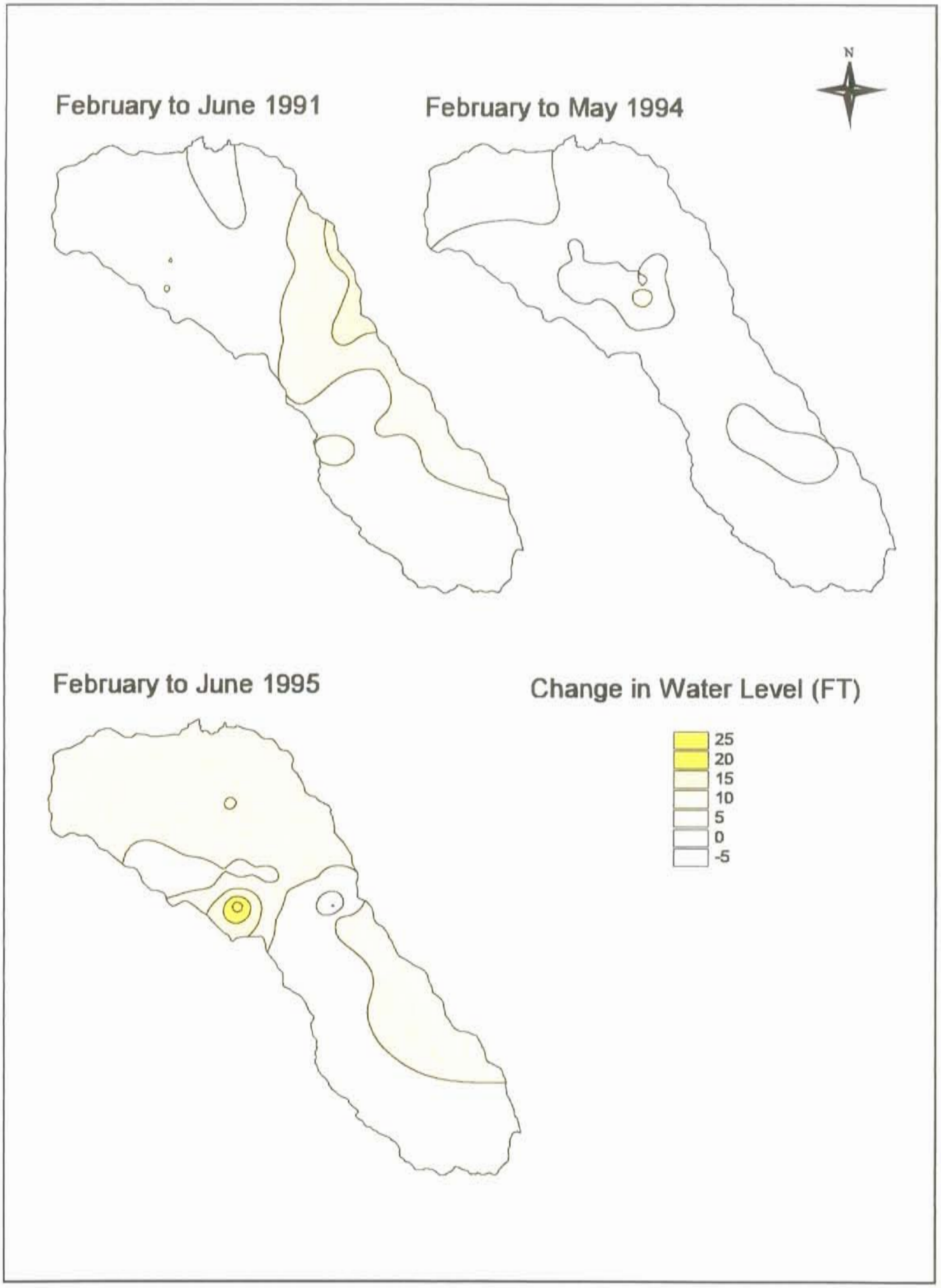


Figure 39. Water level change maps showing changes from winter to spring in 1991, 1994, and 1995.

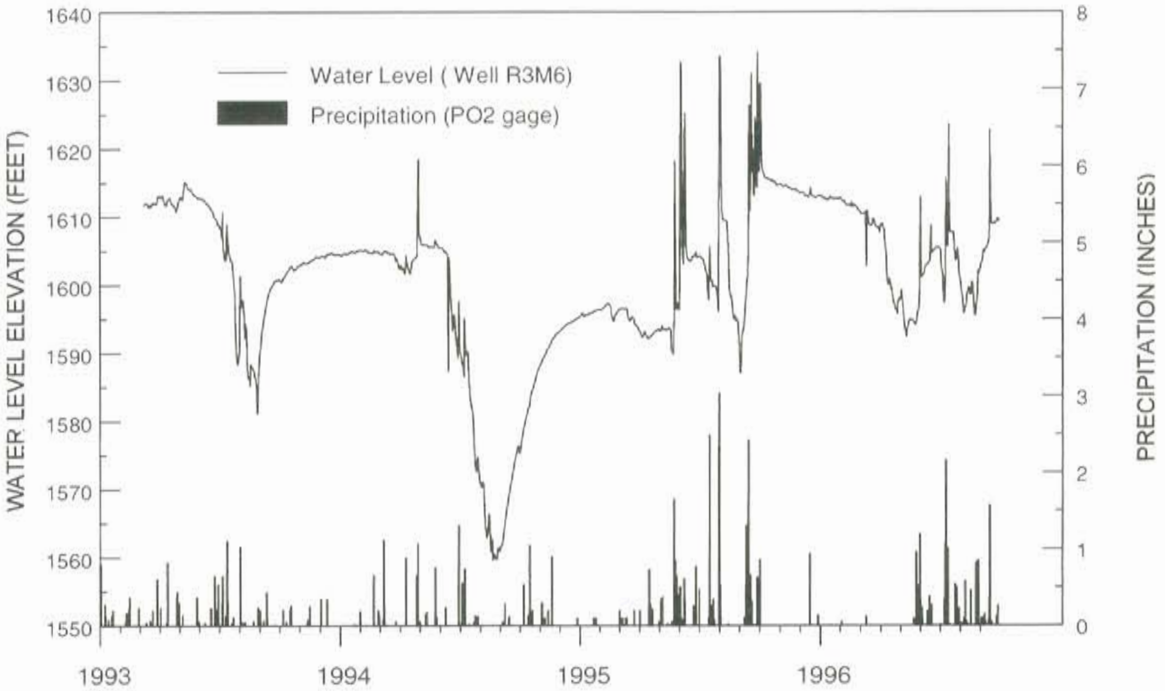


Figure 40. Daily hydrograph of monitoring well R3M6 and precipitation graph of the PO2 rain gauge.

As seen in the daily hydrograph, the water level response to recharge is flashy, as is typical of karst aquifers. For example, on July 3, 1995 the water level in well R3M6 rose 25 feet in one hour, and 37 feet in a 24-hour period.

Daily hydrographs of representative wells from each recharge site are very similar, as illustrated in Figure 41. Although the general trend in water level fluctuations is similar, the magnitude of response varies. Wells at the R05 site show the greatest change in water level.

Water Level Response to Recharge

Water level response to injection of recharge water is the inverse of its response to a pumping well. Pumping causes water levels to decline, while injection causes water levels to rise. Just as a cone of depression develops around a pumping well, a cone of impression (or recharge) develops around an injection well (Driscoll, 1989).

An example of water level response to a recharge event is illustrated in Figure 42, which shows the hydrograph of well R3M6, the precipitation graph of the P02 rain gauge, and the recharge rate of the R3 recharge well. Well R3M6 is located 142 feet downgradient of the recharge well, and next to the precipitation gauge. The hydrograph shows hourly water levels recorded during a recharge event from September 15-16, 1996. The rain gauge recorded 1.93 inches of rain in 19 hours. A total of 11.7 acre-feet of recharge water was recorded entering the recharge well over a 48-hour period. The water level in well R3M6 rose a maximum of 20 feet.

Water level in the same monitoring well responds similarly to other recharge events, as illustrated in Figures 43, 44, and 45. Of these examples, the greatest change in water level was 43 feet in August 1995 (Figure 43). During this recharge event, a total of 6.01 inches of rain fell, and 29.9 acre-feet of water entered the recharge well over a 131-hour period. In all of the examples, the hydrographs are characterized by a flashy response, with very little lag time from the beginning of the recharge event to a sudden increase in water level.

The water level response to recharge events varies from site to site. Figure 46 shows graphs of the recharge rate for each of the five recharge wells during the September 1996 recharge event, and Figure 47 shows well hydrographs for each site. Table 6 lists the recharge rates, volumes, and maximum change in water level for each site. Usually, the larger the recharge volume, the greater the change in water level. The exception to this is the R04 site, which had a very low water level response.

Water level responses in monitoring wells at the same recharge site vary slightly from each other. Figure 48 shows hydrographs of all the monitoring wells at the R03 site during the September 1996 recharge event shown in Figure 42. Maximum changes in water level (amplitudes) range from 12 feet in well R3M1 to 21 feet in well R3M3.

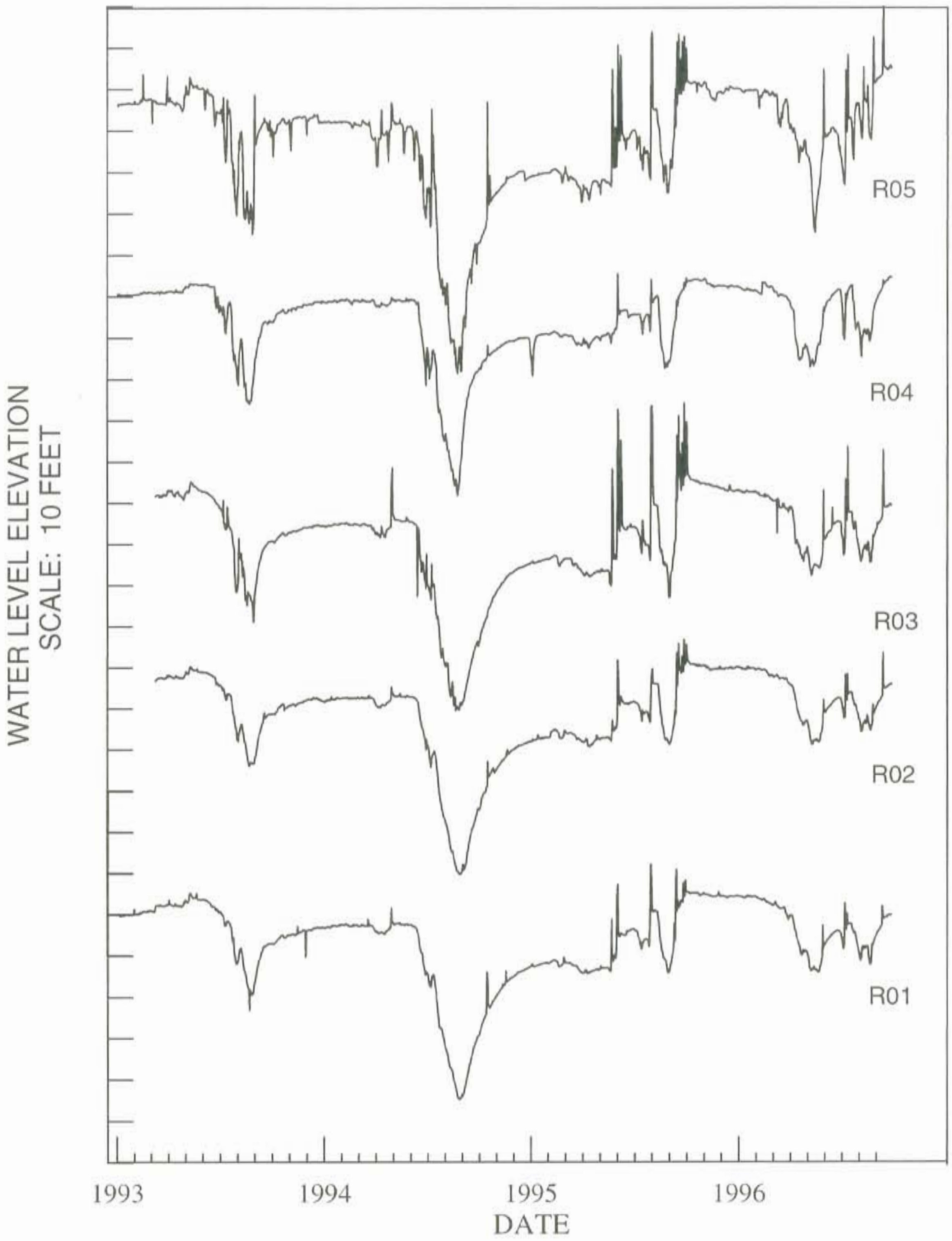


Figure 41. Representative daily well hydrographs of each recharge site.

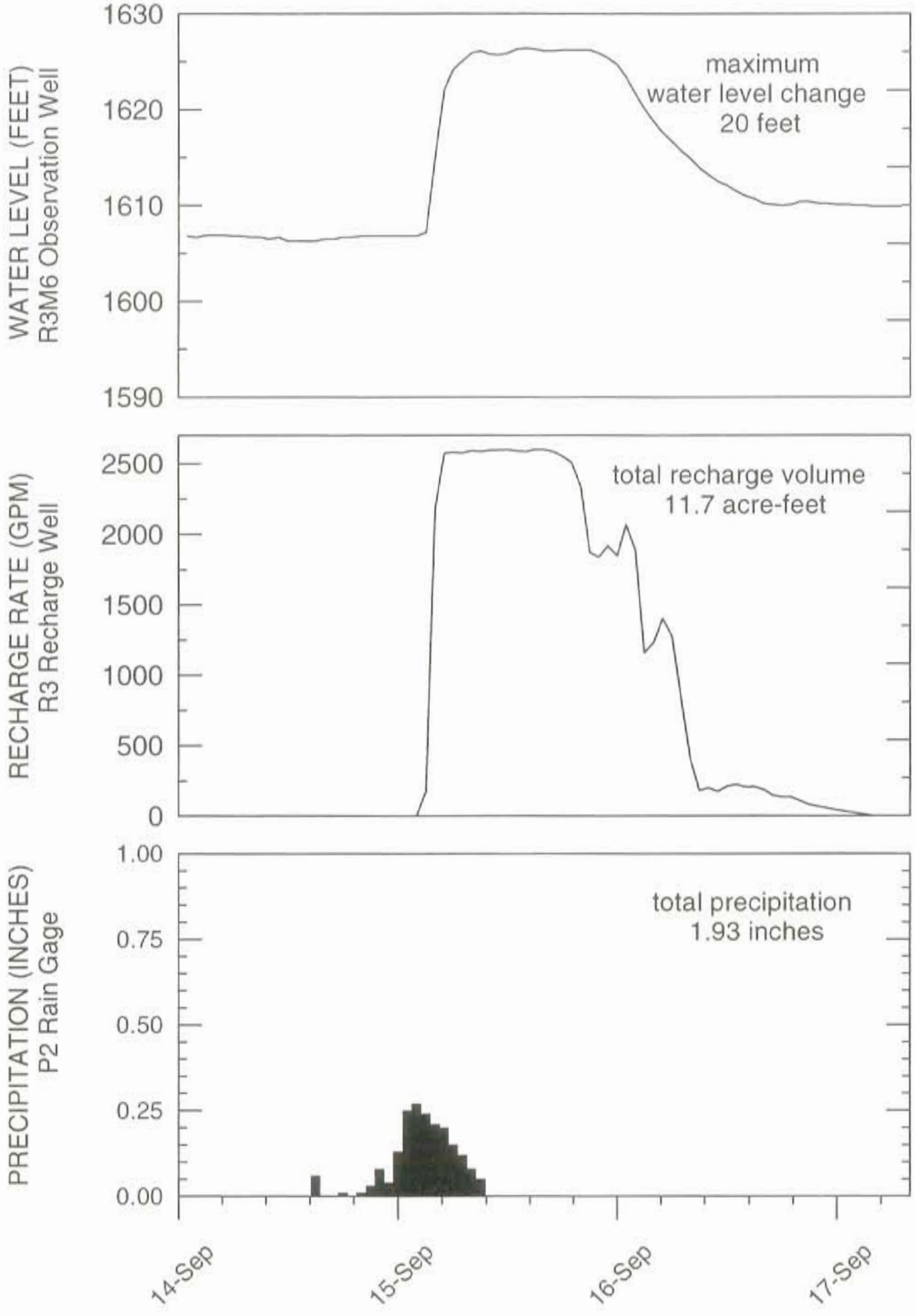


Figure 42. Hourly response to a recharge event from September 15-16, 1996.

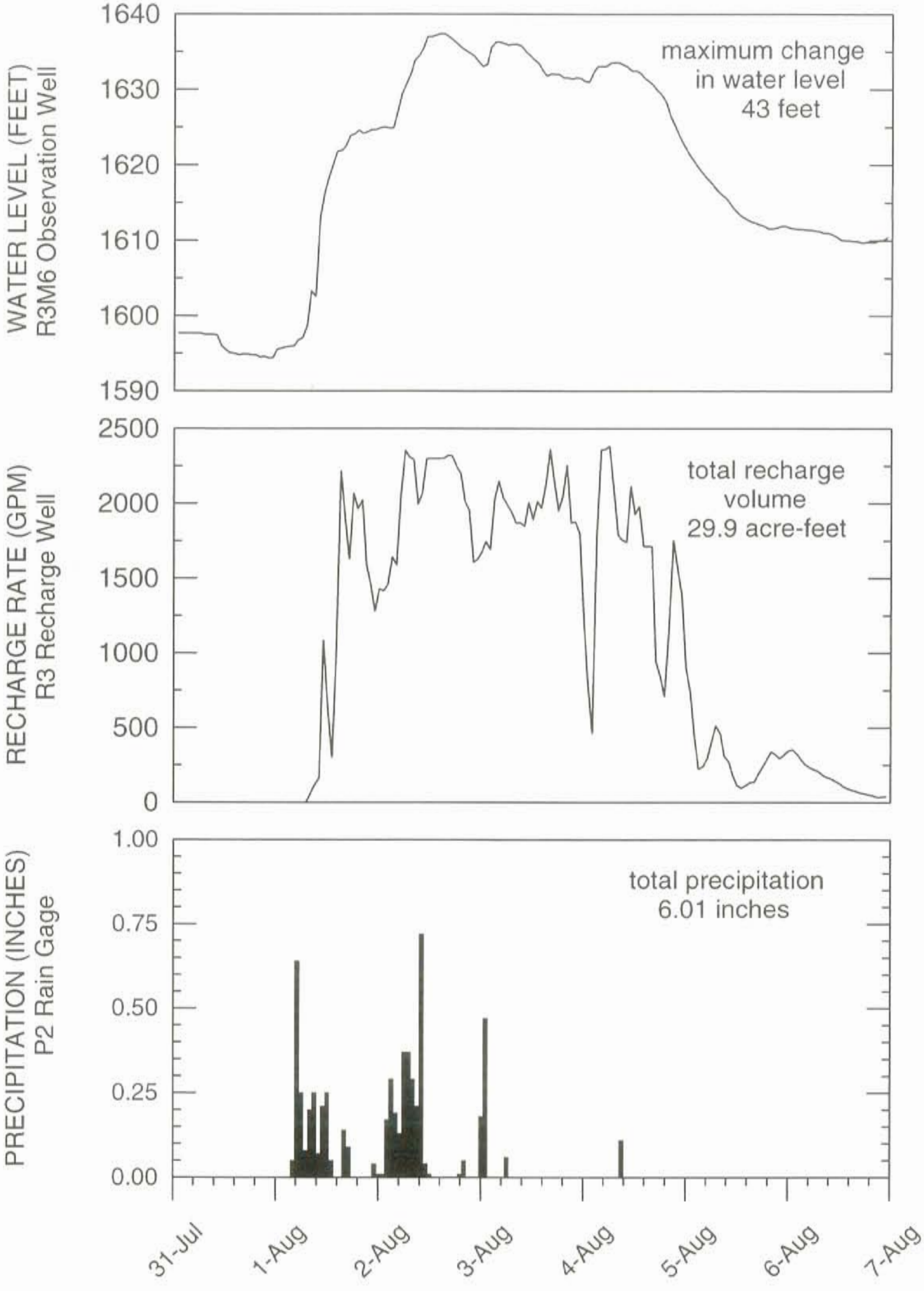


Figure 43. Hourly response to a recharge event in August 1995.

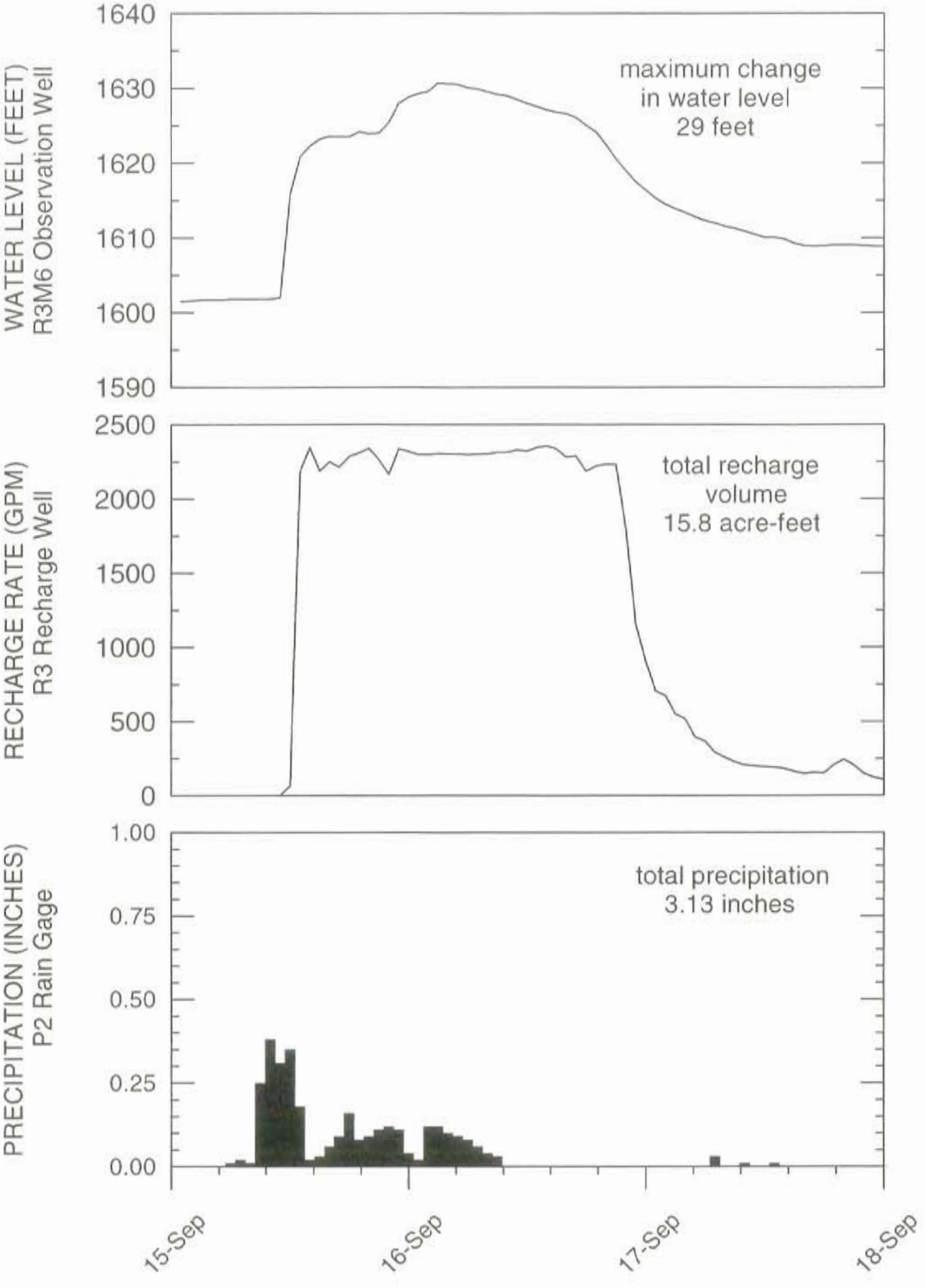


Figure 44. Hourly response to a recharge event in September 1995.

