LA-11332-MS

UC-202

Issued: August 1988

LA--11332-MS

DE89 002109

Water Supply at Los Alamos: Current Status of Wells and Future Water Supply

W. D. Purtymun
A. K. Stoker

Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

WATER SUPPLY AT LOS ALAMOS: CURRENT STATUS OF WELLS AND FUTURE WATER SUPPLY

by

W. D. Purtymun and A. K. Stoker

ABSTRACT

The municipal and industrial use of groundwater at the Los Alamos National Laboratory and Los Alamos County was about 1.5 billion gallons during 1986. From a total of 19 wells that range in age from 5 to 41 years, the water was pumped from 3 well fields. The life expectancy of a well in the area ranges from 30 to 50 years, dependent on the well construction and rate of corrosion of the casing and screen. Twelve of the wells are more than 30-years old and, of these, four cannot be used for production, three because of well damage (LA-1, LA-4, and G-3) and one (LA-6) because the quality of water is not suitable for use. Eight (LA-2, LA-3, LA-5, G-1, G-2, G-4, G-5, and G-6) of the twelve oldest wells are likely to be unsuitable for use in the next 10 years because of well deterioration and failure. The remaining 7 wells include 2 (LA-1B, G-1A) that are likely to fail in the next 20 years. Five of the younger wells in the Pajarito well field are in good condition and should serve for another two or three decades.

The program of maintenance and rehabilitation of pumps and wells has extended production capabilities for short periods of time. Pumps may be effectively repaired or replaced; however, rehabilitation of the well is only a short-term correction to increase the yield before it starts to decline again. The two main factors that prevent successful well rehabilitation are: (1) chemicals precipitated in the gravel pack and screen restrict or reduce the entrance of water to the well, which reduces the yield of the well, and (2) the screen and casing become corroded to a point of losing structural strength and subsequent failure allows the gravel pack and formation sand to enter the well. Both factors are due to long-term use and result in extensive damage to the pump and reduce the depth of the well, which in turn causes the yield to decline. Once such well damage occurs, rehabilitation is unlikely to be successful and the ultimate result is loss of the well. Two wells (LA-4 and G-3) were lost in 1987 because of such damage.

It is essential to implement a program to replace wells that have failed or will fail in the next 10 years to ensure a continued and reliable water supply. Any change in operation of the Laboratory or county that will require additional water adds to the urgency to develop a system of new wells. Rehabilitation of the older wells will not ensure a continued or reliable supply, or meet additional demands for water. This report presents the history of the wells and well fields, briefly describes the geology and hydrology of the area, includes a section on production and production capacity, and outlines development of additional water supply.

I. INTRODUCTION

A. Background

The Los Alamos National Laboratory and the communities of Los Alamos and White Rock are supplied by water pumped from deep wells in three well fields located in Los Alamos Canyon, Guaje Canyon, and on the Pajarito Plateau. These wells produce water from the main aquifer of the Los Alamos area that lies at depths varying from several hundred to more than a thousand feet below the mesa tops. The main aquifer is the only aquifer in the area that is capable of municipal and industrial water supply.

Water moves eastward through the aquifer from the major recharge area in the Valle Caldera, several miles west of Los Alamos, toward the Rio Grande, where a part is discharged into the river through seeps and springs. The upper surface of the main aquifer slopes gently downward through the lower part of the Puye Conglomerate beneath the central and western parts of the plateau and then through the Tesuque Formation down to the Rio Grande at the eastern margin of the plateau. The main aquifer is under water table conditions beneath the western and central part of the Pajarito Plateau; along the eastern margin and near the Rio Grande it is under artesian conditions.

This groundwater resource was developed as a result of the decision to make Los Alamos a permanent research facility after World War II. Water supply through the World War II period had been from surface water sources. During the winter of 1945-1946 surface water supply failed and for several weeks water had to be hauled from the Rio Grande. The U. S. Geological Survey began investigations in 1946 to develop a reliable water supply.