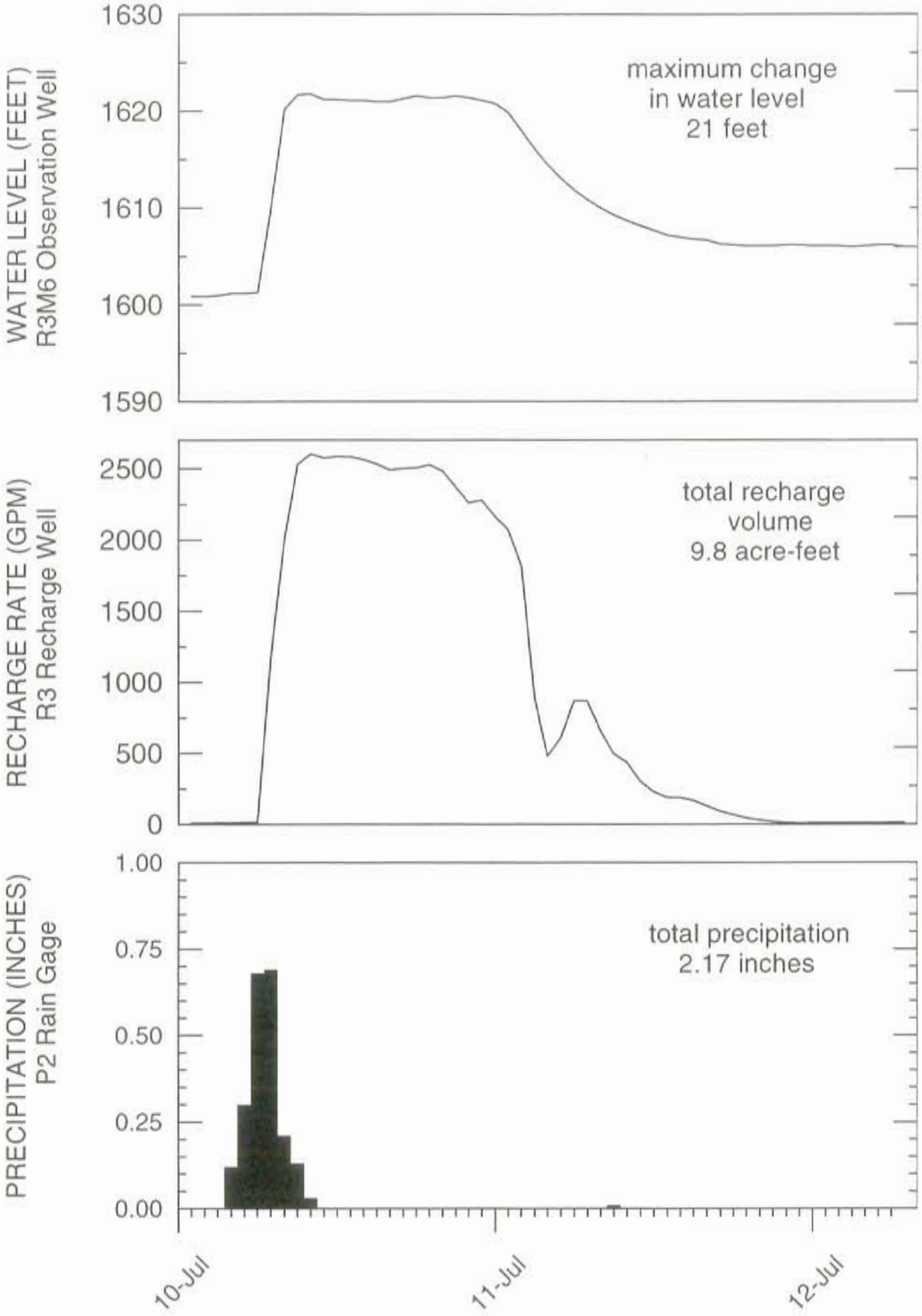


Figure 45. Hourly response to a recharge event in July 1996.

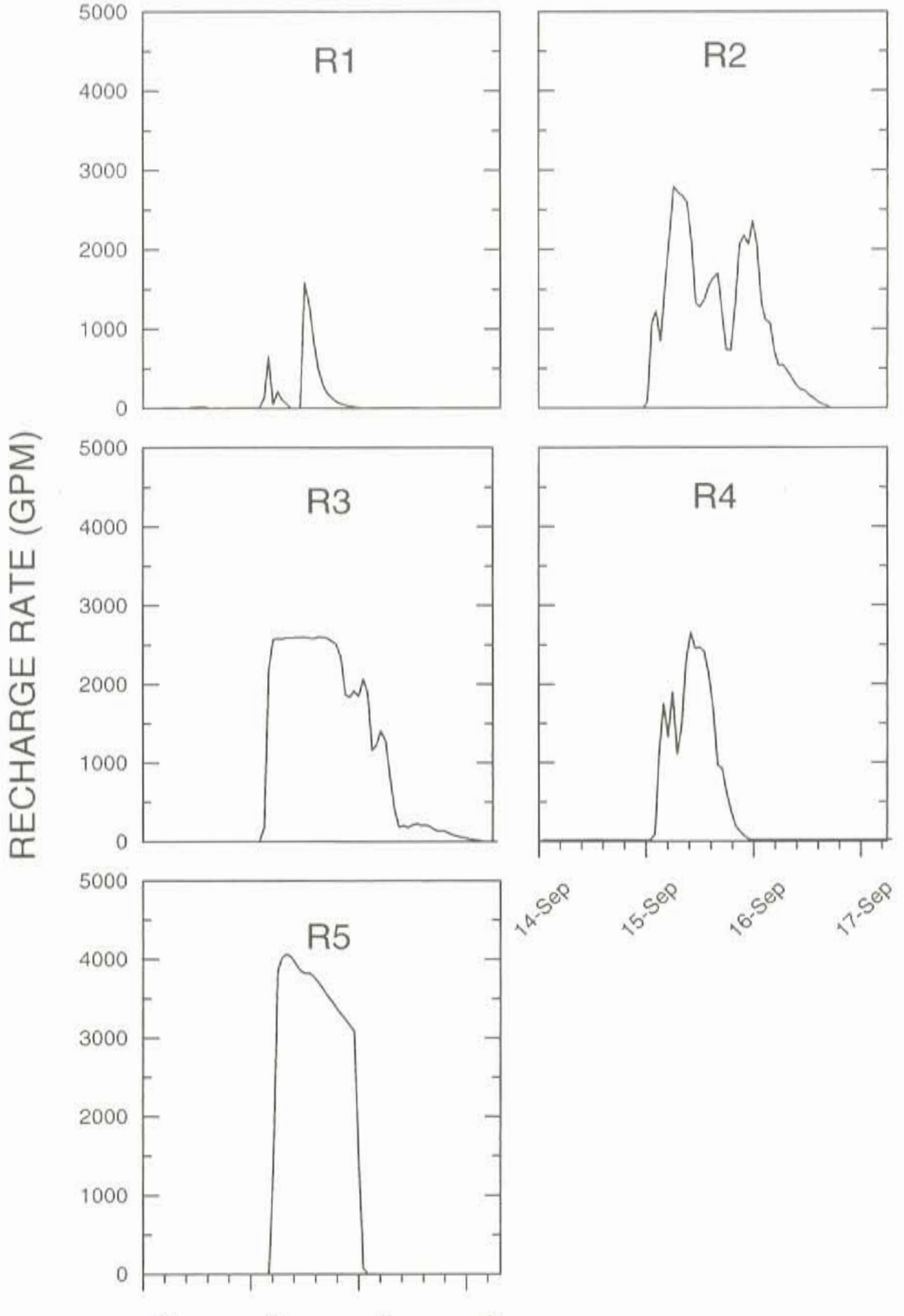


Figure 46. Hourly recharge rate at each recharge well during a recharge event from September 15-16, 1996.

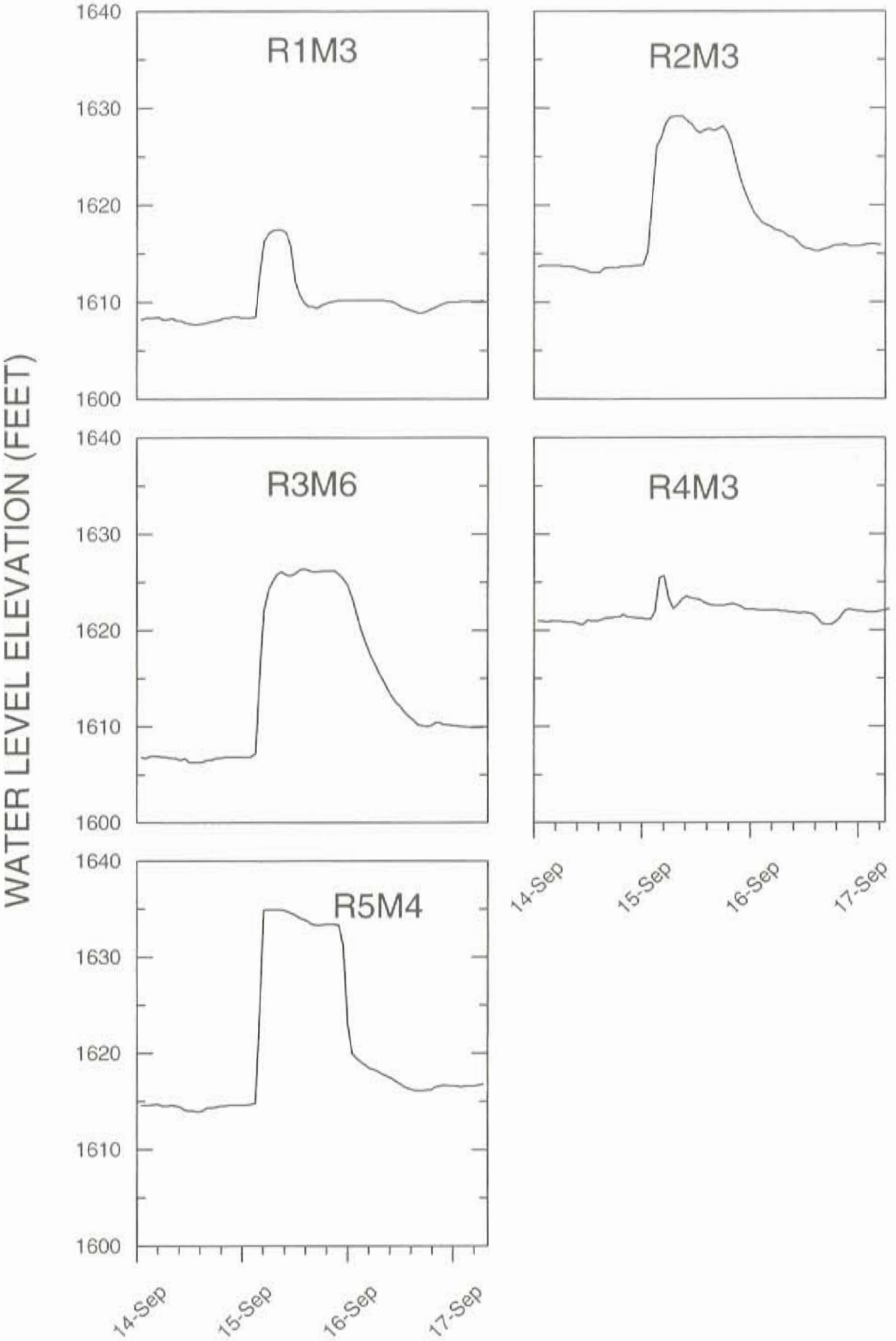


Figure 47. Hourly hydrographs of a representative monitoring well at each recharge site during a recharge event from September 15-16, 1996.

Table 6. Recharge rates and change in water level during a recharge event from September 15-16, 1996

SITE	MAX. RECHARGE FLOW RATE (GPM)	DURATION OF RECHARGE (HOURS)	RECHARGE VOLUME (ACRE-FEET)	MAX. CHANGE IN WATER LEVEL (FEET)
R01	1584	17	1.2	9.8
R02	2793	42	9.4	16.1
R03	2601	48	11.7	20.1
R04	2663	22	5.2	5.1
R05	4067	21	12.7	21

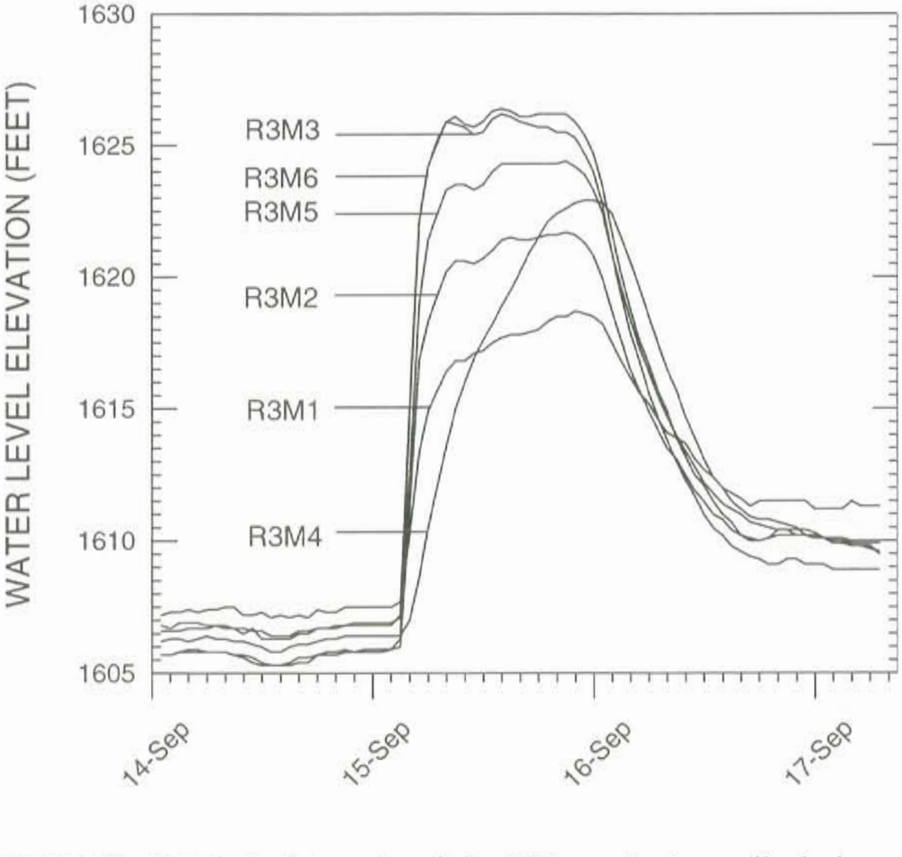


Figure 48. Hourly hydrographs of site R03 monitoring wells during a recharge event from September 15-16, 1996.

The water level responses in monitoring wells at the five recharge sites were examined to determine if downgradient wells responded differently than upgradient wells. Because of the variability of several factors that affect water level response, upgradient and downgradient responses to recharge could not be compared.

Factors that affect the water level response to recharge in a monitoring well include:

- Various sources of recharge water
- The distance from the recharge source
- The transmissivity and storage coefficient of the aquifer
- Construction and development of the monitoring well
- Silting-in of the well

During a recharge event, water enters the aquifer by several means other than through the recharge well. Point recharge occurs through other recharge wells and through naturally occurring fractures, sinkholes, and sinking streams. Diffuse recharge also occurs when rainfall percolates through the subsurface. Thus, water levels in monitoring wells may be affected by sources of recharge other than the adjoining recharge well. This is in contrast to controlled aquifer pumping or injection tests, where pumping or injection is limited to one well.

Because karst aquifers are typically heterogeneous and anisotropic (Ford and Williams, 1989), transmissivity can vary significantly from one well to another. Inadequate development of the well, placements of the well screen, and silting-in of the well are possible complications that could affect the water level response in the monitoring wells.

Injection and Dye Tracing Test

A combined injection and dye tracing test was conducted at the R01 site on April 2, 1996. The purpose of the injection test was to determine aquifer parameters and to field-verify injection rates. The dye tracing test was conducted to determine if hydrologic connection exists between the recharge well and the monitoring wells, and to determine groundwater velocity. A full report on the test is in Appendix C of the *Blaine Gypsum Groundwater Recharge Demonstration Project Final Report.*

The injection rate was recorded at one-minute intervals, and the water levels in the site's monitoring wells were recorded at 15-second intervals. Because of the flashy water level response to recharge, the smaller interval provided better definition of the initial response curve than the one-hour intervals that are usually recorded.

Groundwater from an aquifer pumping test, conducted a week earlier, was stored in the impoundment and used for injection. During the three-hour injection test, 558,000 gallons of water flowed into the R1 recharge well at an average initial rate of 3,360 gpm. Water level in the R1M2 well, located 130 feet from the recharge well, stabilized after 40 minutes of injection, with a rise of 6.8 feet (Figure 49).

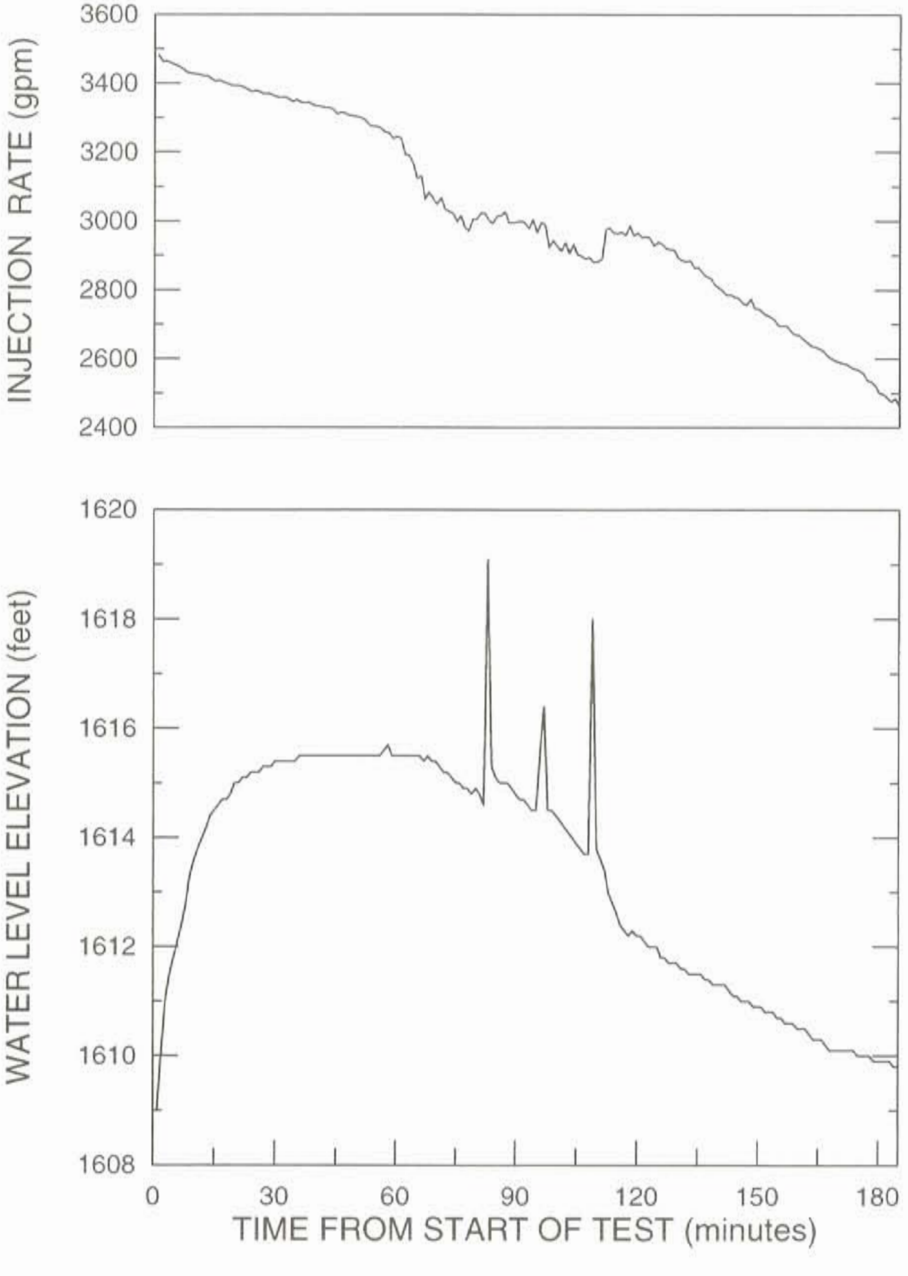


Figure 49. Injection rate and hydrograph of well R1M2 during the injection test at the R01 site on April 2, 1996.

As seen in Figure 49, three rapid increases in water level occurred half way through the test. The greatest change was 10.3 feet in one minute. The cause of these rapid water level increases is unknown. One possibility is conduits that were temporarily plugged with sediment or entrained air broke open and a sudden rush of water surged into the well.

Change-in-water level values for the monitoring wells were plotted on time-drawdown graphs and analyzed using the Theis solution for confined aquifers. Transmissivity was calculated to be about 23,000 ft^2/day, and storage coefficient to be 0.005.

A gallon of liquid Rhodamine WT dye was poured into the injection water at the start of the injection test. Groundwater was pumped from the R1M3 monitoring well, located 102 feet from the recharge well. Water was pumped from the monitoring well with a portable pump at an estimated rate of 1 to 3 gpm. Grab samples were collected every five minutes for the first 30 minutes of the test, and then periodically throughout the test.

Figure 50 is a photograph of the grab samples. The first arrival of dye occurred between 10 and 15 minutes, and the peak arrival of dye occurred at approximately 25 minutes. The pink dye was readily distinguished in the samples, as illustrated in the picture. The positive dye test confirmed hydrologic connection between the recharge well and the R1M3 monitoring well. The muddy sample collected at 1:35 was collected during one of the rapid water level increases.

The maximum groundwater velocity, based on time of first arrival, was between 9,792 and 14,688 feet per day (1.9 to 2.8 miles per day). The average groundwater velocity, based on time of peak arrival, was about 5,875 feet per day (1.1 miles per day). These test results indicate that groundwater velocities can be very high, at least locally.

Values obtained from this test are site-specific and may not represent the aquifer as a whole. The values represent the groundwater velocity during injection, which is higher than during ambient conditions. Different water level conditions could also affect velocities. The results reflect groundwater conditions between the R1 recharge well inlet and the R1M3 monitoring well. Due to the heterogeneity of the karst aquifer, velocities may vary greatly from site to another.

The regional velocity is estimated to be much slower. Assuming a regional gradient of 0.002, an average hydraulic conductivity of 71 ft/day, and an average porosity of 0.016 (the average specific yield), regional groundwater velocity is about nine feet per day.

RECHARGE WATER

Description

The inlet structures to recharge wells R2-R5 are located in intermittent streams and ditches. Water in the streams and ditches is derived from surface runoff and sometimes from irrigation tailwater. Streams contain water for short periods after rainfall, and then go dry. The inlet structure to recharge well R1 is fed by an impoundment, which drains

Figure 50. Grab samples from dye tracing study.

369 acres and has a capacity of 25 acre-feet. Watersheds contributing to the recharge wells vary in size from about 250 to 14,000 acres. The total drainage area for the project's recharge wells is more than 23,000 acres.

We refer to a *Recharge event* when sufficient runoff from precipitation has collected in the streams or the impoundment to flow into the inlet structure of the recharge wells. Recharge events occur rapidly and have a short duration, lasting from a few hours to a few days. The number of recharge events per year varied from as few as nine in 1994 to as many as 17 in 1995. During most recharge events, the inlet structures are overlain by two to four feet of water. In large events, up to eight feet have been observed.

Figures 51-58 are photographs of some recharge sites taken during and after a recharge event in April 1997. Figure 51 shows the intake valves in the impoundment at the R01 site during the recharge event. Water level above the inlet pipe was 5.5 feet. Figure 52 shows the site a week later. The staff gauge, which measures up to five feet, is submerged in Figure 51, but can be seen on the lower left side of the intake valves in Figure 52.

Figure 53 shows the R02 site during a recharge event. The housing for the flowmeter/sampler unit can be seen in the upper center. The inlet pipe and debris screen are under 4.7 feet of water in Figure 53, but can be seen in Figure 54. Figures 55 and 56 were taken looking north along the ditch. The housing can be seen on the left.

In Figure 57, 4.75 feet of water is covering the inlet pipe in Bitter Creek. Turbulence is from rip rap in the creek bed (Figure 58) added by the District to retard the flow of runoff in order to increase flow into the well.

Besides recharge from precipitation, some recharge is derived from irrigation tailwater. Recharge was attributed to tailwater when there was no known precipitation event. In most cases, these designations were verified with field observations. A substantial portion of the recharge to the R04 site and small amounts to the R02 and R03 sites was from tailwater.

Recharge Volume

The recharge wells were opened in June 1993. Due to programming errors with the flowmeter/samplers, flow measurements did not begin until August. The first recorded recharge was August 30, 1993 when a small amount of recharge entered the R1 and R5 wells. Recharge measurements included in this report cover the period between August 1993 and September 1996.

Only the 1994 and 1995 totals include recharge records for the entire year. In 1993, measurements began in August, after most of the year's precipitation occurred. The 1996 record is also incomplete; some recharge events occurred after September and are not included in this report. Recharge volumes would have been higher if wells were not closed when the monitoring equipment had problems.

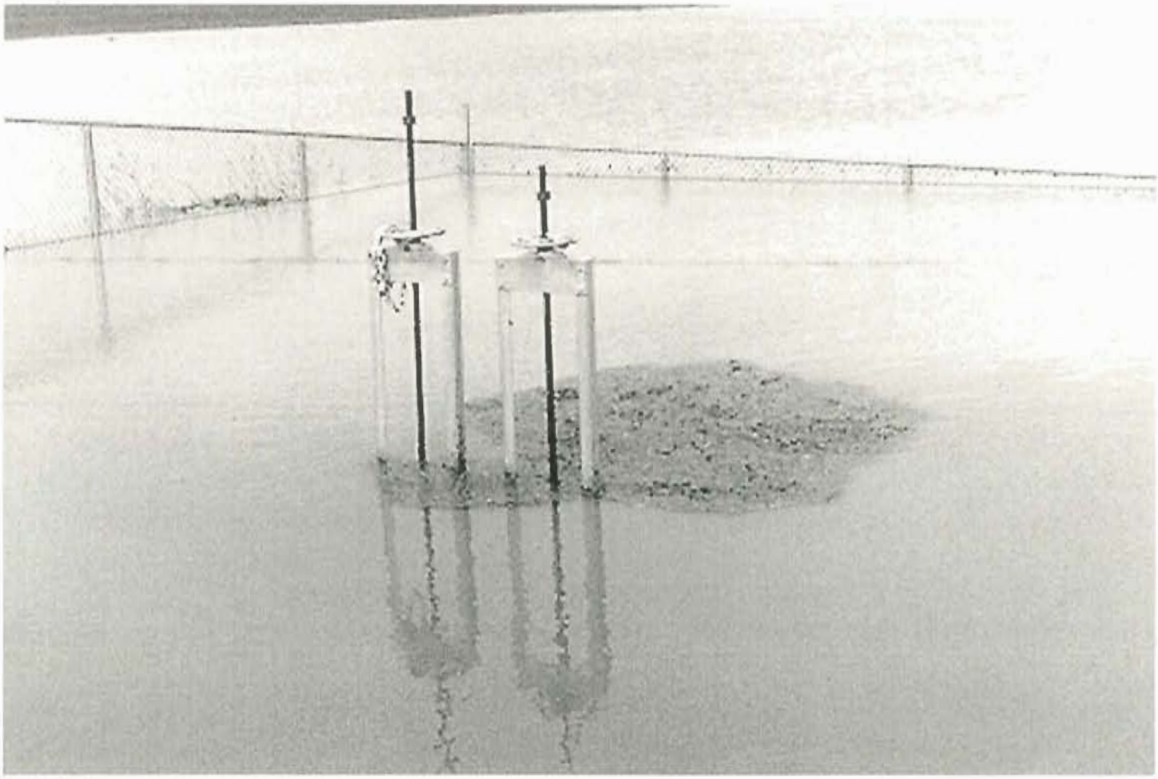


Figure 51. Intake valves at the R01 (Conservation Dam) site during a recharge event in April 1997.

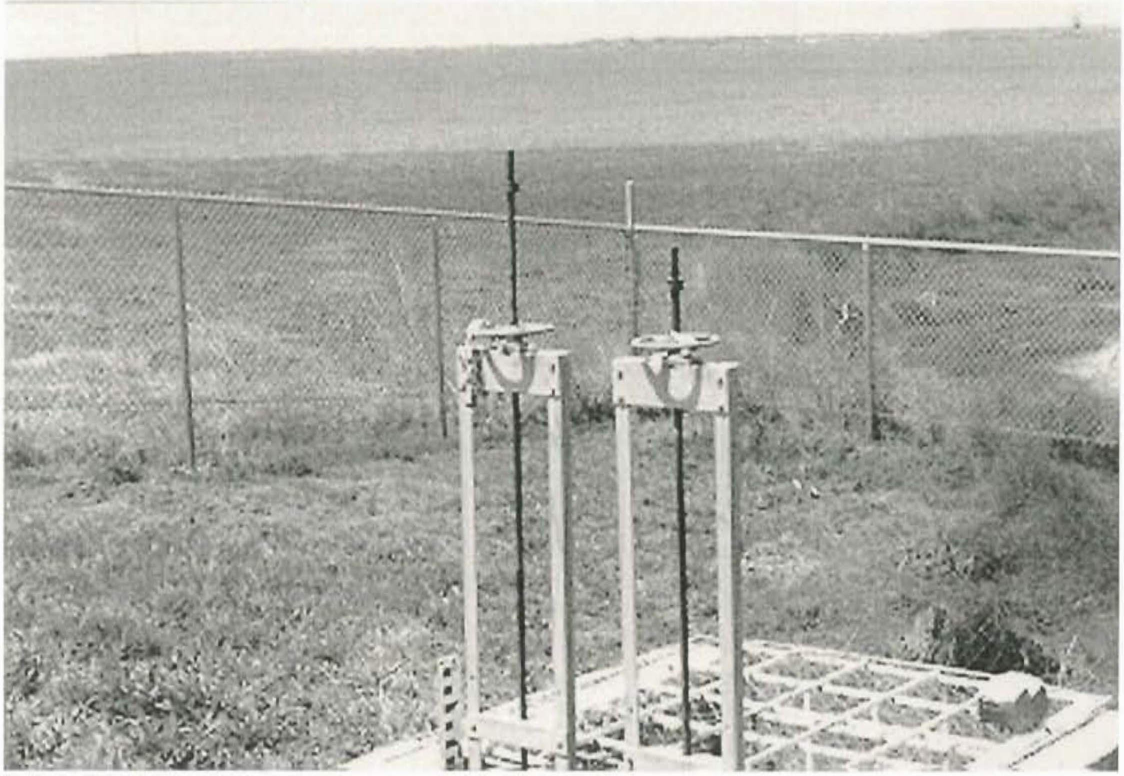


Figure 52. Intake valves at the R01 site a week after the recharge event in April 1997.

Figure 53. R02 site during recharge.

Figure 54. R02 site after recharge.

Figure 55. R02 site, looking north, during recharge.

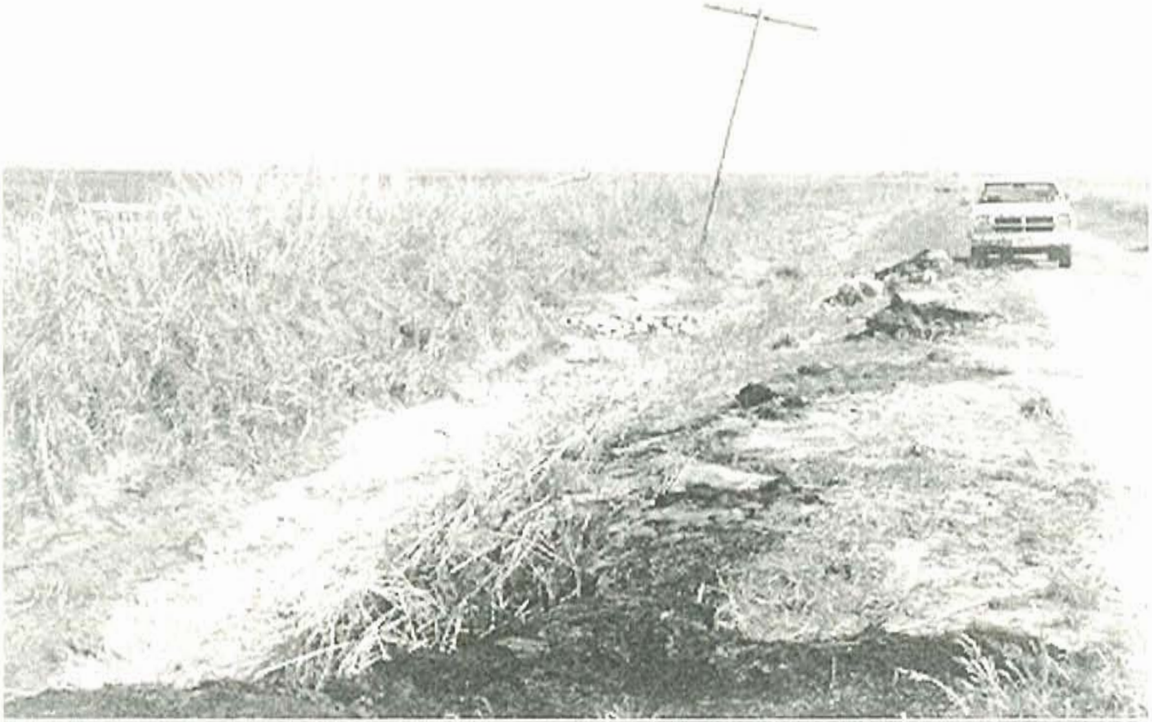


Figure 56. R02 site, looking north, after recharge.

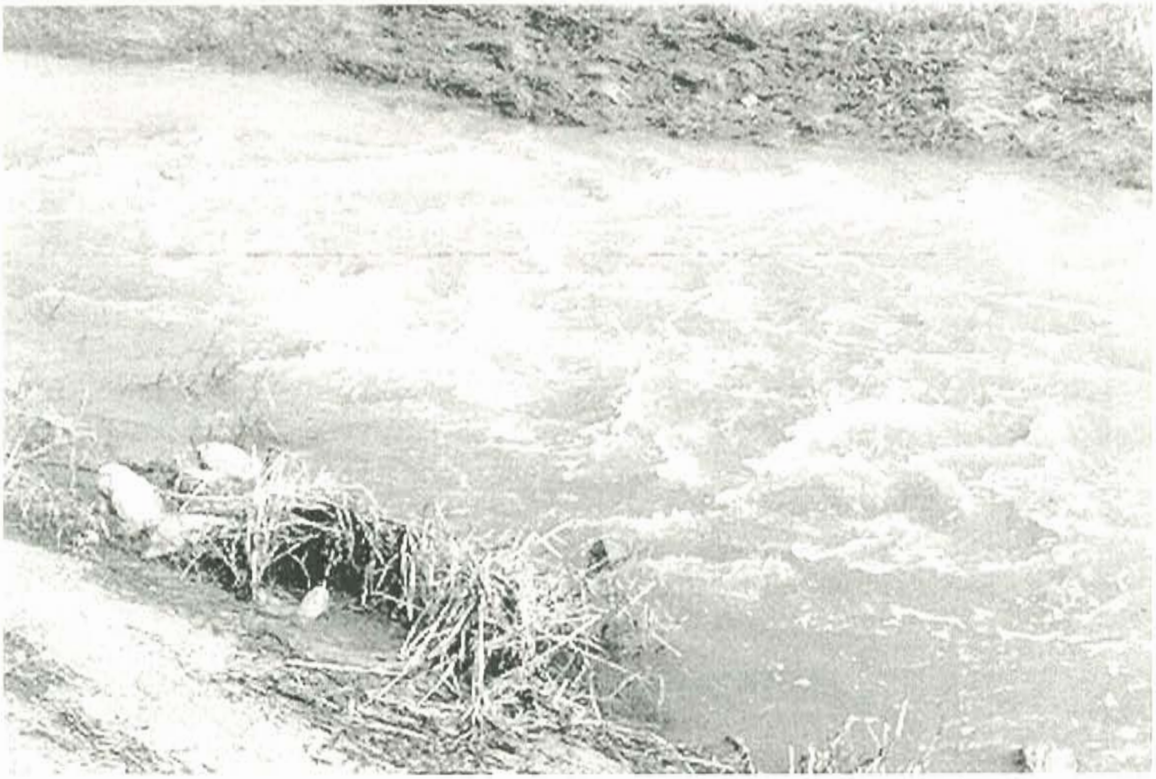


Figure 57. R03 site during recharge.

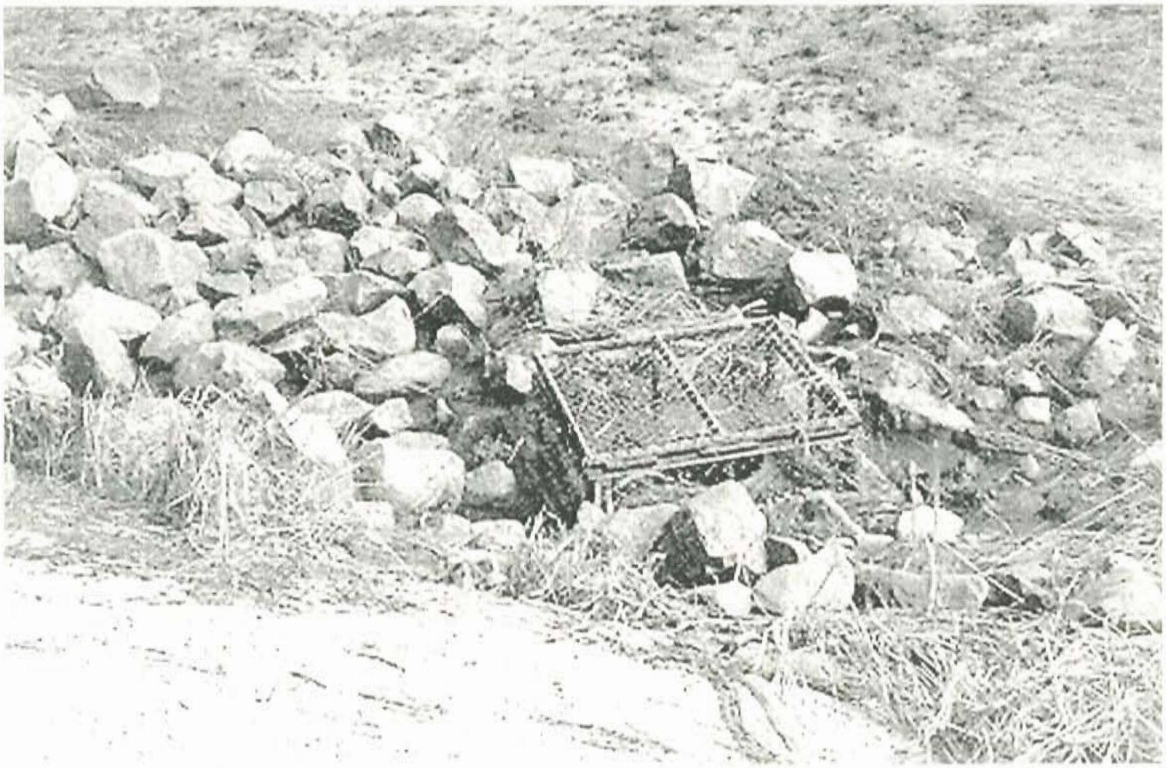


Figure 58. R03 site after recharge.

While the exact volume of recharge contributed by the project could not be determined due to the methodology and equipment limitations discussed below, the recharge volume was estimated based on the existing data. An estimated recharge volume of 1,056 acre-feet of recharge water entered the aquifer from 1994 through 1996. Of this, 188 acre-feet were obtained from irrigation tailwater. Table 7 lists and Figure 59 graphically displays the total recharge volume by year. The most annual recharge occurred in 1995 with 726 acre-feet, and the least in 1994 with 72 acre-feet.

Table 7. Estimated total recharge volume (acre-feet)

	WELL ID	1993	1994	1995	1996	TOTAL
Estimated precipitation recharge	R1	0.3	24	92.4	35.4	152.1
	R2	0	9.9	114.3	44.4	168.6
	R3	0	13.9	134.5	49.7	198.1
	R4	0	6.6	97.3	14.7	118.6
	R5	6	17.9	153.0	52.9	229.8
TOTAL		6.3	72.3	591.5	197.1	867.2
Tailwater recharge	R2	0	0	0	3	3
	R3	0	0	0	1	1
	R4	0	0	134	50	184
TOTAL		0	0	134	54	188
Total recharge (precipitation + tailwater)	R1	0.3	24	92.4	35.4	152.1
	R2	0	9.9	114.3	47.4	171.6
	R3	0	13.9	134.5	50.7	199.1
	R4	0	6.6	231.3	64.7	302.6
	R5	6	17.9	153.0	52.9	229.8
PROJECT TOTAL		6.3	72.3	725.5	251.1	1055.2

The average annual recharge volume per well was 70 acre-feet, and the average annual pumpage per irrigation well was 142 acre-feet. Thus, each recharge well provided about one half the water produced from one irrigation well.

Monthly recharge volumes are shown with monthly precipitation amounts in Figure 60. As expected, there is a relation between recharge and precipitation. The highest volumes were recharged during the floods in 1995. In June 1995, an estimated 153 acre-feet were recharged into the wells, and in August and September, 334 acre-feet were recharged.

Most of the recharge from irrigation tailwater occurred during months with high precipitation. This is probably due to over application of irrigation water in the R04 site's watershed. Cotton is the primary crop in the watershed, and is irrigated by flooding. Although the crops were heavily irrigated in 1994, soil moisture conditions were low, and runoff did not occur.

Estimated total recharge volumes by well are shown in Figure 61. Caution should be used in comparing one site to another due to the potentially large error in the volume estimations. The volume for the R5 well is believed to be lower than the other wells because the formation did not take much water at this site, while the volumes for the R2-R4 wells are believed to be higher. The R4 well received the lowest volume in recharge from precipitation runoff, but the highest in recharge from tailwater.

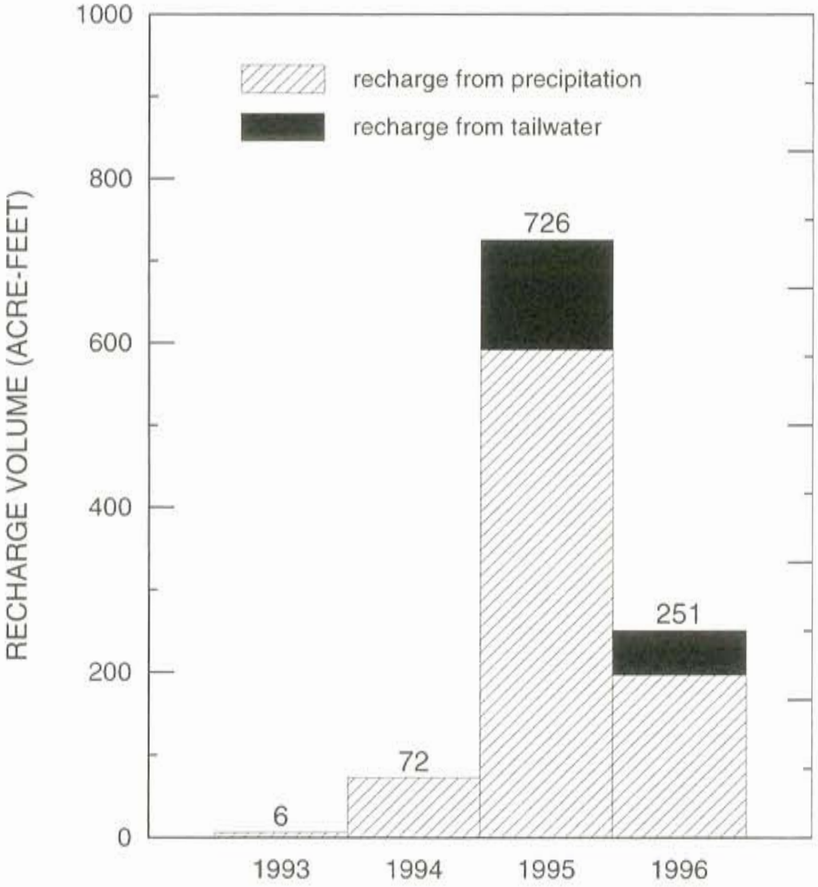


Figure 59. Total estimated recharge volume by year.

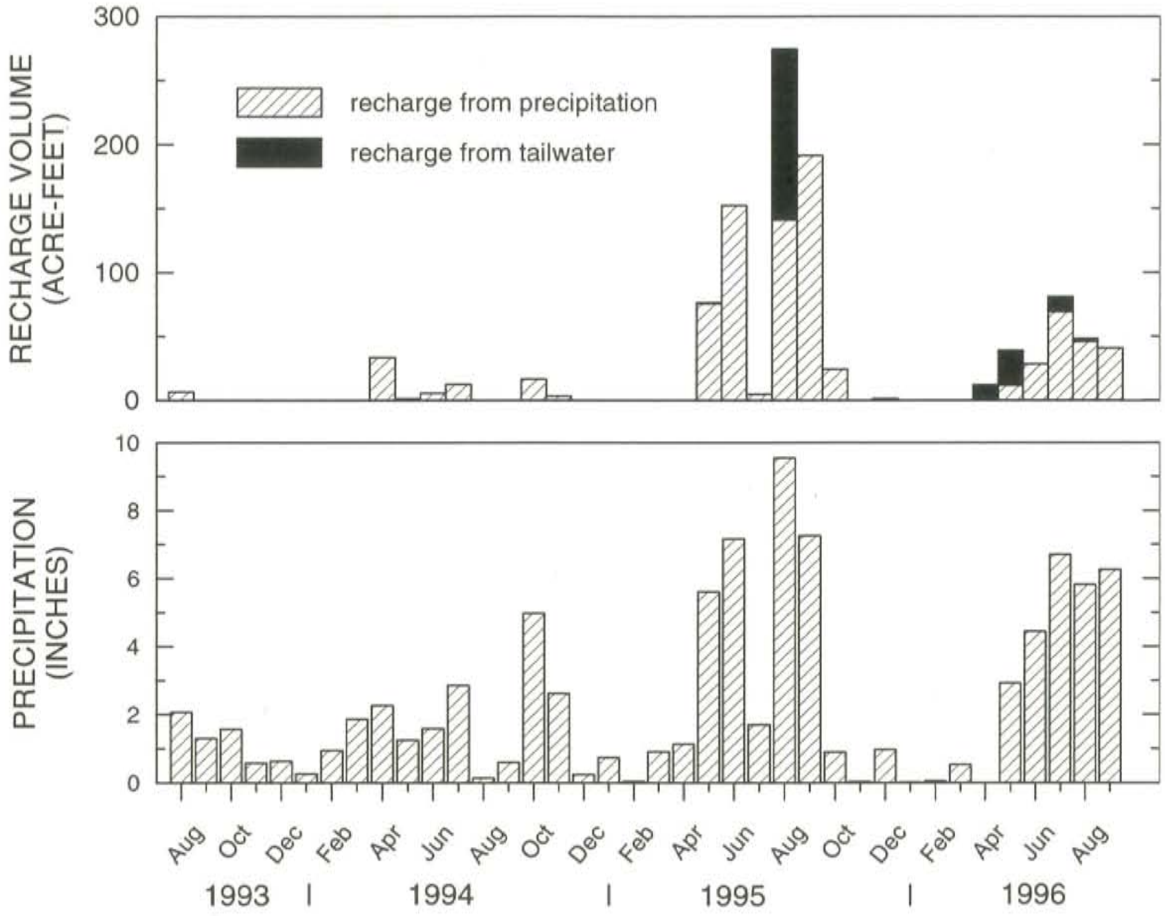


Figure 60. Monthly estimated recharge volume of all sites and precipitation graph of the Hollis rain gauge.

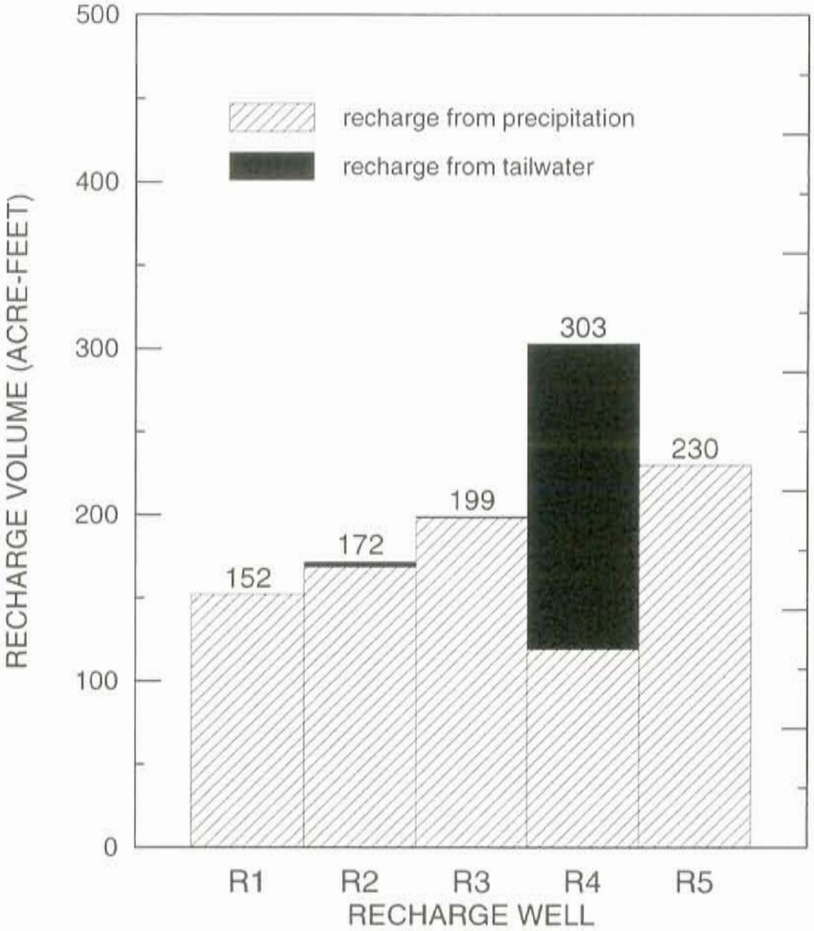


Figure 61. Total estimated recharge volume by well.

Methodology

The volume of recharge to the aquifer could not be precisely determined because of the methodology, equipment limitations, and incomplete flow measurements. Flow measurements were incomplete due to equipment problems that resulted from mechanical failure; damage from environmental factors such as fire, lightning, flooding, and rodents; and programming errors.

A significant limitation with the flowmeter/sampler units was that they did not directly measure the flow rate. Each recharge well was equipped with a pressure transducer, installed within the inlet pipe near the entrance of the inlet structure. The pressure transducer measured the overlying water depth from which the volumetric flow rate was calculated.

Two problems arose from using the pressure transducers. First, the pressure transducers did not accurately measure water depth due to turbulent flow at the inlet structure. The resulting flow rates were an order of magnitude too low for the R02-R04 sites, resulting in recharge volumes that were too low. Secondly, when the well or aquifer did not accommodate all of the water, the recorded flow rates were too high. This resulted in recharge volumes that were too high at the R05 site, and possibly the R01 site.

Recharge volumes were estimated for events where flow measurements were incomplete or missing. Total estimated recharge volumes appear reasonable; however, caution should be used in comparing the volumes of one site to another. For the reasons discussed above, recharge volumes at the R02-R04 sites may be underestimated and the volume at the R05 site may be overestimated.

Factors Affecting Recharge Volume

Several factors affect the amount of water recharged to the aquifer through a recharge well. These include surface runoff, well capacity, and aquifer storage capacity.

Surface Runoff

The amount of surface runoff generated in the watersheds of the recharge wells is a primary factor. The Natural Resources Conservation Service (USDA, 1989) defines surface runoff as "the volume of excess water that runs off a drainage area". Runoff is influenced by several climatic and physiographic factors. Climatic factors include precipitation (type, amount, intensity, duration, time distribution, areal distribution, frequency of occurrence, and antecedent precipitation), evaporation, and transpiration. Physiographic factors include basin characteristics (size, shape, and slope of watershed), soil properties (type, soil moisture, infiltration capacity, and organic content) and physical properties (vegetative cover, land use, conservation practices, manmade structures, and sinkholes) (Chow, 1964).

The main factors affecting runoff from rainfall are the size of the watershed, the kind of soil, the type of vegetative cover, and conservation practices in the watershed. Soils with low infiltration rates have the highest runoff potential. Row crops have a higher runoff potential than small grains, and small grain crops have a higher potential for runoff than pastures. Conservation practices such as contouring and terracing decrease runoff by forming small reservoirs. However, this effect diminishes with increasing storm magnitude (USDA, 1989).

Large watersheds are influenced by channel storage and flow while small watersheds are influenced by land use and overland flow. Small watersheds are also more sensitive to high-intensity rainfalls of short duration (Chow, 1964).

Peak discharge, the "peak rate of runoff from a drainage area for a given rainfall" (USDA, 1989) is an important factor in flood control and dam design, but is not as important for this study because the rate the recharge wells take water is controlled by the inlet design and well capacity.

Some factors affect the rate at which water runs off more than they affect the volume of runoff. These factors include intensity of rainfall and the slope and shape of the watershed. The slopes in a watershed affect the peak discharge at downstream points, but do not affect how much of the rainfall will run off. As watershed slope increases, velocity increases, time of concentration decreases, and peak discharge increases (USDA, 1989).