Studies were first made in the Valle Caldera, Valle Grande, and Valle Toledo, west of Los Alamos. The plan was to develop wells and transmission lines over the mountains to Los Alamos. The completion of test holes and aquifer tests indicated a potential water resource; however, the surface water and groundwater in the area were connected and pumping of the wells reduced stream flow. Fully appropriated surface water rights in the drainage area precluded use of the resource for water supply.

At the same time, additional studies were conducted north of Otowi along the Rio Grande and in the lower part of Los Alamos Canyon. These studies indicated that a water supply could be developed in lower Los Alamos Canyon.

The original six wells in the Los Alamos field were drilled and completed from 1946-1948. An additional well was completed in 1960. Water from the Los Alamos field is lifted vertically about 1,800 ft through four booster stations into storage to serve both Laboratory and community areas.

Water usage at the Laboratory and the community during the late 1940s continued to increase, and to meet this increased need, five wells were completed in 1950 and 1951 to form the Guaje Canyon field. Two wells were added to the field to replace declining yield of older wells in 1954 and 1965. Water from the Guaje field is lifted vertically about 1,500 ft through four booster stations into storage, mainly serving the northernmost community areas.

The Pajarito field consisting of five wells was developed from 1965-1982 to supply increased demand for water and to supplement the declining production from the wells in the Los Alamos and Guaje well fields. There are three booster stations that can lift water to White Rock or the Laboratory and the townsite area.

A small amount of the original surface water sources are still used for water supply. In 1986 this amounted to about 4% of the total production or about 28×10^6 gal.

The wells in the three well fields range in age from 5 to 41 years. Declining production from deteriorating wells in the Los Alamos and Guaje fields in the past few years has become significant. Recent attempts to rehabilitate older wells to restore production have failed and focus concern on the need for a comprehensive plan to ensure a reliable water supply for the long term. The purpose of this report is to review and evaluate the condition of the wells and well fields as to their reliability to meet future water demands. A rationale for constructing new wells is based on these conclusions and understanding of the geohydrology of the area.

B. Geology and Hydrology

The geology and hydrology of the wells and well fields have been presented in detail in another report (Purtymun 1984a). A summary of the major geologic and hydrologic features is included through a series of figures appearing in that report. These figures will provide information for discussions of the wells and well fields in this report and can be referenced as a basis for understanding the geohydrology. Fundamental geologic and hydrologic data were compiled from observations and measurements from supply wells, stock wells, and test holes completed in the main aquifer or springs that discharge from the main aquifer (Fig. 1). The geologic data were used to prepare a diagrammatic section of geologic units (Fig. 2) and a geologic section showing the stratigraphy and structure from the Sierra de los Valles across the Pajarito Plateau to the Rio Grande (Fig. 3). The section shows the top of the main aquifer and its relation to the geologic units. The depth to water in the main aquifer was used to determine and map the surface of the main aquifer essential to defining the hydrologic gradient of the groundwater (Fig. 4). Interpretations of aquifer tests performed in the supply wells and test holes provided the basis for