The watersheds of the five recharge sites were delineated using U.S. Geological Survey topographic maps and then field-verified (Figure 62). Field verification was crucial due to the extensive modification of drainage with ditches, culverts, and dikes. The surface area for each watershed is listed below:

SITE	**WATERSHED AREA (acres)**
R01	369
R02	1,520
R03	7,294
R04	253
R05	13,995

The entire watershed for the R2 recharge well encompasses the watershed for the R3 well because the R3 well does not capture all of the runoff. However, water flow in the ditch that contributes water to the R2 well is generally less than the flow in Bitter Creek by the R3 well. Water in Bitter Creek often disappears a few hundred yards downstream of the R03 site, becoming a disappearing stream, a common phenomenon in karst aquifers. Therefore, for estimating surface runoff, the watershed for the R2 well does not include the R3 watershed.

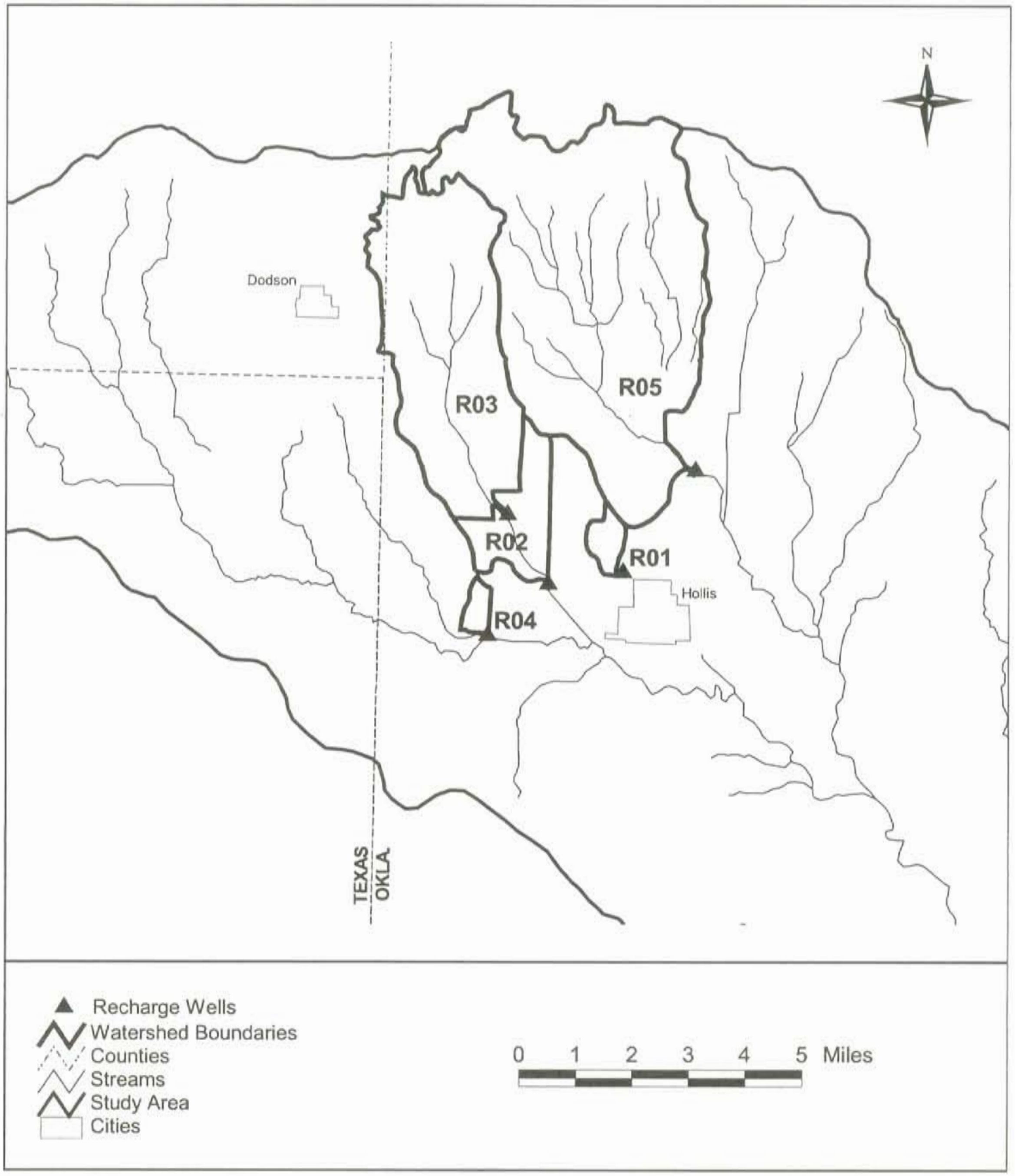


Figure 62. Map showing the watersheds of the five recharge sites.

During most recharge events, the R4 well captures water from a ditch that drains a watershed of 253 acres. The inlet structure for the R4 well, placed about 200 feet north of a tributary to the West Fork of Sandy Creek, is about three feet higher in elevation than the tributary. During heavy rains and floods, water from the tributary back flows into the R4 inlet pipe. Thus, for large recharge events, the watershed for the R4 well is much larger than the delineated one.

Two basic types of soils are present over the five watersheds: (1) deep to shallow, well drained, loamy and sandy soils on uplands (Grandfield-Devol and Tipton-Westview-Altus map units) and (2) very shallow to deep, well drained to excessively drained, sandy, loamy, and clayey soils on uplands (Tillman-Vernon map unit) (USDA, 1984).

The Grandfield-Devol map unit consists of nearly level to strongly sloping soils on smooth to hummocky uplands. The Tipton-Westview-Altus map unit consists of nearly level to very gently sloping soils on smooth concave and slightly convex stream terraces. The Tillman-Vernon map unit consists of areas of soils on smooth, broad uplands. The slope over the five watersheds ranges from zero to 12 percent, but predominately ranges from one to three percent (USDA, 1984).

The Soil Conservation Service Division of the USDA (SCS) has defined four hydrologic soil groups: Groups A, B, C, and D. Group A soils have the lowest runoff potential and highest infiltration rates (> 0.30 in/hr) while Group D soils have the highest runoff potential and lowest infiltration rates (0 to 0.05 in/hr) (USDA, 1989). All four soil groups are present in the watersheds.

The vegetative covers over the watersheds are primarily row crops, small grains, and pasture. The predominant conservation practice is straight row with crop residue cover. The hydrologic condition, which is based on the density of plant cover and residue on the ground surface, is generally good.

Two methods were used to determine the mean annual precipitation runoff of each watershed. The first method was to use the mean annual precipitation runoff calculated by the USGS. According to the publication "Average Annual Runoff in the United States, 1951-80" (Gebert et. al., 1987), the mean annual precipitation runoff for the Blaine study area ranges from 0.5 inches in the west to 0.75 inches in the east. The recharge sites have a mean annual precipitation runoff value of 0.6 inches. This value was multiplied by the watershed area of each site to produce the mean annual runoff volume (Table 8).

The second method employed was the SCS curve number (CN) method. The SCS developed runoff curve numbers by examining rainfall runoff data from small agricultural watersheds. The curve numbers take into account initial abstraction, which includes all losses before runoff begins, and potential maximum retention after runoff begins. The specific parameters used to determine the CN are the SCS hydrologic soil group, vegetative cover type, treatment type (conservation practices), and hydrologic conditions of the watershed. A representative curve number was estimated by computing a weighted average for the various land uses and hydrologic soil groups of each watershed.

The runoff from each basin, expressed as the average depth of water (inches) that would cover the entire basin, was determined from the CN and rainfall amount. The one-year, 24-hour rainfall of 2.5 inches for Harmon County was used for the rainfall amount. The runoff volume was then computed by converting depth over the watershed to volume (acre-feet). Because 1995 and 1996 were wetter than normal years, runoff volumes were also computed using the 100-year, 24-hour rainfall of 7.5 inches. Results from this method are shown in Table 8. The two volumes represent a range that may be expected for each watershed.

As seen in Table 8, runoff volumes computed with the one-year, 24-hour rainfall are similar to those computed with the precipitation runoff of 0.6 inches, calculated by the USGS. In both methods, the primary factor controlling the runoff volume is the size of the watershed. The parameters (soil hydrologic group, cover type, treatment, and hydrologic condition) required by the SCS curve number method cause slight variations in the runoff volume from site to site.

The total average annual runoff volume for the five sites, computed with the SCS curve number method with the one-year, 24-hour rainfall, is 1,245 acre-feet. The R04 site, with the smallest watershed of 253 acres, has an average annual runoff volume of 18 acre-feet, and the R05 site, with the largest watershed of 13,995 acres, has a runoff volume of 758 acre-feet.

In Table 9 the estimated project precipitation recharge volumes are listed by year along with the runoff volumes calculated with the SCS curve number method. If runoff was the only factor affecting the recharge volume to the wells, runoff volume and recharge volume would be about the same. However, as can be seen in Table 9, this is not so; several other factors affected how much runoff entered the wells.

Other Factors

Probably the most important factor affecting the amount of runoff that enters the recharge wells is the amount of runoff that is captured by the wells. The inlets for wells R2 through R5 are in stream beds where a large amount of runoff flows past and continues downstream. The impoundment at the R01 site enables the R1 well to capture most of the runoff. (Some runoff is lost through the emergency spillway and bypass valve, and some is lost to evaporation and seepage.)

The annual recharge volume at the R01 site should be similar to the calculated runoff because the impoundment captures most of the runoff. Surface runoff for the R01 site, calculated with the SCS curve number method for the one-year, 24-hour rainfall, is 21 acre-feet. This compares favorably with the 24 acre-feet recharged into the R1 well in 1994. In 1995, when precipitation was higher than normal, 92 acre-feet was recharged into the R1 well. This value lies between the runoffs calculated with the one-year and

Table 8. Watershed size and runoff volumes of the five recharge sites

SITE ID	WATER-SHED (acres)	CURVE NUMBER (CN)	RUNOFF (inches)		RUNOFF VOLUME (acre-feet)		
			1-year 24-hr rain (2.5 in)	100-year 24-hr rain (7.5 in.)	USGS 1-year 24-hr rain (0.6 in)	SCS 1-year 24-hr rain (2.5 in)	SCS 100-year 24-hr rain (7.5 in.)
R01	369	76	0.69	4.71	18	21	145
R02	1,520	74	0.61	4.48	76	77	567
R03	7,294	74	0.61	4.48	365	371	2,723
R04	253	79	0.84	5.04	13	18	106
R05	13,995	75	0.65	4.59	700	758	5,353

Table 9. Runoff volumes and corrected recharge volumes of the five recharge sites

SITE ID	WATER-SHED AREA (acres)	RUNOFF VOLUME FROM SCS-CN METHOD (acre-feet)		ESTIMATED PRECIPITATION RECHARGE VOLUME FROM PROJECT (acre-feet)		
		one-year 24-hr rain (2.5 in.)	100-year 24-hr rain (7.5 in.)	1994	1995	1996
R01	369	21	145	24	92	35
R02	1,520	77	567	10	114	44
R03	7,294	371	2,723	14	135	50
R04	253	18	106	7	97	15
R05	13,995	758	5,353	18	153	53

100-year, 24-hour rainfalls (21 to 145 acre-feet). The amount of recharge captured by the other wells ranges from two to 36% of the calculated runoff.

While some runoff flows past the recharge wells, other runoff is intercepted by other recharge wells and sinkholes before reaching the inlet. A dramatic example of this is Bitter Creek, which disappears a few hundred yards downgradient of the R03 site.

Another factor is the spacial variability of rainfall over the watersheds. It is not uncommon for a recharge well to receive the most recharge during one event and then receive none during another event.

The variability of rainfall distribution is illustrated in Figure 63, which is a Next Generation Weather Radar (NEXRAD) image of 24-hour precipitation on July 10, 1996, obtained from the Reclamation's River Systems and Meteorological Group. The radar measurements were calibrated with precipitation gauges. The image shows that rainfall was heaviest over the R01, R02, and R04 watersheds, and lighter over the upper portions of the R03 and R05 watersheds. During this recharge event, the R01, R03, R04, and R05 sites received 12.9, 9.8, 0.3, and 9.4 acre-feet of recharge, respectively.

Figure 64 is a NEXRAD image of June 4, 1995. The recharge event, which occurred June 3-7, resulted in flooding that damaged the recorders at the R01, R02, and R04 sites. The R03 site recorded 18.6 acre-feet of recharge, and the R05 site 19.3 acre-feet. Heaviest rainfall (5.36 inches in 24 hours) occurred over the R03 and R05 watersheds.

How much water a recharge well can take is limited largely by its capacity. Well capacity is a function of the length, diameter, and slope of the inlet pipe, the diameter of the well casing, the difference in hydraulic head, and the design and placement of the well screen. While all of the recharge wells were constructed with a 12-inch diameter casing, the other factors vary slightly among the five wells.

The storage capacity of the aquifer can also limit how much water a well takes. The aquifer storage capacity is determined by permeability, specific yield, aquifer thickness, and the fluctuation of the water table (Asano, 1985), all of which vary from site to site. As previously discussed, the permeability of the aquifer at the R05 site and possibly the R01 site is low, resulting in low storage capacities and low recharge volumes.

Another factor to be considered in the recharge totals is that some sites were shut in due to equipment problems and did not take recharge during some recharge events. The total recharge volume would have been larger if the wells had been open during the entire project.

Finally, accuracy of recorded flow rates depends on the accuracy with which the pressure transducers measured water depth. Due to variations in turbulence and flow paths at the inlet structures, accuracy may vary from site to site.

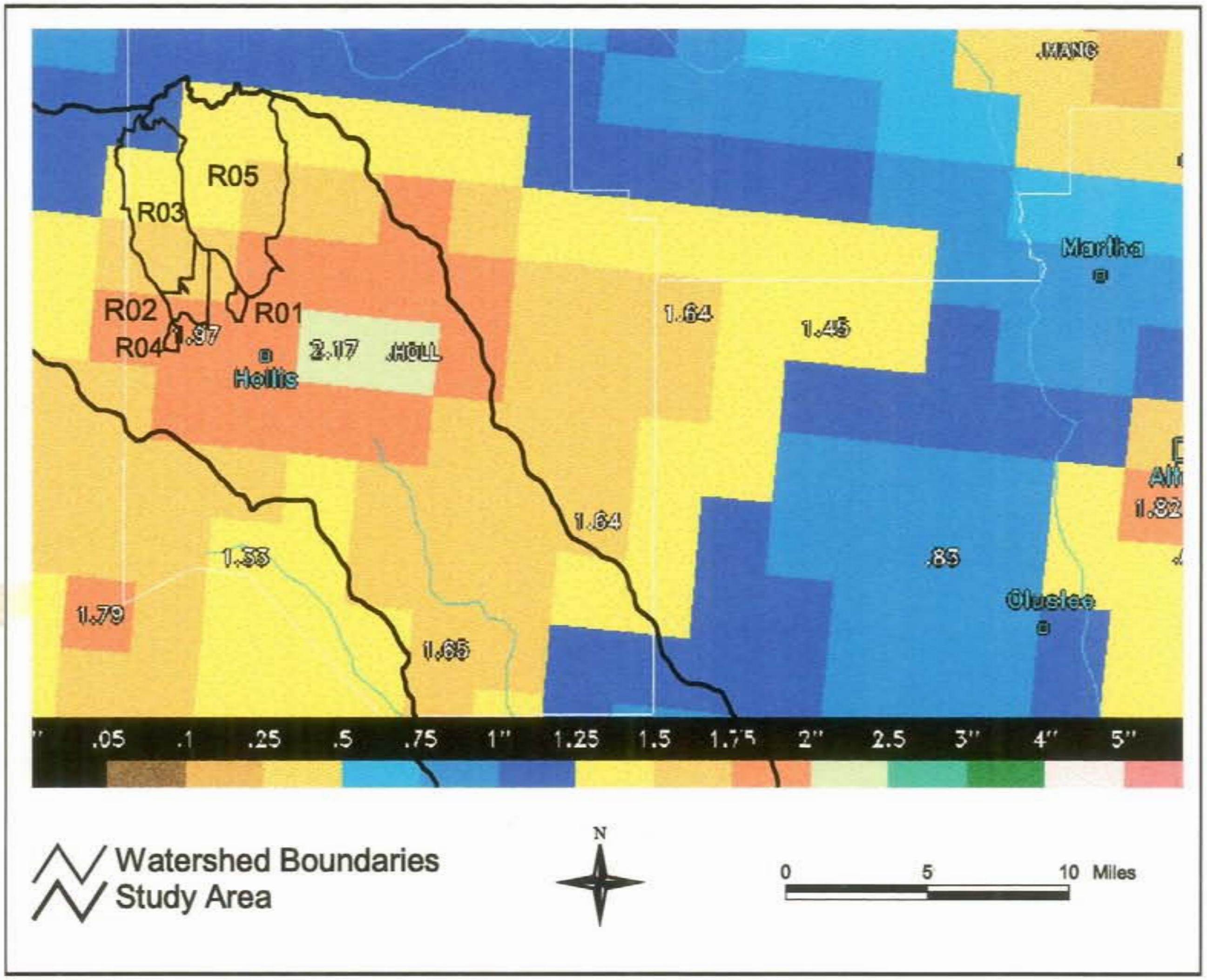


Figure 63. NEXRAD image showing spatial rainfall distribution during a recharge event on July 10, 1996.

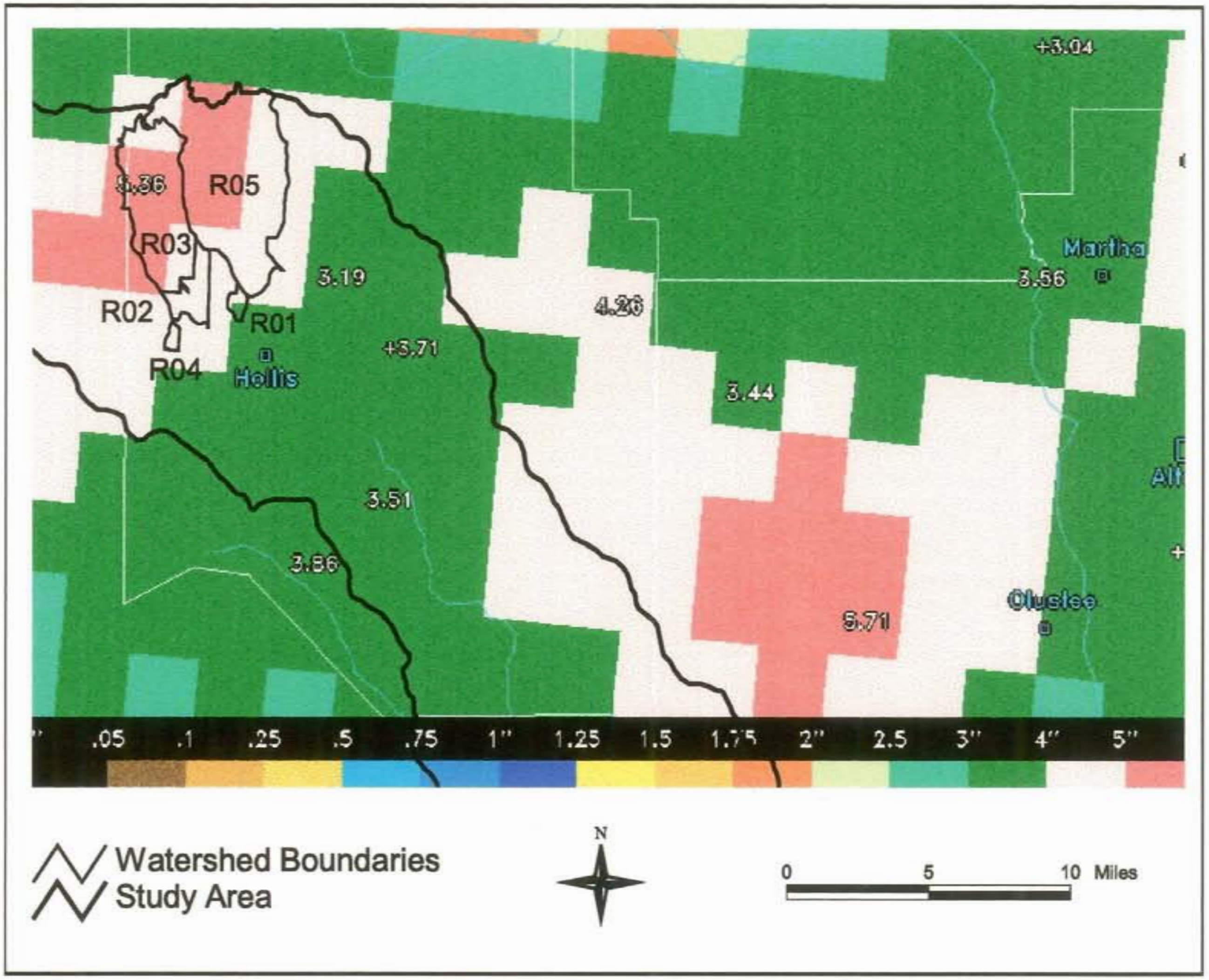


Figure 64. NEXRAD image showing spatial rainfall distribution during a recharge event on June 4, 1995.

EVALUATION OF RESULTS

Effectiveness of Artificial Recharge

For the years 1994 to 1996, the average annual recharge volume per well ranged between 14 acre-feet in 1994 and 145 acre-feet in 1995, with an average of 70 acre-feet.

The reported pumpage for the study area ranged from 13,969 acre-feet in 1995 to 22,373 acre-feet in 1994, with an annual average of 17,000 acre-feet. The three-year average is about the same as the historic average of 17,130 acre-feet. Water is withdrawn from an estimated 120 irrigation wells within the study area. The average pumpage per well ranged from 116 acre-feet in 1995 to 186 acre-feet in 1996, with an average annual pumpage per well of 142 acre-feet.

If we assume that on average, each recharge well contributes 70 acre-feet per year and each irrigation well produces about 140 acre-feet, then each recharge well provides about one half the water produced from one irrigation well.

In addition to the five project recharge wells, about 45 of the District's recharge wells are in operation throughout the study area. Assuming the existing recharge wells perform the same as the project wells, then the total 50 recharge wells contribute about 3,500 acre-feet of water a year to the study area. This is about 20% of the average 17,000 acre-feet produced each year. To compensate for the water produced, an additional 193 recharge wells would need to be drilled.

Recommendations

Placement of New Recharge Wells

The amount of water recharged to the aquifer could be increased by installing additional recharge wells in appropriate locations. Recharge wells should be placed in areas where the aquifer storage capacity is good. This is generally where the aquifer is permeable, which correlates to areas with good cavern development. Cavern development is generally best in areas where the thickness of the overlying Dog Creek Shale is less than 60 feet and lowest where it is greater than 100 feet. Figure 65 is a map showing the 0-, 60-, and 100-foot contours of the Dog Creek Shale (Johnson, 1985). The shaded areas correspond to areas where conditions for good cavern development are most favorable.

Aquifer storage capacity is also influenced by the aquifer thickness and height of the water table. Where the aquifer is unconfined and the water table is near the land surface, there is little room for additional storage. Figure 66 is a depth-to-water map for February 1994. The water table is near the surface (where depth to water is low) in the southern portion of the study area where groundwater from the aquifer discharges to Sandy Creek. It is also near the surface in a few isolated areas near Hollis. Recharge wells placed where the depth to water is greater than 20 feet, as shown in the shaded areas, should have sufficient aquifer storage for recharge.

In order for recharge wells to have the most effect on replacing produced water and preventing irrigation wells from going dry, wells should be placed upgradient of or within irrigation pumping centers. Recharge wells placed downgradient of the main pumping areas would add water to the groundwater basin, but would not prevent irrigation wells from going dry. The area most affected by irrigation pumping is represented by the shaded area in Figure 67, and is defined by where the water level declined more than 35 feet between May and August 1994 (Figure 37). The area covers the northern portion of the study area, except for the recharge area south of Hollis.

Figure 68, generated with the ARC/INFO geographic information system, shows the overlapping shaded areas of Figures 65, 66, and 67. The resulting map shows the optimal area to install recharge wells. This area is upgradient of or within the irrigation pumping center, where conditions for cavern development are most favorable, and where water depth is greater than 20 feet.

Other Enhancements

The runoff captured by the wells can be greatly enhanced with an impoundment or retention structure. The Conservation Dam Site (R01) illustrates the effectiveness an impoundment has on the volume of recharge water. The impoundment enabled the site to capture all of the calculated runoff, while wells at the other sites captured only from 2-36% of the calculated runoff. The impoundment covers five acres of land area, a small investment considering the returns.

A few wells with impoundments could capture the same amount of runoff as more wells that do not have impoundments. Building an impoundment large enough to capture all of the runoff from a large watershed would not be practical. However, even a small increase in the amount captured could potentially add much water.

Examples of retention structures include low water dams in channelized streams and small earthen or rock berms constructed downstream of an inlet structure. The channelized stream, bordered by dikes, at the R03 site makes it a suitable site for a low water dam. A small dam or berm constructed about 20 to 50 feet downstream of the inlet structure would pond some storm runoff, allowing the recharge well to capture more water.

Small berms may benefit the R02 and R04 sites. The inlet structures at these sites, which are in ditches next to county roads, are not suitably placed for impoundments or low water dams.

The primary limitation at the R05 site is the tight rock formation with limited fracture and cavern development. The R5 recharge well may benefit from an aquifer development technique such as hydrofracturing.