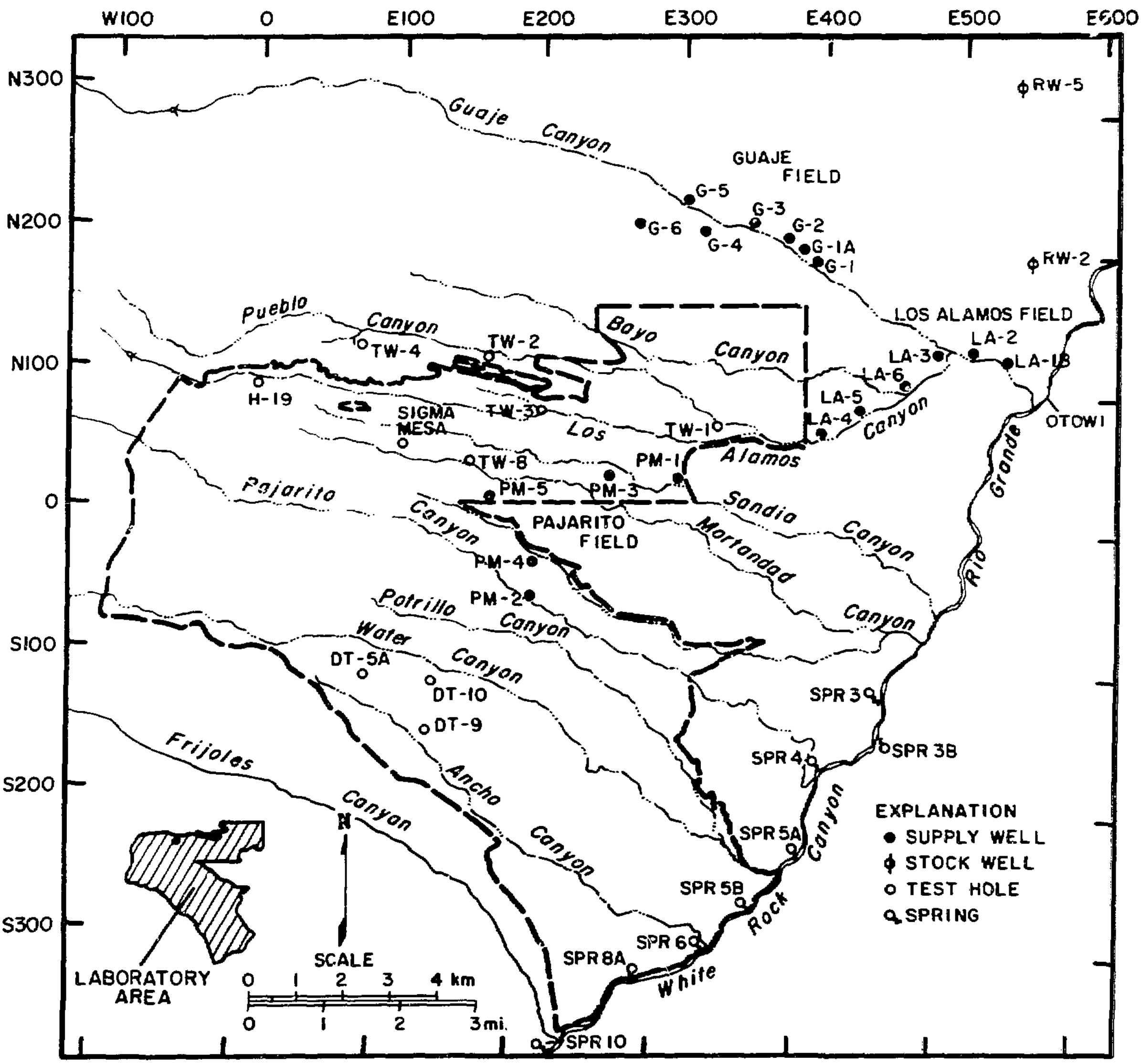

Figure 1. Location of supply, test, and stock wells completed or spring discharging from the main aquifer.

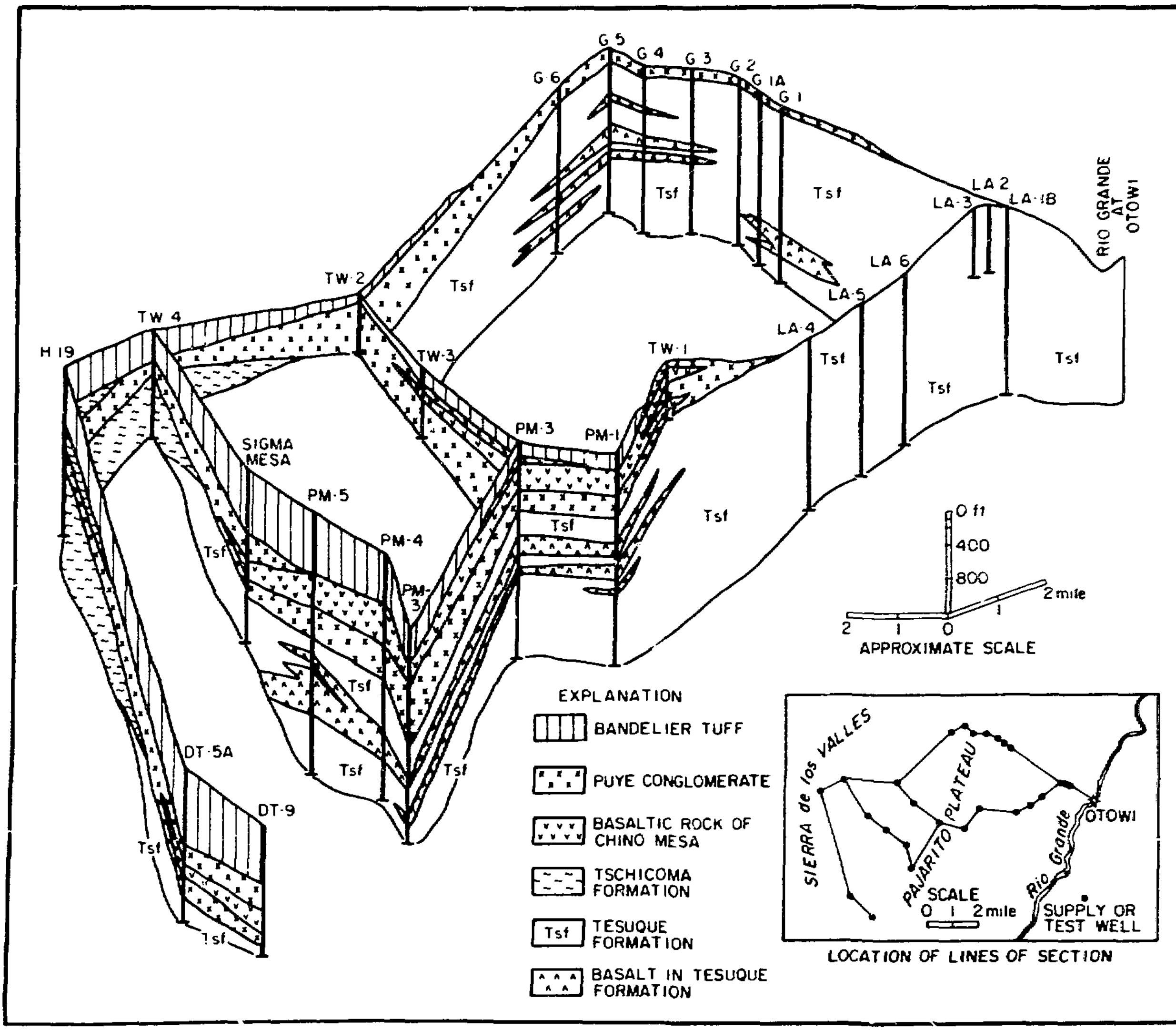

Figure 2. Diagrammatic section of geologic units in the Los Alamos area.

defining the hydrologic characteristics of the main aquifer (Fig. 5). The movement of water in the aquifer was inferred by combining the gradient and the hydrologic characteristics of the aquifer. Movement is basically perpendicular to the water surface contours, generally to the east and southeast toward the Rio Grande with estimated rates of flow in the aquifer ranging from about 20 to about 350 ft/yr (Fig. 6). Periodic water level data were used to determine trends of water level declines in wells or test holes completed in the main aquifer (Fig. 7). Water-level declines related to production are used for comparison of production per ft of water-level decline in the Los Alamos and Guaje fields and wells PM-1, PM-2, and PM-3 of the Pajarito field (Fig. 8). The basic chemical quality and graphic depiction of principal chemical quality parameters determined by analysis of samples from supply wells, test holes, stock wells, and springs shows basic similarity throughout the main aquifer (Figs. 9 and 10).