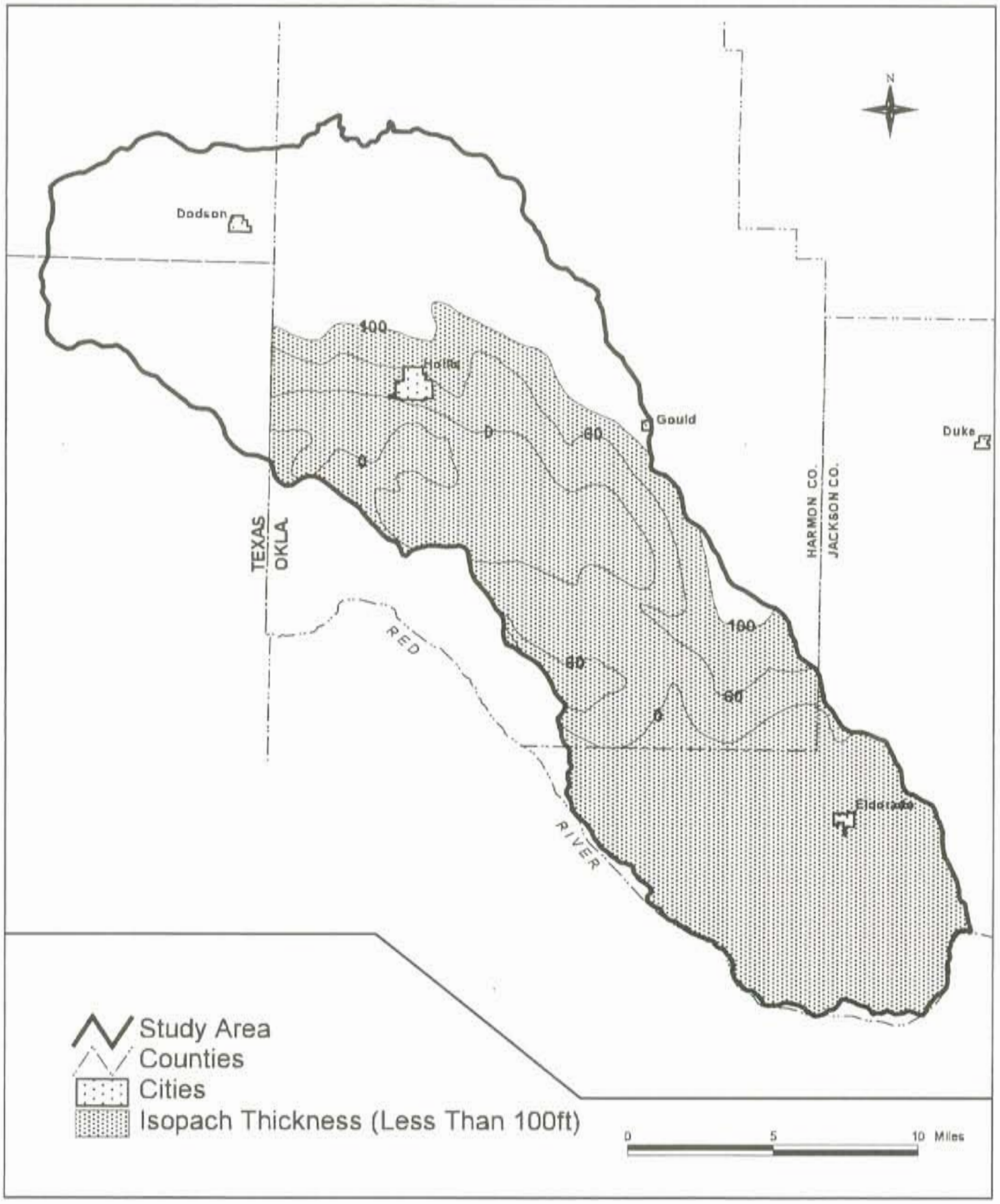


Figure 65. Isopach map of the Dog Creek Shale where the formation is ≤ 100 feet thick (from Johnson, 1985).

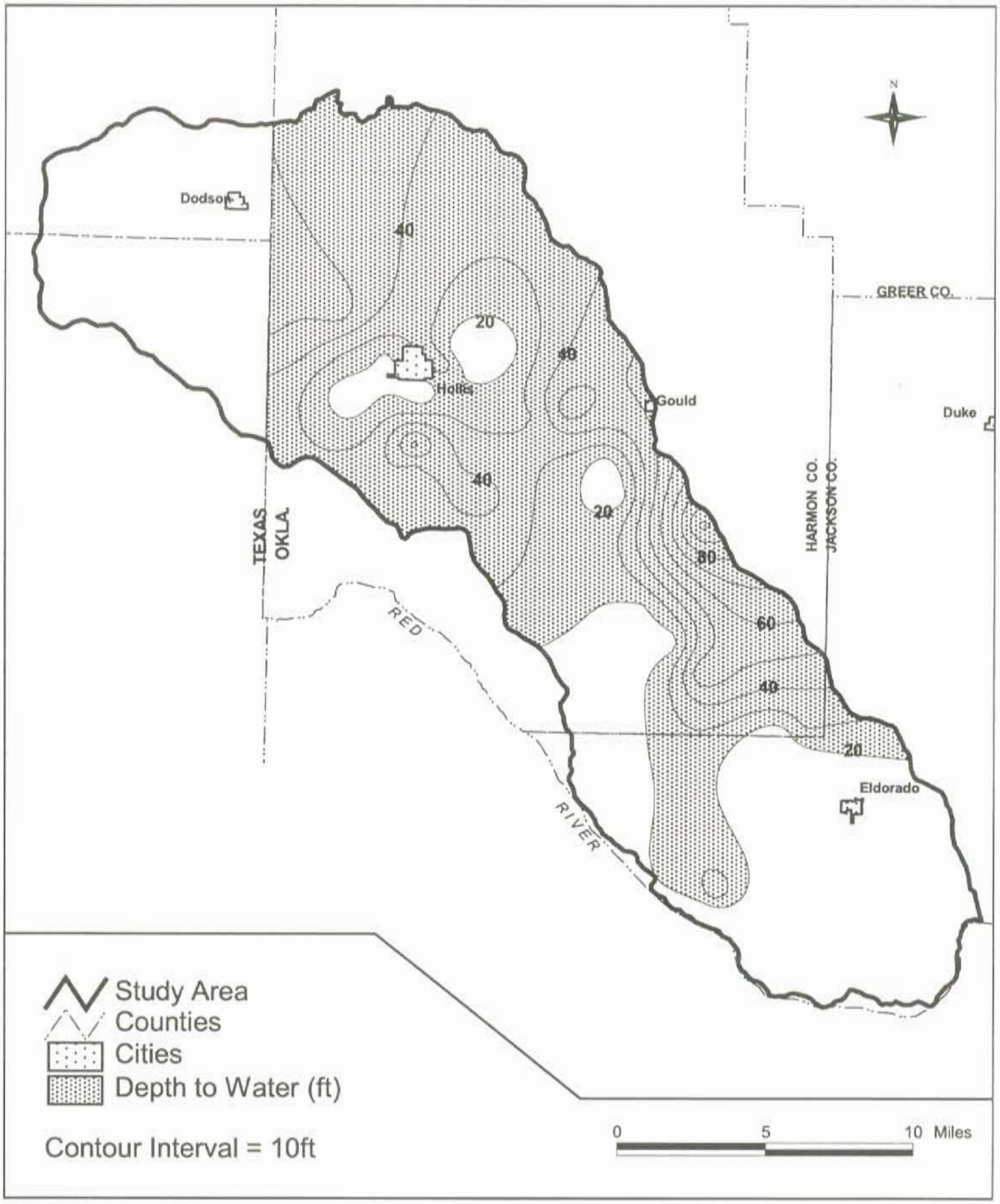


Figure 66. Depth to water map of the Blaine aquifer in February 1994 where the depth to water is ≥ 20 feet..

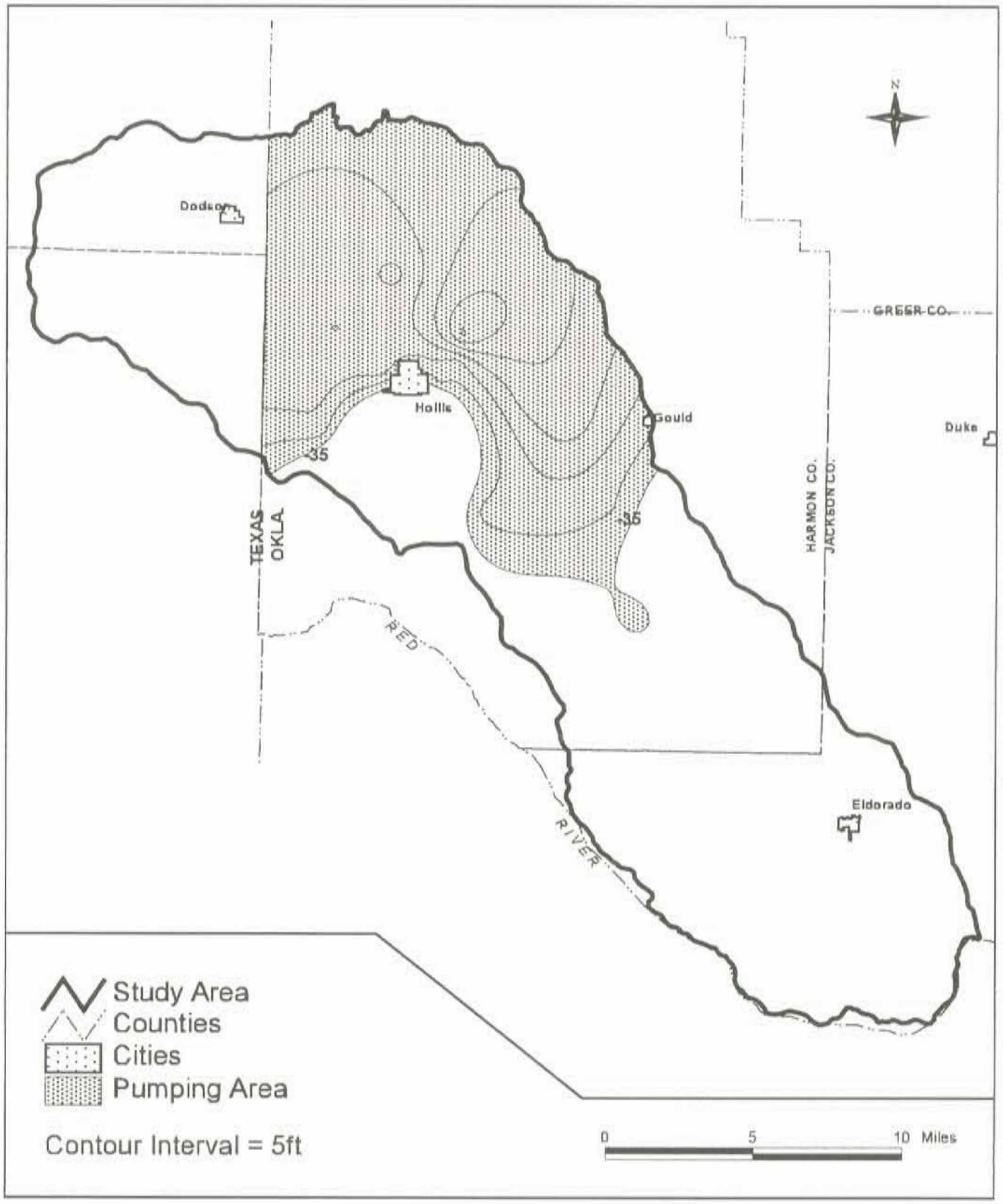


Figure 67. Map showing the irrigation pumping center, defined by where the water level declined more than 35 feet between May and August 1994 (see Figure 37).

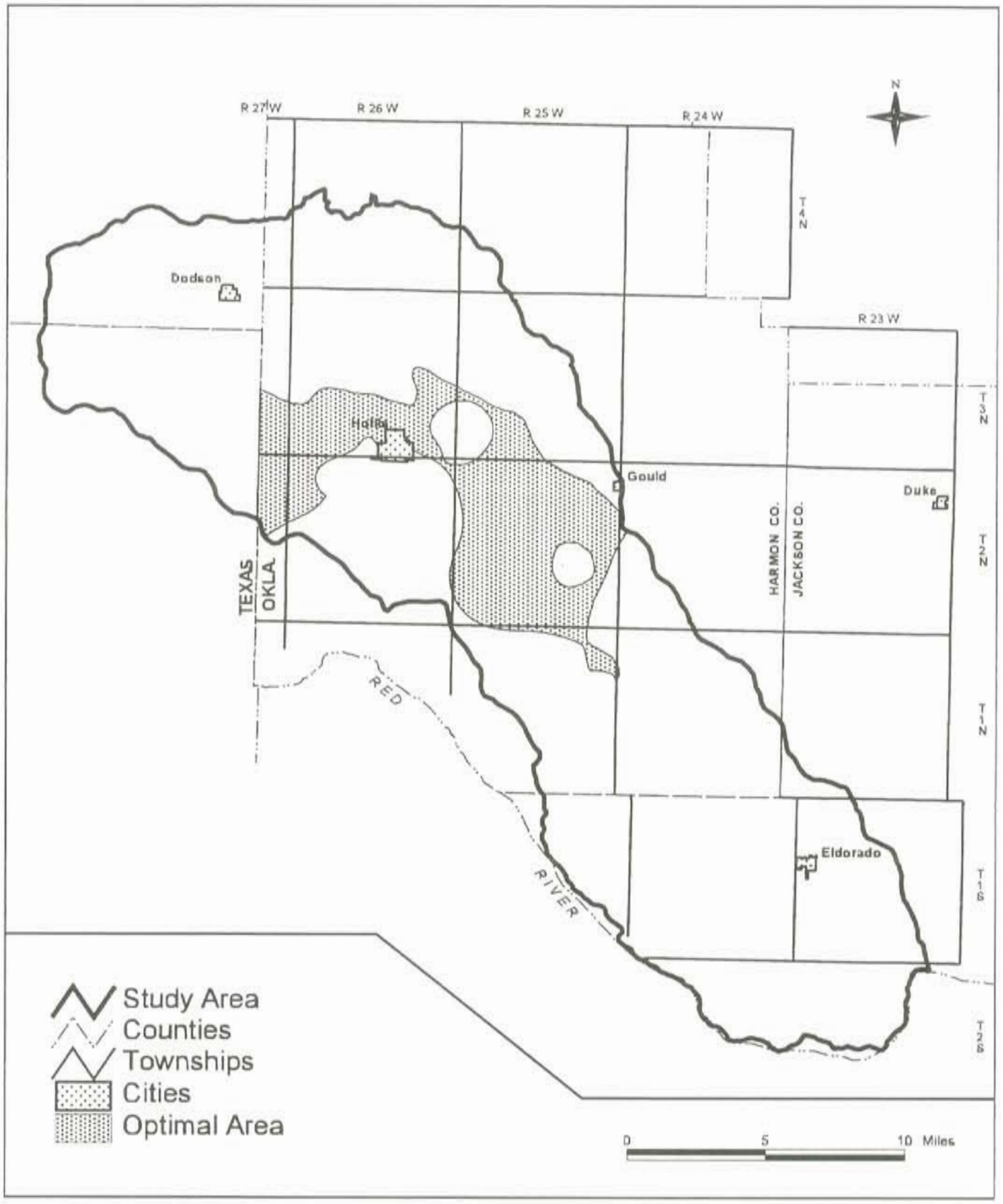


Figure 68. Map showing optimal location for new recharge wells.

Hydrofracturing has been successfully used to increase the yield of low-production water wells in rock where fracture systems are poorly developed or so tight that little water can move through them. High-pressure pumps are used to inject fluids into newly opened fractures, causing small, tight breaks in the rock to open and spread radially. During pumping, sand or small particles of high-strength plastic are introduced into the fractures to keep the cracks open after the pressure has been released (Driscoll, 1986).

WATER QUANTITY IMPACTS

Artificial recharge does not appear to damage the aquifer. In fact, the experience of the District is that the storage capacity of the aquifer can improve over time as dissolution of gypsum increases the size of caverns and conduits.

Some of the District's recharge wells have suffered from subsurface collapse of the formation. The effect on the aquifer is temporary, as recharge will eventually increase with the development of new conduits. However, subsurface collapse could result in damage or destruction of the well. Subsurface collapse around some of the District's wells has also resulted in the development of sink holes, which can harm property and hinder farming operations.

The OWRB added some design features to the project wells to prevent collapse from occurring. Time will tell how effective these measures were. In the four years of project operation, there were no problems.

Positive impacts outweigh the negative ones. Artificial recharge provides an effective method in offsetting seasonal and long-term water level declines. The wells augment groundwater supplies in an aquifer that is heavily pumped for irrigation. In times of drought, this management technique could help prevent wells from going dry and from inducing salt water from underlying formations. Recharge wells capture storm runoff that otherwise would leave the area and eventually flow into the Red River. The impoundment has the additional benefit of providing flood control for Hollis.

Water Quality Findings and Results

INTRODUCTION

A primary objective of the project was to determine the impact of artificial recharge on the quality of the aquifer. In order to assess the impact, baseline conditions were compared with conditions after recharge operations began. Summary statistics were generated to describe the general water quality conditions existing before and after recharge operations began.

Summary statistics were prepared for the general chemistry parameters when the sample size was six or greater. Only cation and anion analyses for samples that balanced within ± 10% were used to compute the summary statistics. Summary statistics were not prepared for the trace elements due to the influence of total suspended solids, nor for organics due to the small number of detections. Trace elements and organics were evaluated in terms of their respective maximum contaminant levels (MCLs). All summary statistics were computed using STATISTICA software (StatSoft, 1997). A detailed discussion of the statistical analyses and methodology is in *Blaine Gypsum Groundwater Recharge Demonstration Project Final Report.*

GENERAL CHEMISTRY

Baseline Groundwater Samples

Baseline samples are those that were not collected in association with a recharge event. They include samples collected from the upgradient monitoring wells in 1992, upgradient and downgradient wells in 1993, and upgradient and downgradient wells collected after 1993 that were not associated with a recharge event.

A piper plot of all the baseline samples is shown in Figure 69, and plots of individual sites are shown in Figures 70-74. All piper plots were produced using Plotchem software (Tecsoft, 1997). The proportions of calcium to magnesium to sodium in the cation portion of the plot show quite a bit of variance from site to site. Similarly, the anions show a difference in proportions of sulfate to chloride. The type waters include:

Site	Type
R01	$CaMgSO_4$
R02	$CaSO_4$
R03	$CaMgSO_4$
R04	$CaSO_4$
R05	$CaNaSO_4$, $CaNaSO_4Cl$ and $CaSO_4$

The water from all sites is high in total dissolved solids (TDS), ranging from 1,449 to 7,940 mg/L. Table 10 lists summary statistics for the baseline samples.

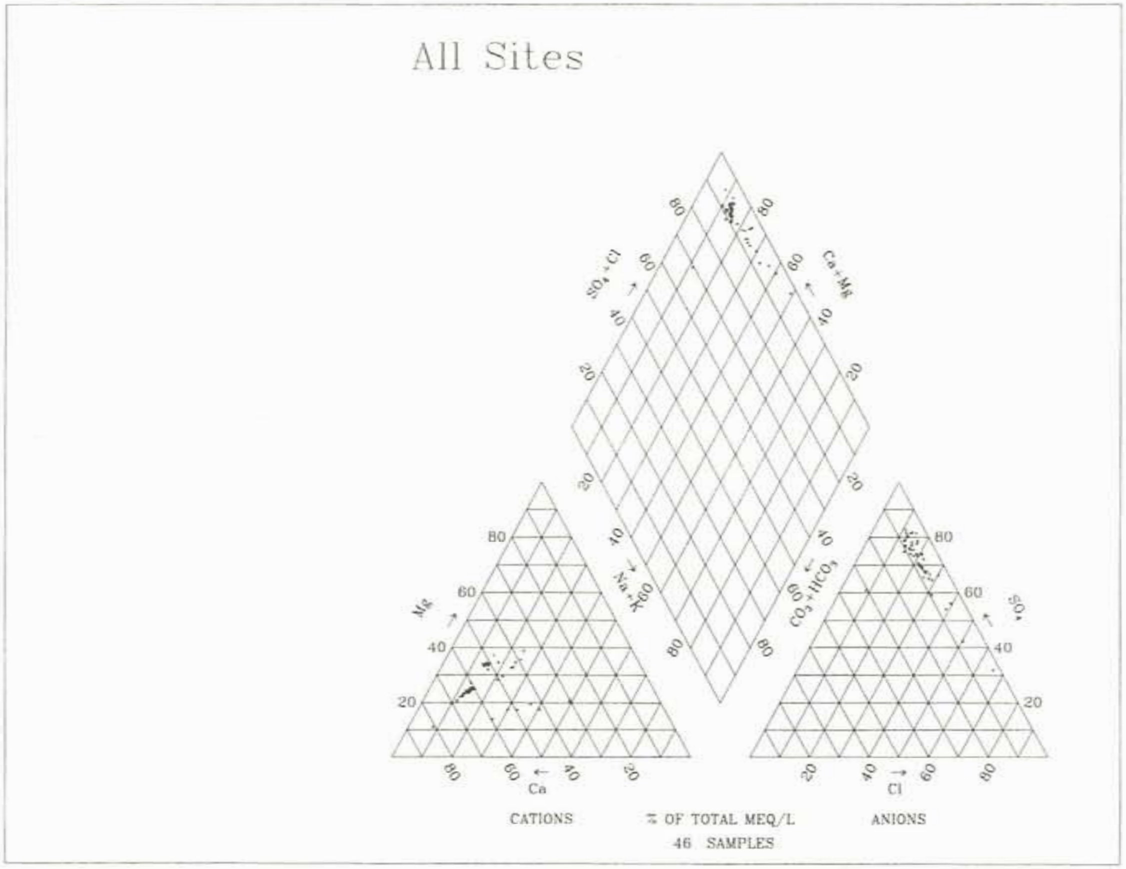


Figure 69. Piper plot for baseline samples from sites R01 through R05 combined.

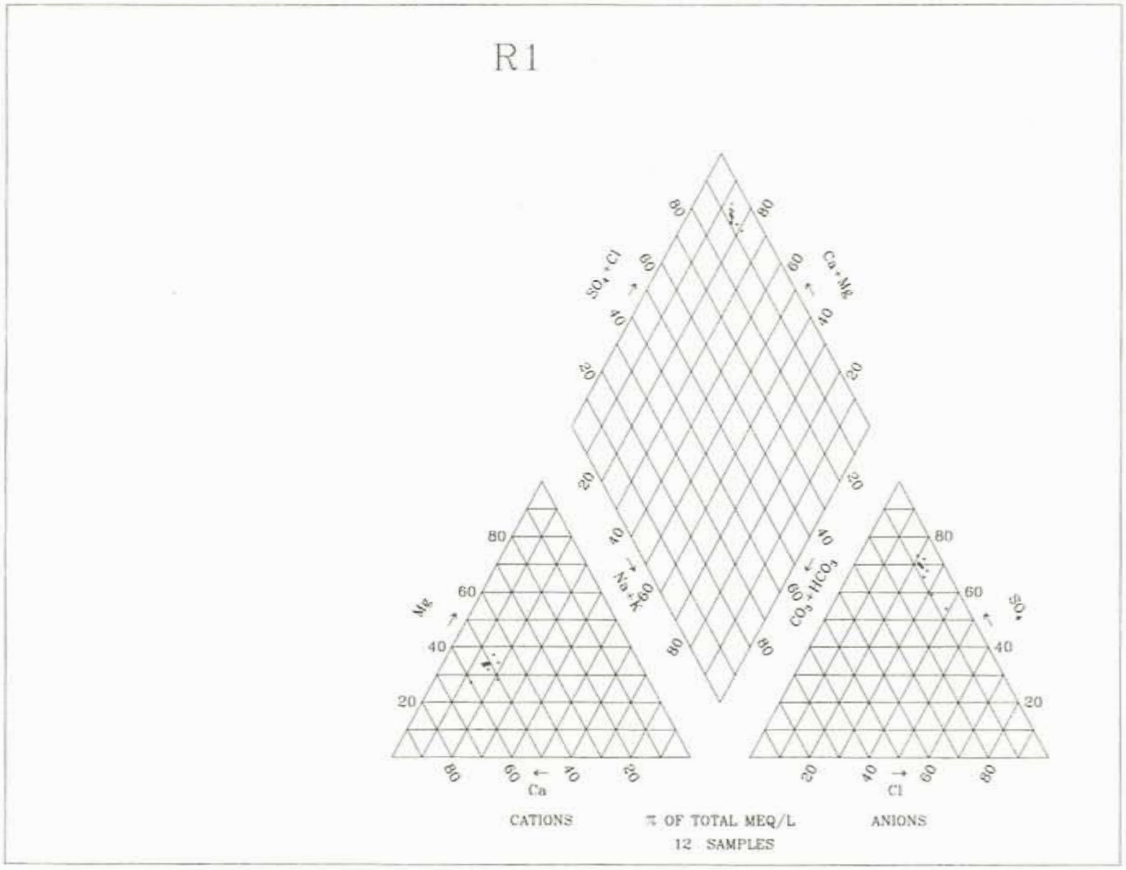


Figure 70. Piper plot for baseline samples from site R01.