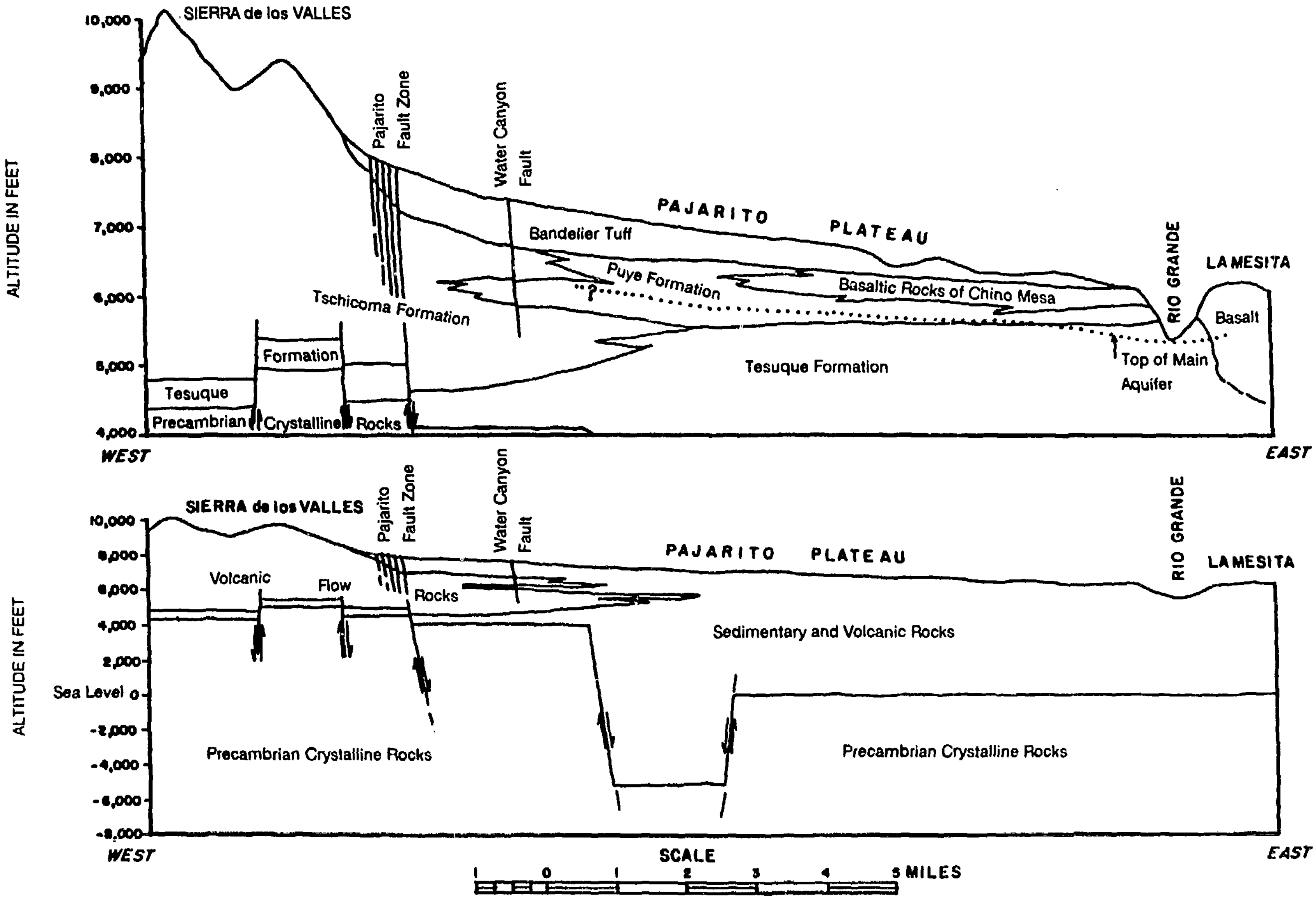

Figure 3. Geologic section showing stratigraphy and structure from the Sierra de los Valles, across the Pajarito Plateau to the Rio Grande.