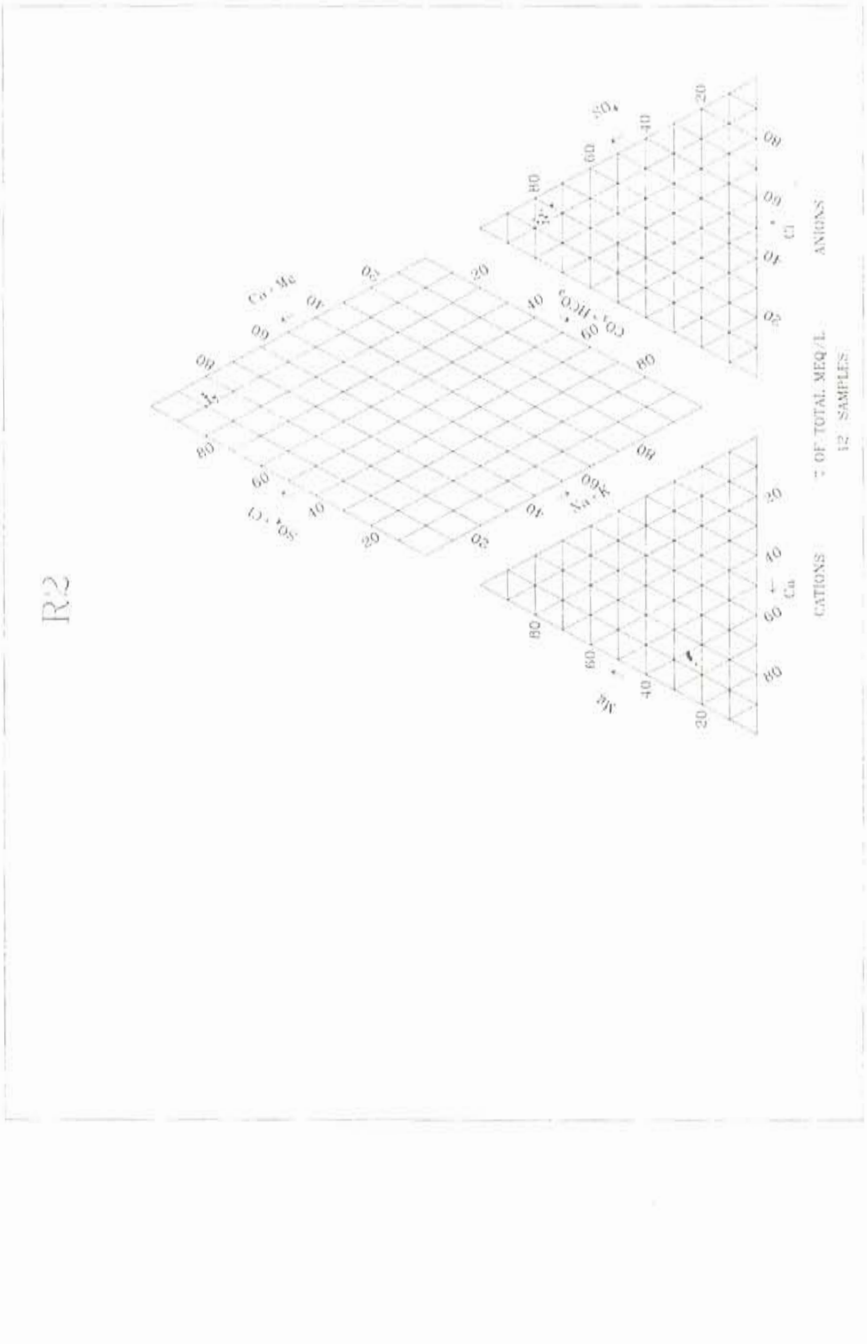


Figure 71. Piper plot for baseline samples from site R02.

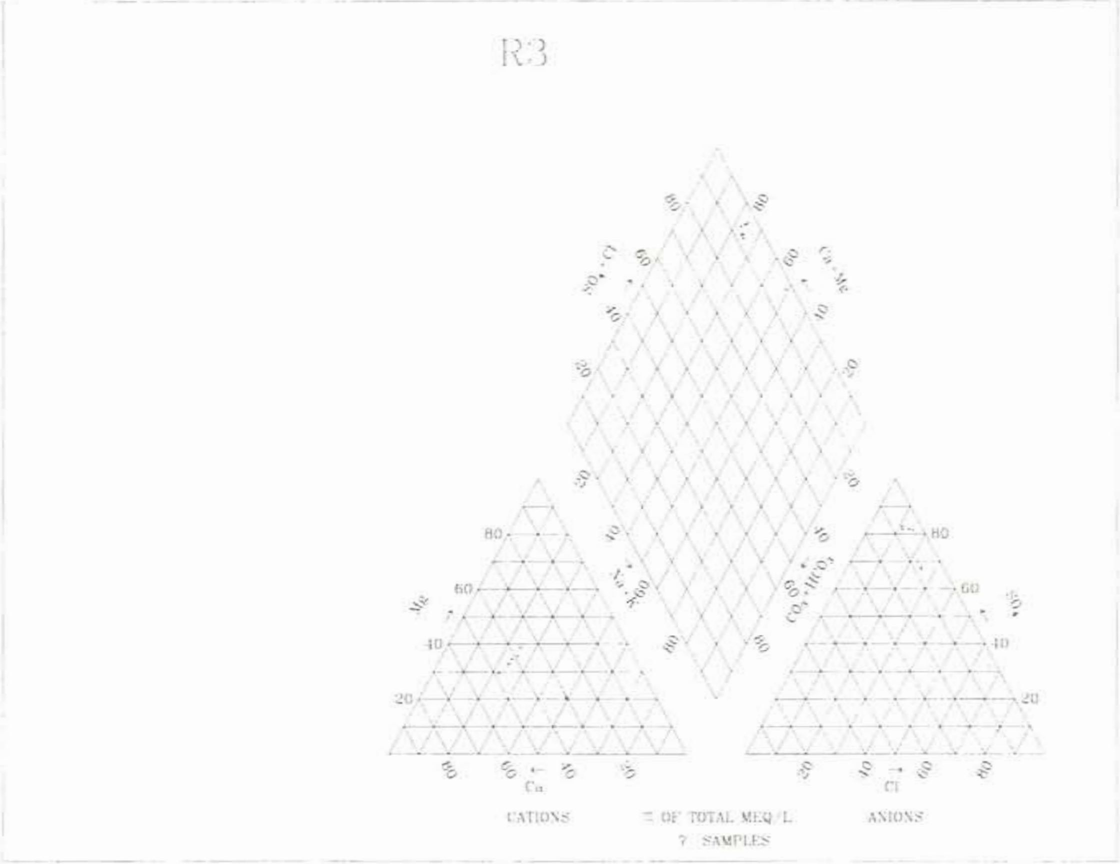


Figure 72. Piper plot for baseline samples from site R03.

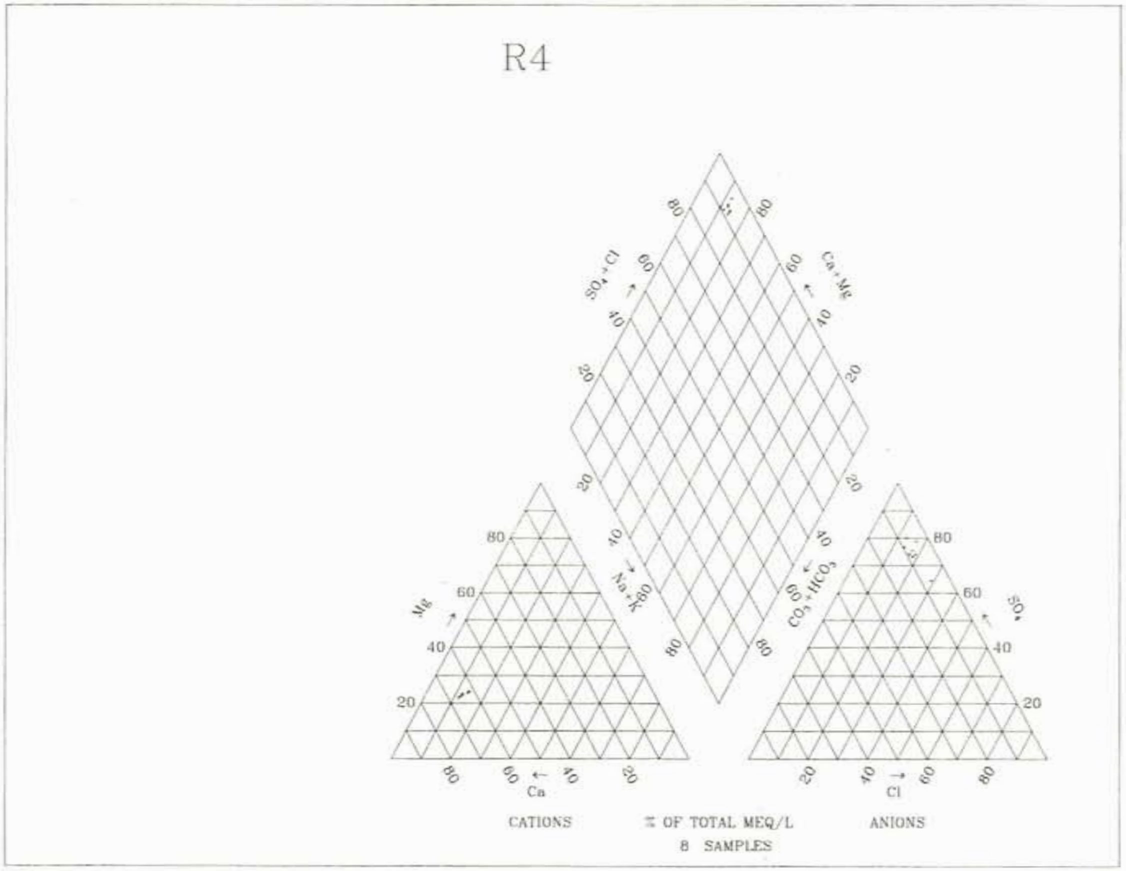


Figure 73. Piper plot for baseline samples from site R04.

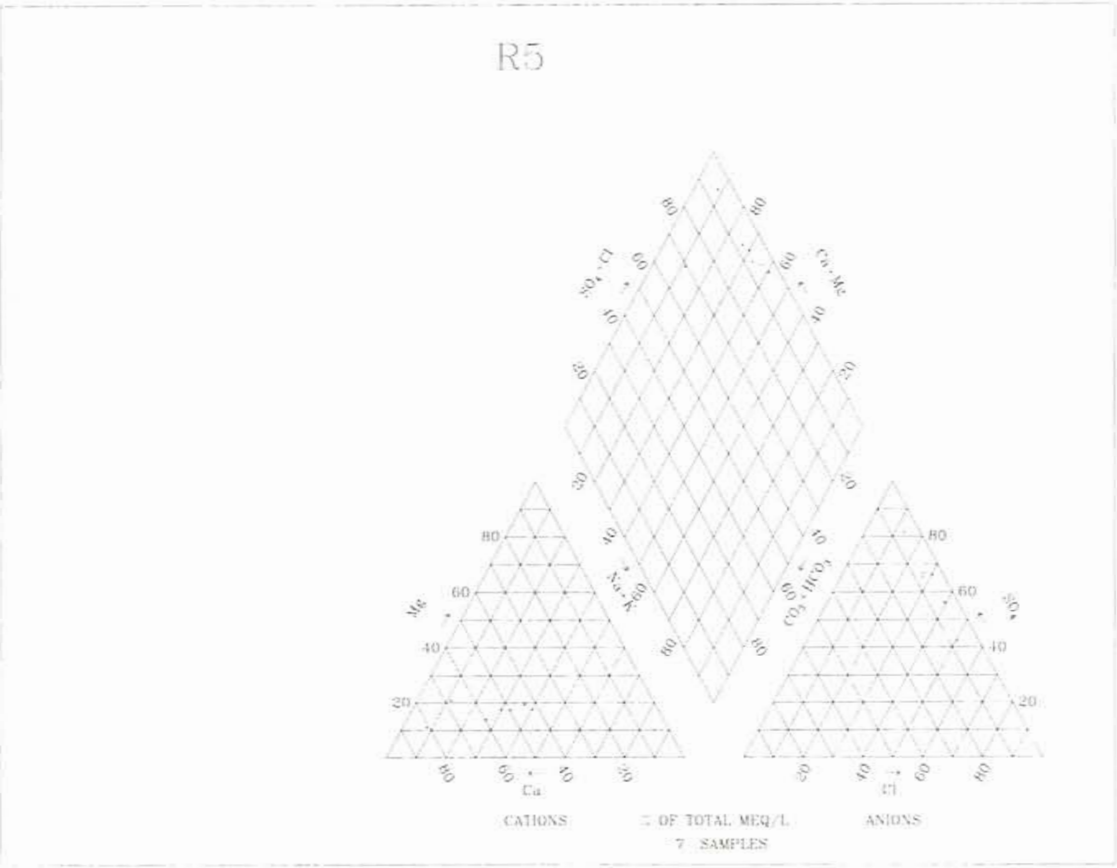


Figure 74. Piper plot for baseline samples from site R05.

Table 10. Summary statistics for baseline groundwater, general-chemistry parameters

All Sites

PARA- METER	UNITS	VALID - N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	46	193	108	293
TDS	mg/L	71	3702	1449	7940
TSS*	mg/L	69	20	< 1	2810
Nitrate	mg/L	71	6.66	< 0.5	22.6
P*	mg/L	63	0.086	< 0.05	5.7
CA	mg/L	46	522	253	664
MG	mg/L	46	131	47	308
NA	mg/L	46	143	46	1226
K	mg/L	46	7.7	1.5	20
CL	mg/L	46	297	48	2652
SO4	mg/L	46	1482	461	2718
F	mg/L	46	0.53	0.37	1.04

R1

PARA- METER	UNITS	VALID - N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	12	238	139	261
TDS	mg/L	19	3864	3148	4338
TSS*	mg/L	19	7.00	< 1	172
Nitrate	mg/L	19	11.8	2.05	22.6
P*	mg/L	18	0.06	< 0.05	0.16
CA	mg/L	12	518	467	586
MG	mg/L	12	208	150	232
NA	mg/L	12	166	129	275
K	mg/L	12	8.6	5.8	20.0
CL	mg/L	12	394	321	811
SO4	mg/L	12	1575	1306	1839
F	mg/L	12	0.49	0.37	0.54

R2

PARA- METER	UNITS	VALID - N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	12	192	124	207
TDS	mg/L	16	3249	2876	3324
TSS*	mg/L	16	24.5	5.00	2024
Nitrate	mg/L	16	6.80	3.45	8.78
P*	mg/L	16	0.10	< 0.05	2.11
CA	mg/L	12	533	446	565
MG	mg/L	12	125	109	135
NA	mg/L	12	125	110	138
K	mg/L	12	7.0	1.5	14
CL	mg/L	12	205	158	293
SO4	mg/L	12	1431	1110	1885
F	mg/L	12	0.52	0.45	0.56

*Some values are estimated.

R3

PARA- METER	UNITS	VALID - N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	7	170	145	280
TDS	mg/L	15	4659	3320	7940
TSS*	mg/L	14	83.5	3	2810
Nitrate	mg/L	15	3.8	< 0.5	9.34
P*	mg/L	12	0.384	< 0.05	5.7
CA	mg/L	7	485	378	664
MG	mg/L	7	244	140	308
NA	mg/L	7	317	193	1226
K	mg/L	7	8.3	5	16
CL	mg/L	7	374	168	2652
SO4	mg/L	7	1745	1661	2718
F	mg/L	7	0.785	0.5	1.04

R4

PARA-METER	UNITS	VALID - N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	8	177	114	193
TDS	mg/L	8	3147	2788	3881
TSS*	mg/L	8	15.0	5.00	198
Nitrate	mg/L	8	6.77	4.80	8.31
P*	mg/L	7	0.03	< 0.05	0.07
CA	mg/L	8	542	495	552
MG	mg/L	8	116	93.0	120
NA	mg/L	8	116	88.0	126
K	mg/L	8	6.9	4.0	15.0
CL	mg/L	8	241	166	428
SO4	mg/L	8	1370	1237	1595
F	mg/L	8	0.59	0.48	0.61

*Some values are estimated.

R5

PARA-METER	UNITS	VALID - N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	7	177	107.8	292.5
TDS	mg/L	13	4664	1449	5160
TSS*	mg/L	12	67	3	870
Nitrate	mg/L	13	1.34	< 0.5	5
P*	mg/L	10	0.137	< 0.05	0.42
CA	mg/L	7	--	253	629
MG	mg/L	7	--	47	157
NA	mg/L	7	--	46	560
K	mg/L	7	--	4.1	13
CL	mg/L	7	--	48	897
SO4	mg/L	7	--	461	1737
F	mg/L	7	--	0.5	0.9

Injectate Samples

Table 11 lists the summary statistics for the injectate samples. Cation-anion balances were attempted for the injectate samples; however, due to the high total suspended solids (TSS) only a few samples balanced. Summary statistics were therefore not calculated for cations, anions and other parameters influenced by TSS.

The range of TDS concentrations in injectate at all sites ranges from 80 to 3,442 mg/L. The higher TDS concentrations may be due to the mixing of irrigation tailwater with the surface runoff. Use of the highly mineralized groundwater for irrigation may cause a buildup in the soil of elements such as calcium and sulfate. These elements may in turn be redissolved by surface runoff, resulting in increased TDS.

Recharge water, in contrast to the mineralized groundwater, is generally low in dissolved solids. The median TDS concentration in injectate samples is 255 mg/L, which is significantly less than the median of 3,702 mg/L in the baseline groundwater samples.

TSS, however, is considerably greater in injectate than in groundwater. The median TSS concentration in injectate is 1,123 mg/L, while the median concentration in the baseline groundwater samples is 20 mg/L.

The TSS concentrations in injectate range from 25 to 4,020 mg/L. The lowest median TSS concentrations are 412 mg/L from the R04 site and 930 mg/L from the R05 site. The soil at these two sites is sandier than at the other sites, and may account for the lower TSS concentrations. The R02 site has the highest median TSS concentration of 1,685 mg/L. This site appears to receive sediment from upstream soil erosion.

Nitrate concentrations range from <0.50 to 14.1 mg/L. The median concentrations for nitrate range from 0.8 at site R02 to 1.2 mg/L at site R05. Although some individual concentrations exceed the MCL of 10 mg/L, the median nitrate at all sites is less than the MCL.

After-recharge Groundwater Samples

Samples from the after-recharge group were collected within ten days of a recharge event. Summary statistics for these samples are shown in Table 12. The water in this group is high in TDS with concentrations for all sites ranging from 700 to 8,265 mg/L and with a median of 2,960 mg/L.

Piper plots for the after-recharge sample group at sites R01-R05 are shown in Figures 75-79. These show that the water in both groups is a calcium-sulfate to calcium-magnesium-sulfate type. Little change in the composition of the water from baseline to after-recharge is indicated at sites R02, R03, or R04 except a slight shift toward calcium and sulfate in the samples collected after recharge. At sites R01 and R05 the composition changes considerably. Both sites show a shift in cation proportions to more calcium and anions to more sulfate. Sample concentrations at the R01 site shift from magnesium to more

Table 11. Summary statistics for injectate general-chemistry

All Sites

PARA-METER	UNITS	VALID - N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	41	--	27.0	171
TDS	mg/L	41	255	80.0	3442
TSS*	mg/L	41	1133	25.0	4020
Nitrate	mg/L	41	1.03	< 0.5	14.1
P*	mg/L	41	1.13	0.13	5.35
CA	mg/L	41	--	13.0	541
MG	mg/L	41	--	3.0	159
NA	mg/L	41	--	< 10	193
K	mg/L	41	--	6.0	45.0
CL	mg/L	41	--	10.0	278
SO4	mg/L	41	--	20.0	1223
F	mg/L	41	--	< 0.1	0.63

R1

PARA-METER	UNITS	VALID - N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	8	--	42.4	67.3
TDS	mg/L	8	253	140	1280
TSS*	mg/L	8	1245	663	3360
Nitrate	mg/L	8	1.11	0.66	2.99
P*	mg/L	8	1.25	0.14	2.39
CA	mg/L	8	--	26.0	49.0
MG	mg/L	8	--	3.0	48.0
NA	mg/L	8	--	< 10	10.0
K	mg/L	8	--	8.0	34.0
CL	mg/L	8	--	10.0	19.7
SO4	mg/L	8	--	20	60.7
F	mg/L	8	--	< 0.1	0.26

R2

PARA-METER	UNITS	VALID - N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	8	--	35.0	92.0
TDS	mg/L	8	270	112	930
TSS*	mg/L	8	1685	92.0	4020
Nitrate	mg/L	8	0.86	< 0.5	2.80
P*	mg/L	8	1.29	0.51	4.43
CA	mg/L	8	--	13.0	117
MG	mg/L	8	--	6.0	64.0
NA	mg/L	8	--	< 10	28.0
K	mg/L	8	--	7.0	33.0
CL	mg/L	8	--	10	32.9
SO4	mg/L	8	--	20	186
F	mg/L	8	--	< 0.1	0.26

*Some values are estimated.

R3

PARA-METER	UNITS	VALID - N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	8	--	37.2	112
TDS	mg/L	8	280	180	3442
TSS*	mg/L	8	1093	25.0	3025
Nitrate	mg/L	8	1.10	< 0.5	12.4
P*	mg/L	8	0.84	0.33	2.11
CA	mg/L	8	--	22.0	417
MG	mg/L	8	--	14.0	159
NA	mg/L	8	--	< 10	193
K	mg/L	8	--	9.0	45
CL	mg/L	8	--	10.0	278
SO4	mg/L	8	--	20.0	1223
F	mg/L	8	--	< 0.1	0.63

R4

PARA-METER	UNITS	VALID -N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	9	--	39.6	171
TDS	mg/L	9	210	80.0	3166
TSS*	mg/L	9	412	178	3380
Nitrate	mg/L	9	0.82	< 0.5	9.24
P*	mg/L	9	1.10	0.43	5.35
CA	mg/L	9	--	23.0	541
MG	mg/L	9	--	4.0	136
NA	mg/L	9	--	< 10	120
K	mg/L	9	--	6.0	16.0
CL	mg/L	9	--	< 10	216
SO4	mg/L	9	--	20.2	254
F	mg/L	9	--	0.12	0.59

*Some values are estimated.

R5

PARA-METER	UNITS	VALID -N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	8	--	27.0	94.3
TDS	mg/L	8	242	120	1600
TSS*	mg/L	8	930	52.0	1380
Nitrate	mg/L	8	1.21	0.63	14.1
P*	mg/L	8	1.13	0.13	4.36
CA	mg/L	8	--	13.0	539
MG	mg/L	8	--	3.0	129
NA	mg/L	8	--	< 10	74.0
K	mg/L	8	--	8.0	43.5
CL	mg/L	8	--	10.0	83.9
SO4	mg/L	8	--	20.0	469
F	mg/L	8	--	< 0.1	0.42

Table 12. Summary statistics for groundwater, general-chemistry parameters in the after-recharge sample group

All Sites

PARA-METER	UNITS	VALID -N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	39	170	73.6	282
TDS	mg/L	134	2960	700	8265
TSS*	mg/L	134	28.0	< 1	5740
Nitrate	mg/L	134	4.54	< 0.5	19.2
P*	mg/L	134	0.18	< 0.05	3.34
CA	mg/L	39	531	142	712
MG	mg/L	39	105	28.0	295
NA	mg/L	39	115	10.0	1559
K	mg/L	39	8.6	5.0	24.0
CL	mg/L	39	201	24.1	2735
SO4	mg/L	39	1444	438	2423
F	mg/L	39	0.45	0.12	1.00

R1

PARA-METER	UNITS	VALID -N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	11	146	82.8	225
TDS	mg/L	32	2429	984	3768
TSS*	mg/L	32	15.5	< 1	44.0
Nitrate	mg/L	32	4.72	1.14	19.2
P*	mg/L	32	0.10	< 0.05	0.41
CA	mg/L	11	449	326	665
MG	mg/L	11	103	36.0	258
NA	mg/L	11	85.0	31.0	171
K	mg/L	11	7.5	6.0	9.5
CL	mg/L	11	171	54.8	373
SO4	mg/L	11	1253	696	1851
F	mg/L	11	0.36	0.29	0.55

R2

PARA-METER	UNITS	VALID -N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	4	--	145	210
TDS	mg/L	24	2972	2418	3488
TSS*	mg/L	24	185	9.00	5740
Nitrate	mg/L	24	5.32	0.66	6.81
P*	mg/L	24	0.34	0.11	3.34
CA	mg/L	4	--	524	702
MG	mg/L	4	--	95.0	130
NA	mg/L	4	--	97.0	127
K	mg/L	4	--	8.0	13.0
CL	mg/L	4	--	126	209
SO4	mg/L	4	--	1268	1709
F	mg/L	4	--	0.33	0.52

*Some values are estimated.

R3

PARA-METER	UNITS	VALID -N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	9	224	188	282
TDS	mg/L	24	4445	2206	8265
TSS*	mg/L	24	146	13.0	2180
Nitrate	mg/L	24	3.48	< 0.5	9.59
P*	mg/L	24	0.41	< 0.05	1.94
CA	mg/L	9	556	432	635
MG	mg/L	9	226	170	295
NA	mg/L	9	238	211	1559
K	mg/L	9	11.0	6.0	24.0
CL	mg/L	9	289	227	2735
SO4	mg/L	9	2028	1448	2423
F	mg/L	9	0.71	0.58	1.00

R4

PARA-METER	UNITS	VALID -N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	6	188	153	254
TDS	mg/L	29	2976	1495	3812
TSS*	mg/L	29	10.8	4.00	188
Nitrate	mg/L	29	6.67	2.23	9.62
P*	mg/L	29	0.09	< 0.05	2.29
CA	mg/L	6	576	515	692
MG	mg/L	6	104	72.5	120
NA	mg/L	6	97.0	63.5	127
K	mg/L	6	6.0	5.0	8.0
CL	mg/L	6	193	124	240
SO4	mg/L	6	1392	1165	1787
F	mg/L	6	0.51	0.35	0.58

*Some values are estimated.

R5

PARA-METER	UNITS	VALID -N	MEDIAN	MINIMUM	MAXIMUM
BICARB	mg/L	9	135	73.6	192
TDS	mg/L	25	2776	700	3953
TSS*	mg/L	25	56.0	4.00	2660
Nitrate	mg/L	25	0.87	< 0.5	8.69
P*	mg/L	25	0.21	0.06	0.99
CA	mg/L	9	511	142	712
MG	mg/L	9	59.0	28.0	80.0
NA	mg/L	9	115	10.0	183
K	mg/L	9	11.0	6.0	14.0
CL	mg/L	9	148	24.1	212
SO4	mg/L	9	1255	438	1728
F	mg/L	9	0.40	0.12	0.47

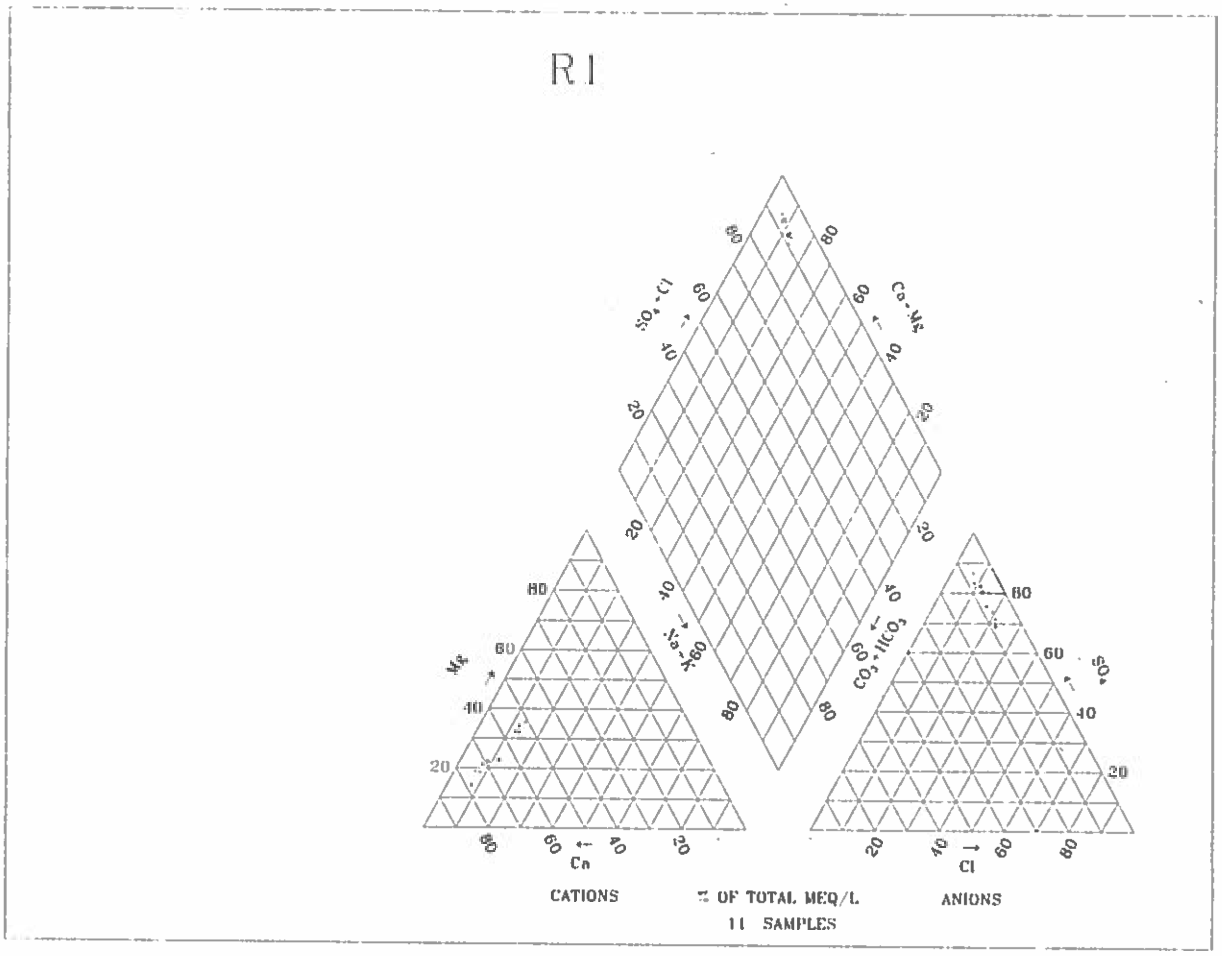


Figure 75. Piper plot for after-recharge samples from site R01.

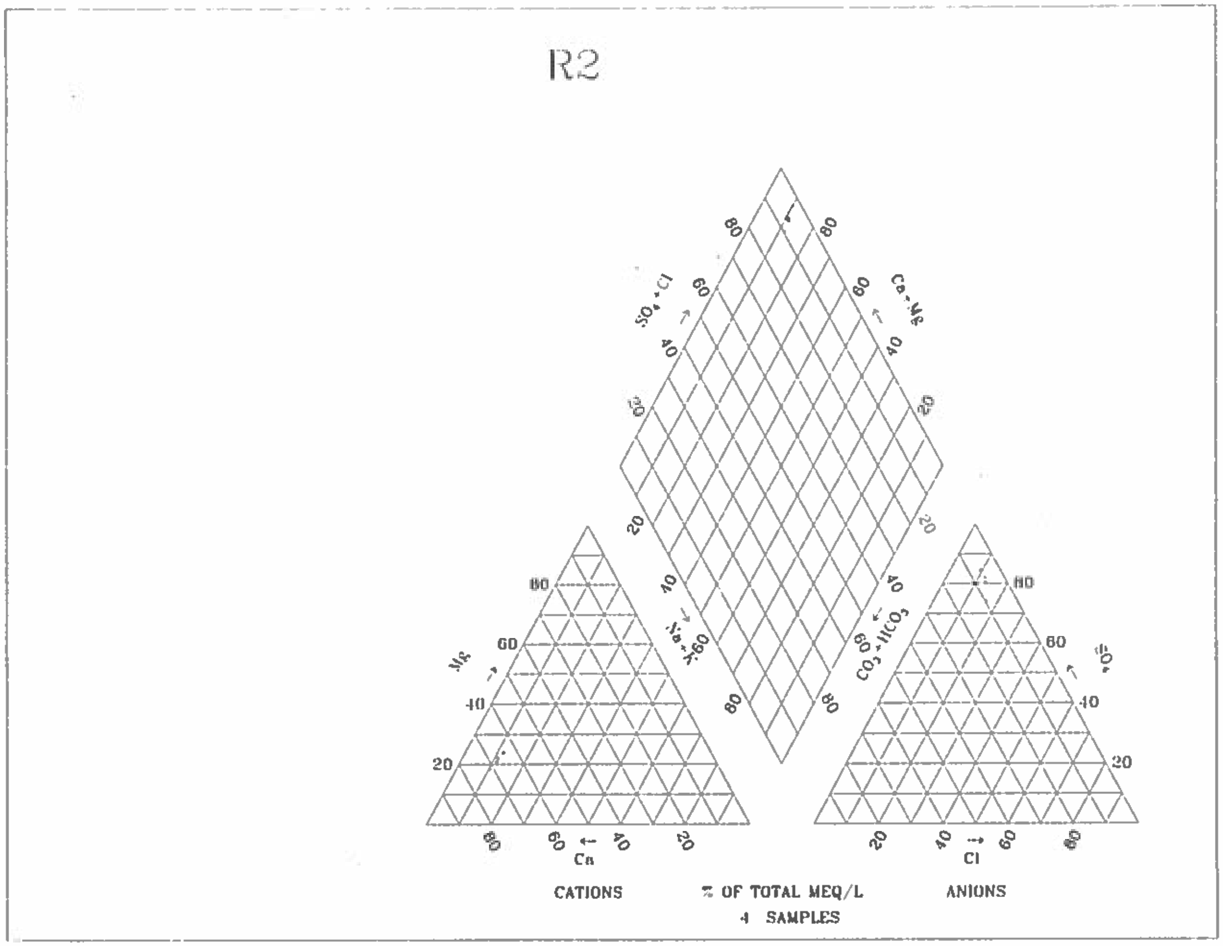


Figure 76. Piper plot for after-recharge samples from site R02.

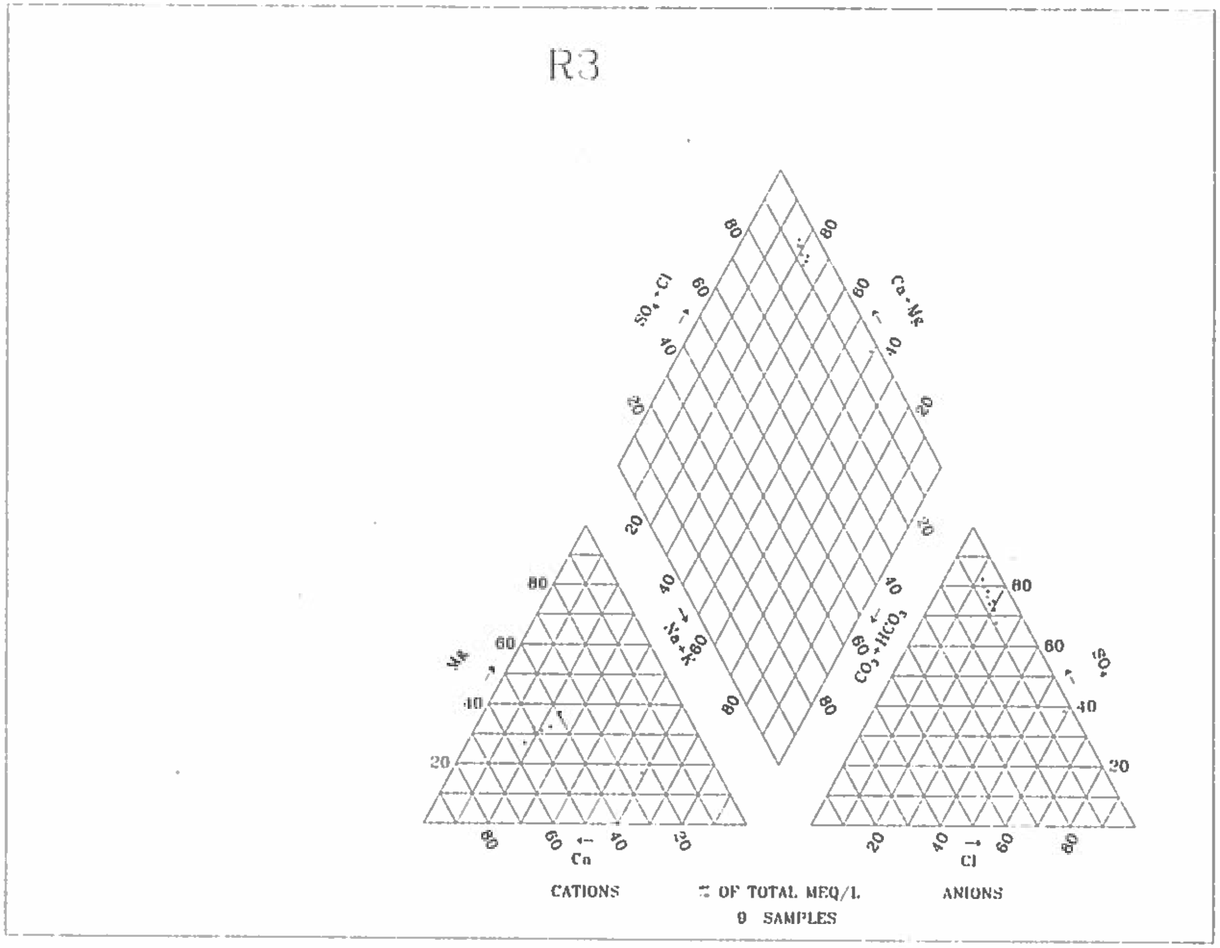


Figure 77. Piper plot for after-recharge samples from site R03.

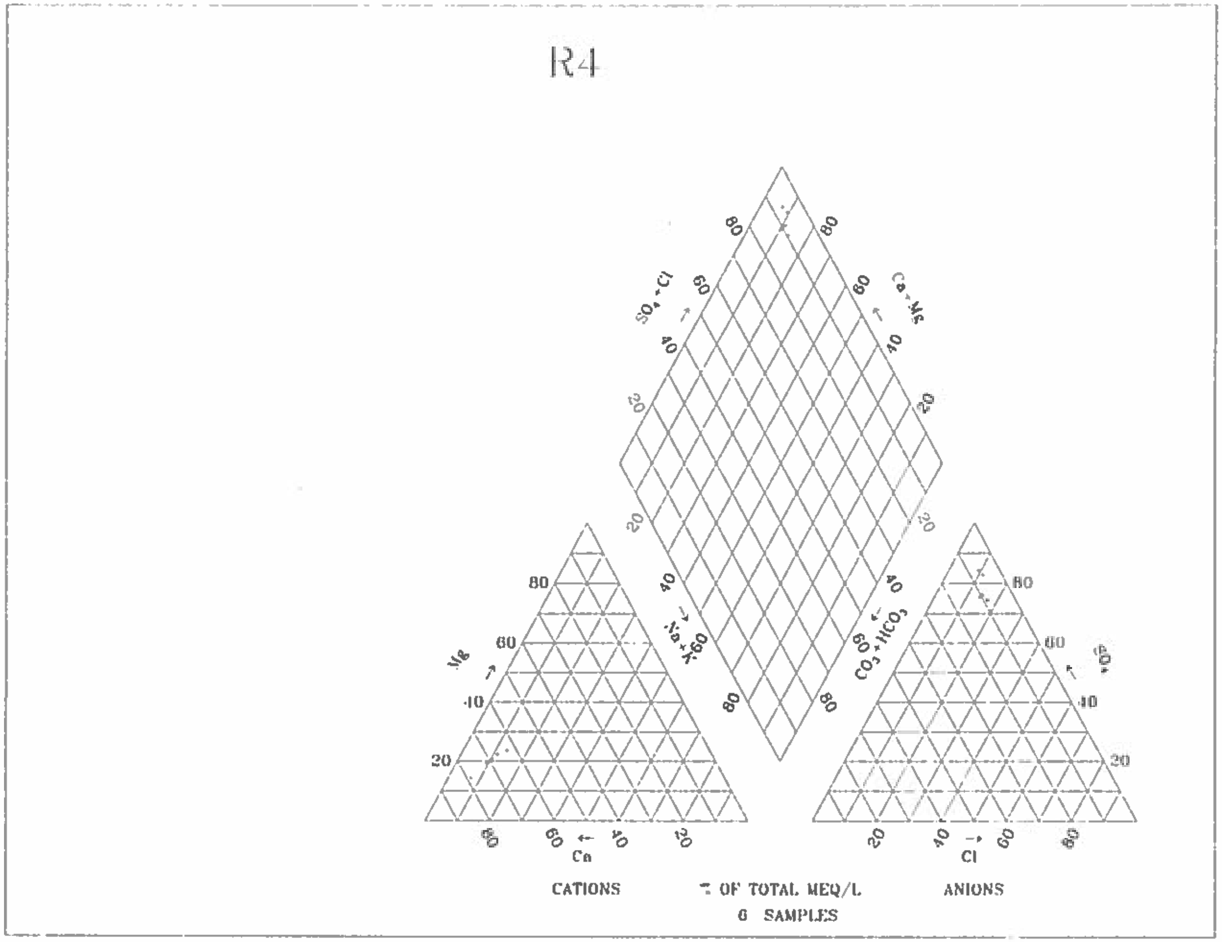


Figure 78. Piper plot for after-recharge samples from site R04.

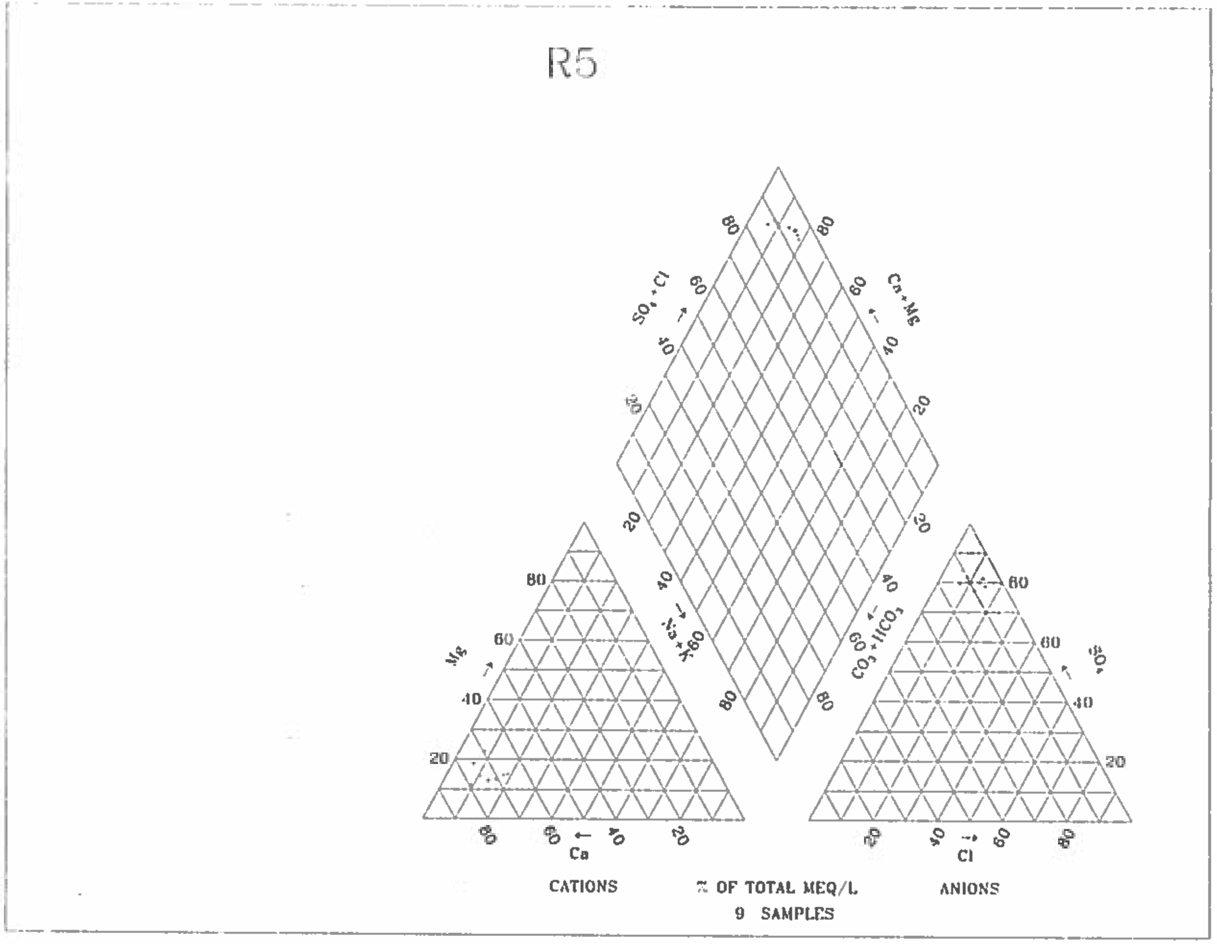


Figure 79. Piper plot for after-recharge samples from site R05.

calcium while R05 samples shift from sodium to more calcium. The shift towards calcium and sulfate may indicate the recharge water is a calcium-sulfate type.

The Mann-Whitney rank-sum test was used to compare the baseline sample group with the after-recharge group to determine if project operations have affected water quality of the aquifer. Analysis of general-chemistry constituents indicates that concentrations of most parameters either decreased after recharge or did not significantly change. TDS, which is a good indicator of general water quality, decreased as much as 1,000 mg/L. The decrease in TDS was statistically significant at four of the sites. A decrease in nitrate occurred at all five sites, but was statistically significant at only two sites. A few parameters (TSS, phosphorus, calcium, and potassium) increased after recharge at some sites. Phosphorus increased at four sites, but this may be due to adsorption of this compound to suspended solids.

The general water quality of the aquifer appears to improve after recharge. As fresh water is introduced into the aquifer, gypsum and dolomite dissolve, causing calcium, magnesium and sulfate concentrations to increase until the water becomes saturated with respect to gypsum and dolomite, and returns to equilibrium. Because the after-recharge samples were collected within ten days of a recharge event, these changes reflect short-term dilution effects on the aquifer and do not necessarily reflect long-term effects.

TRACE ELEMENTS

Trace element analyses appear to be strongly influenced by elevated TSS. Because statistical analyses would be highly biased and would not reflect the true dissolved metal concentration of the water samples, trace elements were evaluated in relationship to their corresponding MCL. Trace element samples collected during 1993 were designated as baseline, and all samples collected after 1993 were designated as post-recharge.

Tables 13 and 14 list the trace elements with a primary MCL for groundwater and injectate, respectively. Listed in the tables are the minimum and maximum reporting limit (MRL), the minimum and maximum concentration, and the number of times an MCL was exceeded. In order to put the occurrence of samples exceeding MCLs in perspective, the ranges of TSS concentrations for the corresponding samples are also shown. The laboratory detection limit for beryllium, thallium and antimony were greater than the MCL. For these parameters, only concentrations over the detection limit are counted. The MCL for lead was 50 μg/L at the inception of this project, but later changed to a treatment standard for drinking water. The earlier MCL is used in the tables.

Except for selenium, the samples that exceeded an MCL generally correspond to samples with high TSS. This relationship is illustrated in Figure 80, which graphically shows the correlation between three common trace elements and TSS in injectate water samples from the R03 site. The median TSS of all post-recharge groundwater samples was 28 mg/L while the median TSS of all groundwater samples with trace element detections above the MCL (excluding selenium) was 2,024 mg/L. Many of the trace elements that exceeded the MCL came from the same sample.

Table 13. Analysis of trace elements in groundwater samples (μg/L)

ELEMENT	MIN. MRL	MAX MRL	MIN. VALUE	MAX. VALUE	MCL	NO. OF DETECTIONS ABOVE MCL		TSS (mg/L) RANGE OF VALUES*
						baseline	after recharge	
Arsenic	<10	<70	<10	144	50	$2^{R1,3}$	0	13780-14960
Barium	<10	<10	<10	2072	2000	1^{R3}	0	13780
Beryllium	<10	<10	<10	<10	4	0	0	
Cadmium	<5	<5	<5	82	5	$3^{R5,3}$	$3^{R2,3}$	1148-14960
Chromium	<10	<10	<10	602	100	$2^{R3,5}$	$4^{R2,3}$	495-14960
Lead	<45	<720	<45	359	50	1^{R5}	$5^{R3,2}$	180-14960
Thallium	<200	<3200	<200	237	2	0	1^{R2}	1388
Nickel	<25	<45	<25	701	100	1^{R3}	3^{R2}	2024-13780
Antimony	<350	<5600	<350	<5600	6	0	0	
Selenium	<5	<100	<5	149	50	17^{R1-4}	22^{R1-4}	1-13780
Mercury	<0.5	<0.5	<0.5	<0.5	2	0	0	
Total # of samples collected						41	195	

* For samples that exceed the standard

Table 14. Analysis of trace elements in injectate samples (μg/L)

METAL	MIN. MRL	MAX. MRL	MIN. VALUE	MAX. VALUE	MCL	NO. OF DETECTIONS ABOVE MCL	TSS (mg/L) RANGE OF VALUES*
Arsenic	<25	<60	<10	93	50	1^{R5}	540
Barium	--	--	62	1129	2000	0	
Beryllium	<10	<10	<10	<10	4	0	
Cadmium	<5	<5	<5	<5	5	0	
Chromium	<10	<10	<10	146	100	$5^{R1,2,3,5}$	1104-3840
Lead	<45	<45	<45	111	50	$7^{R1,3,5}$	540-2210
Thallium	<200	<200	<200	237	2	0	
Nickel	<25	<25	<25	116	100	$4^{R2,3,5}$	1496-3840
Antimony	<350	<350	<350	<350	6	0	
Selenium	<5	<70	<25	<70	50	0	
Mercury	<0.5	<0.5	<0.5	<0.5	2	0	
Total # of Samples Collected						71	

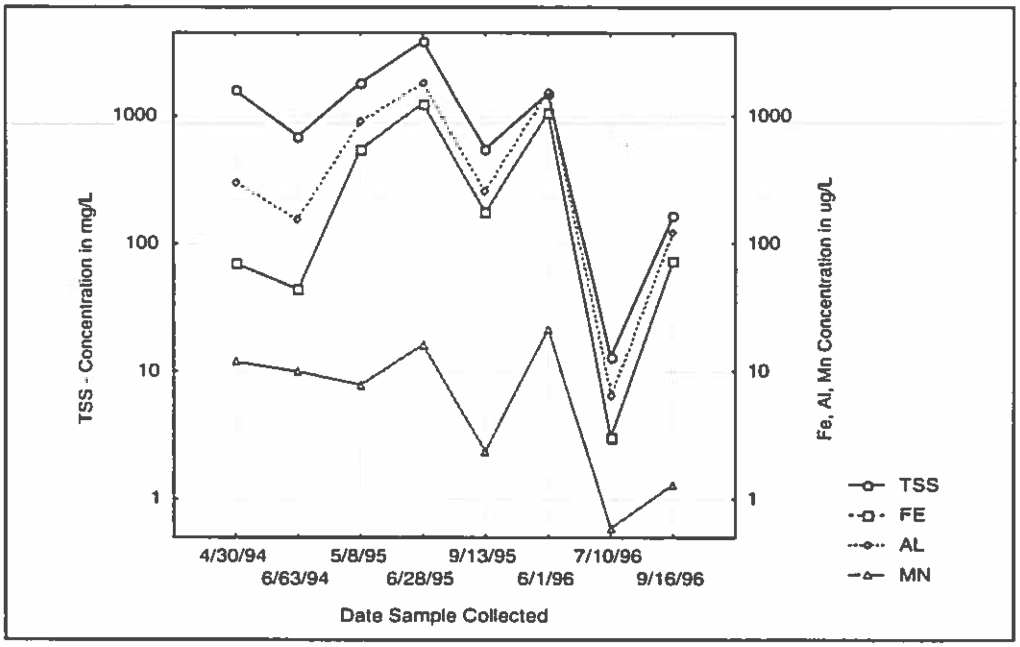


Figure 80. Injectate samples from site R03 showing correlation between selected trace elements and TSS.

Soil is the probable source of most of the trace elements in the injectate and groundwater. Soil samples from three of the recharge sites had levels of arsenic, barium, cadmium, chromium, lead, and nickel above the detection limit (Table 15). These elements are usually bound to the soil and are not mobile under normal conditions. When an analysis of total metals is performed in a laboratory, the metals are removed using a strong acid. Thus, metals analysis of water samples which contain TSS derived from these soils could show traces of the same metals. Although thallium was not analyzed in soil samples, it is known to be highly associated with potassium in soils and to replace potassium in clays when present (Ferguson, 1990).

Selenium was detected above its MCL of 50 μg/L more than any other parameter, with a maximum concentration of 149 μg/L. It was detected 17 times in the baseline samples and 22 times in the post-recharge samples. It was detected in groundwater at all sites except R05, but was not detected in the injectate.

The presence of selenium in the baseline samples suggests it is naturally occurring in the aquifer. Selenium was not detected in the soil samples. It is, however, frequently found in shales. The shales that are interbedded with the gypsum of the Blaine Formation are the probable source for selenium in the groundwater.

Table 15. Chemical analysis of soil samples collected 4/28/93 and 12/28/95

PARAMETER	**R01**		**R03**		**R05**	
	1993	**1995**	**1993**	**1995**	**1993**	**1995**
Arsenic In Sediment (mg/KG)	15.00	< 6.00	20.00	< 6.00	15.00	< 6.00
Barium In Sediment (mg/KG)	116.00	139.00	102.00	52.00	94.00	50.00
Cadmium In Sediment (mg/KG)	0.85	< 0.50	0.84	< 0.50	0.66	< 0.50
Chromium In Sediment (mg/KG)	8.20	14.00	10.00	8.00	7.80	7.00
Lead In Sediment (mg/KG)	4.70	< 4.50	5.20	< 4.50	5.10	< 4.50
Nickel In Sediment (mg/KG)	11.00	14.00	12.00	8.00	8.60	7.00
Phosphorous, Ortho Sediment (mg/KG)	6.70	------	77.00	-----	6.40	-----
Selenium In Sediment (mg/KG)	< 7.00	< 7.00	< 7.00	< 7.00	< 7.00	< 7.00

'<' Less than detection limit

ORGANICS AND CYANIDE

Volatile Organic Compounds

Low levels of volatile organic compounds (VOCs)were detected periodically. VOCs were detected in groundwater at the background monitoring well at the R04 site from two post-recharge sampling events (Table 16). Toluene and total xylenes were detected in May 1994. Total xylenes and 1,2,4-trimethylbenzene were detected in July 1994. Possible sources of contamination are fumes from vehicles or the portable generator used to collect samples, and highway runoff. The low levels that were detected are well below the MCLs for these parameters.

Other VOCs that were detected are 1,1,1-trichloroethane and chloroform. The solvent 1,1,1-trichloroethane was detected in three baseline samples of groundwater collected in July 1992 from the R01, R02, and R03 sites. It was also detected in two injectate samples from the R04 site and one from the R05 site. Concentrations for this compound were low, and below the MCL of 200 μg/L (Table 17).

The chlorine byproduct chloroform was detected once. The groundwater sample collected October 20, 1994 from the R5M4 well had a concentration of 1.30 μg/L. The MCL for chloroform is 100 μg/L.

Table 16. VOCs detected in groundwater at the R04 site

SITE	DATE	TOLUENE (µg/L)	XYLENE (µg/L)	1,2,4-TRIMETHYLBENZENE (µg/L)
		MCL: 1000	MCL: 10,000	MCL: 70
R4M1	05/31/94	0.800	2.00	<0.500
R4M1	07/07/94	<0.500	1.00	0.600
			0.90	0.600

Table 17. 1,1,1-Trichloroethane in groundwater and injectate samples

SITE	DATE	1,1,1-TRICHLOROETHANE (µg/L)	COMMENTS
		MCL: 200	
R1M1	07/28/92	2.1	baseline; groundwater
R2M1	07/28/92	2.6	baseline; groundwater
R3M3	07/28/92	1.1	baseline; groundwater
R04	05/26/94	1.1	injectate
R04	06/30/94	0.7	injectate
R05	07/09/94	0.6	injectate

Pesticides

Insecticides

Parathion, an insecticide used primarily on cotton, was detected in baseline samples in groundwater from the R03 and R04 sites. Concentrations were 0.310 and 0.160 μg/L, respectively. Both samples were collected on May 6, 1992.

Methyl parathion (trade name Penncap-M) was detected in groundwater at the two down-gradient wells at the R02 site in September 1995 (Table 18). Concentrations of 0.620 and 125.000 μg/L were reported for duplicate samples from the R2M6 well. Due to the large discrepancy between the duplicate samples, the groundwater was resampled from monitoring wells R2M2 and R2M6 on November 8. Methyl parathion was not detected in the second set of samples.

Methyl parathion is an organophosphorus insecticide. It is used on cotton and is applied by crop foliar spray or chemigation. Methyl parathion has a low water solubility, high soil retention, and medium runoff potential. It has a very short longevity, with a half-life in soil of five days. EPA lists a lifetime Health Advisory Level (HAL) of 2.00 μg/L for methyl parathion.

Table 18. Methyl parathion in groundwater samples

SITE	DATE	METHYL-PARATHION (µg/L) HAL: 2.00	COMMENTS
R2M3	09/25/95	0.670	groundwater
R2M6	09/25/95	0.620 125.000	groundwater duplicate; value suspect
R2M3	11/08/95	<0.100 <0.100	re-sample
R2M6	11/08/95	<0.100 <0.100	re-sample

Herbicides

The herbicide alachlor was detected in one injectate sample. A concentration of 0.340 µg/L was detected in the sample collected June 30, 1994 from the R03 site. Alachlor has a MCL of 2.00 µg/L.

Two herbicides, trifluralin and pendimethalin, were detected periodically in injectate and groundwater samples. Trifluralin (Treflan) was detected in 14 out of 41 injectate samples at all of the recharge sites (Table 19). The highest level detected in injectate was 0.83 µg/L. Trifluralin was detected in groundwater during the first two sample periods in 1994, with 0.54 µg/L being the highest level. Neither injectate nor groundwater samples exceeded trifluralin's lifetime HAL of 5.0 µg/L.

Pendimethalin (Prowl) was detected in 6 out of 41 injectate samples, with 7.12 µg/L being the highest level (Table 20). It was detected in groundwater samples from the R02 and R03 sites during Sample Period II in 1994. The highest level reported in groundwater was 1.23 µg/L. EPA does not list an MCL or HAL for pendimethalin. However, Arizona has a MCL of 280 µg/L.

Trifluralin and pendimethalin are the most widely used herbicides in the study area. These dinitroanaline herbicides are applied primarily in the spring, and are used for pre-emergent and weed control for cotton. Trifluralin is moderately volatile, and must be incorporated into the soil to reduce vapor loss and obtain maximum weed control effectiveness. Pendimethalin is applied with soil surface spray.

Because both trifluralin and pendimethalin have very low water solubilities and high soil retention, they tend to stay at the soil surface and are carried off in the sediment phase of runoff. Thus, they both have a large runoff potential. Trifluralin and pendimethalin have moderate longevities, with half-lives in soil of 60 and 90 days, respectively. Their presence in groundwater is most likely due to direct injection of runoff containing sediment and suspended solids.

Cyanide

Sample results for cyanide are listed in Table 21. Cyanide was detected in all baseline groundwater samples collected on July 28, 1992. The highest level detected was 0.675 mg/L, which is above the MCL of 0.20 mg/L.

Cyanide was detected periodically in injectate samples. The cyanide concentrations in injectate samples collected during Sample Period I in 1995 were above the MCL. Duplicate samples from the R04 site had a large discrepancy, leading to suspicion of the accuracy of the laboratory analysis. The injectate was resampled for cyanide during a subsequent recharge event that sampling period. Duplicate samples were sent to the Oklahoma City/County Health Department Laboratory. Sample results from the City/County laboratory were below the lab's detection limit of 0.005 mg/L, while sample results from the ODEQ laboratory were below, equal to, or slightly above its detection limit of 0.01 mg/L.

The MCL was again exceeded, with a concentration of 0.203 mg/L, in a sample taken from the R04 site during Sample Period II in 1996. Except for the baseline sampling, groundwater was not routinely sampled for cyanide. However, groundwater samples were collected for cyanide analysis from the R04 site during Sampling Period III in 1996. The samples were analyzed by the City/County lab due to equipment problems at the ODEQ lab. Cyanide concentration were below the detection limit of 0.005 mg/L in all groundwater samples from the R04 site.

Possible sources of cyanide include hydrocyanic acid from Johnson grass (Phillips Petroleum, 1963) which is abundant at all sites, and illegal poisoning of animals such as coyotes. The large discrepancy in duplicate samples suggests possible laboratory errors.

WATER QUALITY IMPACTS

The general water quality of the aquifer appears to improve after recharge. This is due to the fact that recharge water, in contrast to the mineralized groundwater, is generally low in dissolved solids. As fresh water is introduced into the aquifer, gypsum and dolomite dissolve, causing calcium, magnesium and sulfate concentrations to increase until the water becomes saturated with respect to gypsum and dolomite, and returns to equilibrium. Because the after-recharge samples were collected within ten days of a recharge event, these changes reflect short-term dilution effects on the aquifer and do not necessarily reflect long-term effects.

Statistical analysis of general-chemistry constituents indicates that concentrations of most parameters either decreased after recharge or did not significantly change. TDS, which is a good indicator of general water quality, decreased as much as 1,000 mg/L. The decrease in TDS was statistically significant at four of the sites. A decrease in nitrate

Table 19. Trifluralin (Treflan) in injectate and groundwater samples

YEAR	SAMPLE PERIOD	R01		R02		R03		R04		R05	
		INJ	GW	INJ	GW	INJ	GW	INJ	GW	INJ	GW
1992 Baseline	I		<0.020		<0.020		<0.020		<0.020		<0.020
	II		<0.020		<0.020		<0.020		<0.020		<0.020
	III		<0.020		<0.020		<0.020		<0.020		<0.020
1993	II		ND		ND		ND		ND		ND
	III		ND		ND		ND		ND		ND
1994	I	<0.020	ND	<0.020	ND	<0.020	ND	0.830	YES^{1}		ND
	II		ND	0.330	YES^{2}	0.330	YES^{3}	0.490	YES^{4}	0.410 0.420	YES^{5}
	III	<0.020	ND		ND		ND	<0.020	ND	<0.020	ND
1995	I	<0.020	ND	<0.020	ND	<0.020	ND	<0.020	ND	<0.020	ND
	II	<0.020 <0.020	ND	0.250	ND	0.077 0.230	ND	0.127	ND	0.045	ND
	III	<0.020	ND	<0.020	ND	<0.020	ND	<0.020 0.090	ND	<0.020	ND
1996	I	0.110	ND	0.460	ND	0.720	ND	<0.020	ND	0.230	ND
	II	<0.020	ND	<0.020	ND	<0.020	ND	<0.020	ND	<0.020	ND
	III	<0.020	ND	<0.020	ND	<0.020	ND	<0.020	ND	<0.020	ND
Times Sampled		8	14	8	14	8	14	9	14	8	14
Times Detected		1	0	3	1	3	1	4	2	3	1

(See Table 22 for legend)

Table 20. Pendimethalin (Prowl) in injectate and groundwater samples

YEAR	SAMPLE PERIOD	R01		R02		R03		R04		R05	
		INJ	GW	INJ	GW	INJ	GW	INJ	GW	INJ	GW
1992 Baseline	I		<0.100		<0.100		<0.100		<0.100		<0.100
	II		<0.100		<0.100		<0.100		<0.100		<0.100
	III		<0.100		<0.100		<0.100		<0.100		<0.100
1993	II		ND		ND		ND		ND		ND
	III		ND		ND		ND		ND		ND
1994	I	<0.100	ND	<0.100	ND	<0.100	ND	<0.100	ND		ND
	II		ND	<0.100	YES[1]	4.000	YES[2]	<0.100	ND	<0.100	ND
	III	<0.100	ND		ND		ND	<0.100	ND	<0.100	ND
1995	I	<0.100	ND	<0.100	ND	<0.100	ND	<0.100	ND	<0.100	ND
	II	<0.100	ND	3.200	ND	1.630 <0.100	ND	0.588	ND	<0.100	ND
	III	<0.100	ND	<0.100	ND	<0.100	ND	1.970 0.260	ND	<0.100	ND
1996	I	<0.100	ND	5.400	ND	7.120	ND	<0.100	ND	2.370	ND
	II	<0.100	ND	<0.100	ND	<0.100	ND	<0.100	ND	<0.100	ND
	III	<0.100	ND	<0.100	ND	<0.100	ND	<0.100	ND	<0.100	ND
Times Sampled		8	14	8	14	8	14	9	14	8	14
Times Detected		0	0	2	1	3	1	2	0	1	0

(See Table 22 for legend)

Table 21. Cyanide in injectate and groundwater samples

YEAR	SAMPLE PERIOD	R01		R02		R03		R04		R05	
		INJ	GW	INJ	GW	INJ	GW	INJ	GW	INJ	GW
1992 Baseline	I										<0.010
	II		0.044		0.066		0.027		0.058		0.675
	III		<0.010		<0.010		<0.010		<0.010		<0.010
1993	II										
	III										
1994	I	<0.010		<0.010		<0.010		<0.010			
	II			0.019		0.025		0.021		0.025 0.022	
	III	0.110 0.014						0.010 0.011		0.024	
1995	I	0.355				0.762		0.027 0.289			
	I Resample	0.130[1] <0.005[2]		0.010[1] <0.005[2]		0.010[1] <0.005[2]		<0.010[1] <0.005[2]		<0.010[1] <0.005[2]	
	II	0.050		0.030		<0.010		<0.010		0.010	
	III	0.106		0.010		<0.010 <0.010		<0.010 <0.010		0.051 0.044	
1996	I	<0.010		0.04		0.025		0.025		0.020	
	II	<0.010		<0.010		0.018		0.203		0.010	
	III	<0.010		0.02		<0.010	<0.005[2]	<0.010	<0.005[2]	0.020 0.030	<0.005[2]

(See Table 22 for legend)

Table 22. Legend for Tables 19, 20, and 21

TRIFLURALIN (TREFLAN)

Units μg/L

HAL: 5.0 μg/L

ND: not detected with herbicide/pesticide scans

< less than detection limit

1	R4M3	0.540	
	R4M6	0.340	
2	R2M1	0.210	
	R2M2	0.220	
	R2M6	0.120	
3	R3M1	<0.010	
	R3M2	0.100	
	R3M6	0.050	
4	R4M3	0.140	0.074
	R4M6	0.080	
5	R5M3	0.210	

PENDIMETHALIN (PROWL)

Units μg/L

AZ MCL: 280 μg/L

ND: not detected with herbicide/pesticide scans

< less than detection limit

1	R2M1	0.580
	R2M3	0.750
	R2M6	0.690
2	R3M2	0.410
	R3M6	1.230

CYANIDE

Units: mg/L

MCL: 0.200 mg/L

< less than detection limit

1 ODEQ Laboratory results

2 Oklahoma City/County Laboratory results

occurred at all five sites, but was statistically significant at only two sites. A few parameters (TSS, phosphorus, calcium, and potassium) increased after recharge at some sites. Phosphorus increased at four sites, but this may be due to adsorption to suspended solids.

Several trace element analyses exceeded their respective MCL in groundwater and injectate samples. These trace element results generally correspond to samples with high TSS, suggesting the elements were bound to the clay and were not mobile in water.

Low levels of pesticides were periodically detected in groundwater and injectate, but did not persist over time. The most commonly found herbicides were trifluralin and pendimethalin, which are used for pre-emergent control of grass and weeds. Concentrations of both herbicides were below regulatory levels. Methyl parathion, an organophosphorus insecticide, was detected once in groundwater samples from two wells.

Low levels of VOCs and cyanide were also detected periodically. Toluene, xylene, 1,2,4-trimethylbenzene, 1,1,1-trichloroethane, and chloroform were detected in a few groundwater and injectate samples. Concentrations were significantly below the MCLs. Cyanide exceeded the MCL once in the baseline groundwater samples and twice in post-recharge samples. Laboratory error is suspected for some results.

In summary, no harmful effects of the project on the quality of the Blaine aquifer were detected. Although low levels of pesticides and VOCs were periodically detected in groundwater, they did not persist over time. A positive impact of the recharge operations was the short-term improvement of the quality of the aquifer as recharge water diluted the highly mineralized groundwater.

Economic Evaluation

COST OF RECHARGE

Overall costs of recharge are low due to the lack of expensive injection equipment and low operation and maintenance costs. Excluding monitoring costs, which are not required for Class V injection wells in Oklahoma, the cost of recharge would include the test drilling, design, construction, purchase of lands, operation and maintenance, and water rights permits.

A major factor in estimating the cost of recharge is the life of the recharge well. Records for the District's recharge wells do not exist; however, District personnel have stated that a 15-year life span for a recharge well is reasonable. Taking into account differences in design, the recharge wells that are a part of the demonstration project are expected to last a minimum of 20 years. Therefore, estimated cost of recharge over a 20-year life of a recharge well is $2,731 per year. Cost of recharge for the site where land was purchased and a diversion pond was constructed is higher, at $8,210 per year.

The cost per acre-foot of water recharged will vary based on the amount of water a particular recharge well injects into the aquifer. The amount of water injected is controlled by the volume of surface runoff, the amount of runoff captured by the well, well capacity, and aquifer storage capacity. During this study, the five recharge wells injected an average of 70 acre-feet per year.

ASSESSMENT OF ECONOMIC FEASIBILITY

Water from the Blaine aquifer is used exclusively for irrigation of crops, primarily cotton, wheat, peanuts and alfalfa. Irrigated cotton accounts for more than 90 percent of the irrigated crops produced within the study area. Irrigated cotton may be used as the standard for determination of revenue generated by irrigation within the project area, since it is the dominant crop type. Within the study area, 355 irrigation wells are used to irrigate up to 52,143 acres of land.

The average yield of irrigated cotton for 1995 was 291 pounds per acre of land (Oklahoma Agricultural Statistics Service, 1995). According to the publication "Oklahoma Crop Values 1996", during 1995 cotton sold for 0.735 dollars per pound. Therefore, an acre of irrigated cotton would generate $214 of marketable cotton.

Long-term averages show that 15 inches, or 1.25 acre-feet, per year of irrigation water is required to raise irrigated cotton in Harmon County (Bureau of Reclamation, 1986). Therefore, each recharge well can inject enough water into the aquifer to irrigate approximately 56 acres of land. The annual average 70 acre-feet per well of stored water recharged from the project operations has a calculated value of $11,980 crop production. These estimates of crop production value do not take into account other production costs, but only represent the 1995 market value of the crop produced on that amount of land. Averaging these values results in a value of $171 for an acre-foot of water.

The average cost per recharge well is estimated to be $2,899 per year averaged over an expected 20 year life for each of the five recharge sites. Costs include the test drilling, purchase of land, and construction. Tables 23 and 24 summarize these costs and characterize the costs in terms of the value of recharge for 1,000 gallons of water. This cost, divided by the average amount of water recharged, results in a cost of $0.13 per 1,000 gallons of water recharged. Assuming 100 percent recovery of the recharge water, the value of the water based on the crops grown is $0.53 per 1,000 gallons of water used.

Table 23. Estimated cost of recharge

Average Construction Cost per Well ($ per year)	O&M ($ per year)	Total Average Cost for Recharge Well ($ per year)	Average Amount of Water Recharged (1,000 gallons)	Average Cost of Recharge ($ per 1,000 gallons)
$2,846.00	$53.00	$2,899.00	22,810	$0.13

Table 24. Estimated value of recharge

Average Amount of Water Recharged per Well (1,000 gallons)	Average Amount of Acres Irrigated with Average Recharge Amount (acres)	Value of Crops Grown 56 Acres of Land ($)	Value of Irrigation Water ($ per 1,000 gallons)
22,810	56	$11,980.00	$0.53

In conclusion, using gravity-flow recharge wells to augment groundwater supplies is very cost effective, largely because water treatment is not required. Operation and maintenance costs are therefore very low. The average annual cost of recharge is $2,899 per well, including the cost of construction, operation and maintenance. The value of irrigation water is estimated to be $0.53 per 1,000 gallons of water pumped, and the cost of recharge is calculated to be $0.13 per 1,000 gallons of water recharged. This provides a benefit-to-cost ratio of greater than four to one.

Recommendations and Conclusions

RECOMMENDATIONS

The amount of recharge captured by the wells could be increased by making minor modifications to some sites. Small retention structures placed downstream of some project wells may enable the wells to capture more runoff. The R03 site may benefit from a low water dam, and the R02 and R04 sites from small berms. Because the primary limitation at the R05 site is the tight rock formation with poor fracture development, the R5 recharge well may benefit from well development or hydrofracturing.

Recharge volume could be increased further by installing additional recharge wells and retention structures in appropriate locations. The optimal area to drill new recharge wells is upgradient of or within irrigation pumping centers, where conditions for cavern development are most favorable, and where water depth is greater than 20 feet. A few wells with impoundments could recharge the same amount as more wells that do not have impoundments.

The following design features could be incorporated into new recharge wells to prevent dissolution in the shallow zones and subsequent well collapse:

- Pressure cement grout the entire annular space between the outer casing and wall of the hole.
- Add an inner string of casing.
- Cement grout the annular space between the inner and outer casing.

The aquifer's storage capacity could be protected by using erosion control measures to decrease the high sediment load in the recharge water.

The technology used in this project is limited to karst aquifers. It is particularly suitable for the Blaine aquifer, which is in a cavernous gypsum formation and is not used as a drinking water supply. The technology should be applicable to other karst aquifers in other regions. If the recharge project could affect a drinking water supply, pre-treatment of the injectate may be needed.

CONCLUSIONS

The Blaine Gypsum Groundwater Demonstration Project met its objectives:

- The project contributed an estimated total volume of 1,056 acre-feet of recharge water to the aquifer, with an average annual recharge volume per well of 70 acre-feet.

- No harmful effects of the project on the water quality of the Blaine aquifer were detected. A positive impact of the recharge operations was the short-term improvement of water quality of the aquifer as recharge water diluted the highly mineralized groundwater.

- The project demonstrated that artificial recharge using gravity-flow recharge wells in the Blaine aquifer is economically feasible, with a benefit-to-cost ratio greater than four to one. Operation and maintenance costs were very low, largely because water treatment was not required.

- The project has advanced the state-of-the-art technology in artificial recharge by documenting well design features and operational success.

The OWRB views artificial recharge as a water supply management tool that can be incorporated into long-range water resources planning. Results from this study will provide pertinent information in determining the maximum annual yield of the Blaine aquifer.

In conclusion, artificial recharge to the Blaine aquifer provides an effective method in offsetting seasonal and long-term water level declines. The wells augment groundwater supplies in an aquifer that is heavily pumped for irrigation. In times of drought, this management technique could help prevent wells from going dry and from inducing salt water from underlying formations. Recharge wells capture storm runoff that otherwise would leave the area and eventually flow into the Red River.

References

Asano, T. (ed.), 1985, Artificial Recharge of Groundwater: Butterworth Publishers, Stoneham, MA, 767 p.

Cederstrand, J.R., 1997, Digital Geologic Map of Lawton Quadrangle, Southwestern Oklahoma: U.S. Geological Survey Open-File Report 96-376.

Chow, V.T., 1964, Handbook of Applied Hydrology: McGraw-Hill Co., New York, NY.

Driscoll, F.G., 1986, Groundwater and Wells, Second Edition: Johnson Filtration Systems, Inc., St. Paul, MN, 1089 p.

ESRI (Environmental Systems Research Institute, Inc.), 1997, ARC/INFO Version 7.1.1: Redlands, CA.

Ford, D.C., and Williams, P.W., 1989, Karst Geomorphology and Hydrology: Unwin Hyman Inc., Winchester, MA, 601 p.

Fergusson Jack E., 1990, The Heavy Elements: Chemistry, Environmental Impact, and Health Effects: Pergamon Press, New York, 614 p.

Gebert, W.A., Graczyk, D.J., and Krug, W.R., 1987, Average Annual Runoff in the United States, 1951-80: U.S. Geological Survey, Atlas HA-710.

Havens, J.S., 1977, Reconnaissance of the Water Resources of the Lawton Quadrangle, Southwestern Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 6, 4 sheets, scale 1:250,000.

Johnson, K.S., 1985, Structure Contour Map and Stratigraphic/Hydrologic Data on the Blaine Aquifer in the Hollis Basin of Southwestern Oklahoma: Oklahoma Geological Survey.

_____1990a, Standard Outcrop Section of the Blaine Formation and Associated Strata in Southwestern Oklahoma: Oklahoma Geology Notes, vol. 50, p. 144-168.

_____1990b, Hydrogeology and Karst of the Blaine Gypsum-Dolomite Aquifer, Southwestern Oklahoma; Field Trip #15 Guidebook: Oklahoma Geological Survey Special Publication 90-5, 31 p.

NOAA (National Oceanic and Atmospheric Administration), 1992-1996, Climatological Data, Annual Summary, Oklahoma 1992-1996.

Oklahoma Agricultural Statistics Service, 1995, Oklahoma Agricultural Statistics, 1995, 104 p.

Phillips Petroleum Co., 1963, Pasture and Range Plants, p. 63.

Runkle, D.L. and Johnson, K.S., 1988, Hydrogeologic Study of a Gypsum-Dolomite Karst Aquifer in Southwestern Oklahoma and Adjacent Parts of Texas, U.S.A., *in* Karst Hydrogeology and Karst Engineering Protection: Geological Publishing House, Beijing, China, Proceedings of the IAH 21st Congress, Guilin, China, v. 21, pt. 2, p. 400-405.

Runkle, D.L. and McLean, J.S., 1995, Steady-State Simulation of Ground-Water Flow in the Blaine Aquifer, Southwestern Oklahoma and Northwestern Texas: U.S. Geological Survey Open-File Report 94-387, 92 p., 1 diskette.

Runkle, D.L. Bergman, D.L., and Fabian, R.S., 1997, Hydrogeologic Data for the Blaine Aquifer and Associated Units in Southwestern Oklahoma and Northwestern Texas: U.S. Geological Survey Open-File Report 97-50.

StatSoft, Inc., 1997, STATISTICA for Windows: Tulsa, OK.

Steele, C.E. and Barclay, J.E., 1965, Ground-Water Resources of Harmon County and Adjacent Parts of Greer and Jackson Counties, Oklahoma: Oklahoma Water Resources Board Bulletin 29, 96 p.

Tecsoft Inc., 1997, Plotchem for Windows: Fort Collins, CO.

USDA (United States Department of Agriculture, Soil Conservation Service Division), 1984, Soil Survey of Harmon County, Oklahoma.

USDA (United States Department of Agriculture, Natural Resources Conservation Service Division), 1989, Engineering Field Handbook, Chapter 2: Estimating Runoff and Peak Discharges.