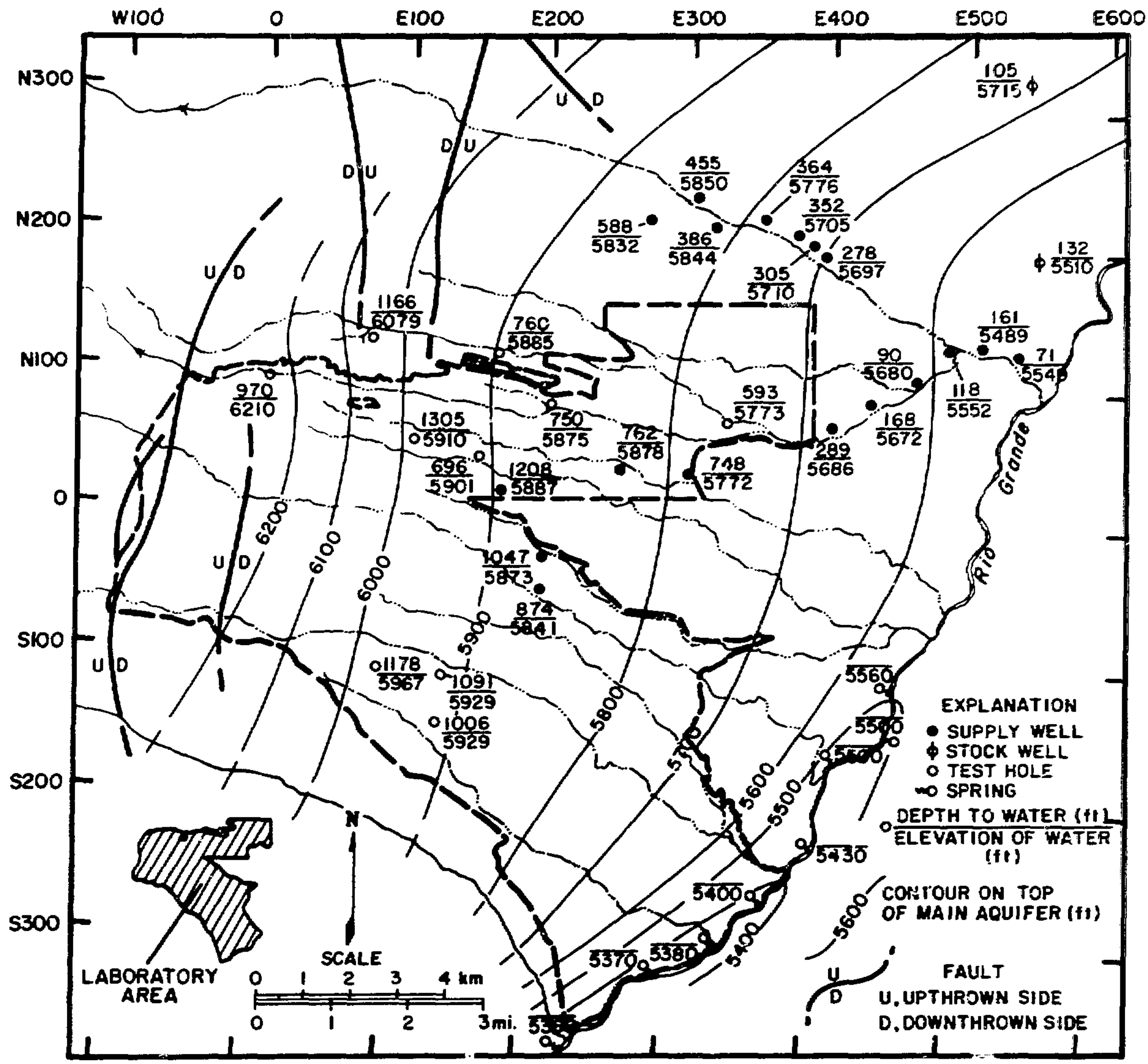

Figure 4. Generalized contours on the surface of the main aquifer.

C. Data Sources

The data presented in this report have been collected from a number of published and unpublished reports, unpublished notebooks, and operating records. Reports include the "Summary of Los Alamos Municipal Well Field Characteristics, 1947-1971" (Purtymun 1972) and the series of annual water supply reports covering the years 1972-1987 (Purtymun 1972a-1987). Other reports included Theis (1962), Cushman (1965, 1975), Purtymun (1977), and Purtymun (1984a). Well-field development and well locations were described in two reports from the U.S. Geological Survey (Purtymun 1965, 1969). A description of early developments of the Los Alamos and Guaje well fields is found in Griggs (1964) and Black (1951). Some data were taken from planning reports (Herkenhoff 1974; Keiser 1984). Measuring points of the various wells and well conditions were taken from an unpublished notebook from the U. S. Geological Survey. Notes and data collected during well rehabilitation or testing of the wells were reviewed. Notes and video tapes taken

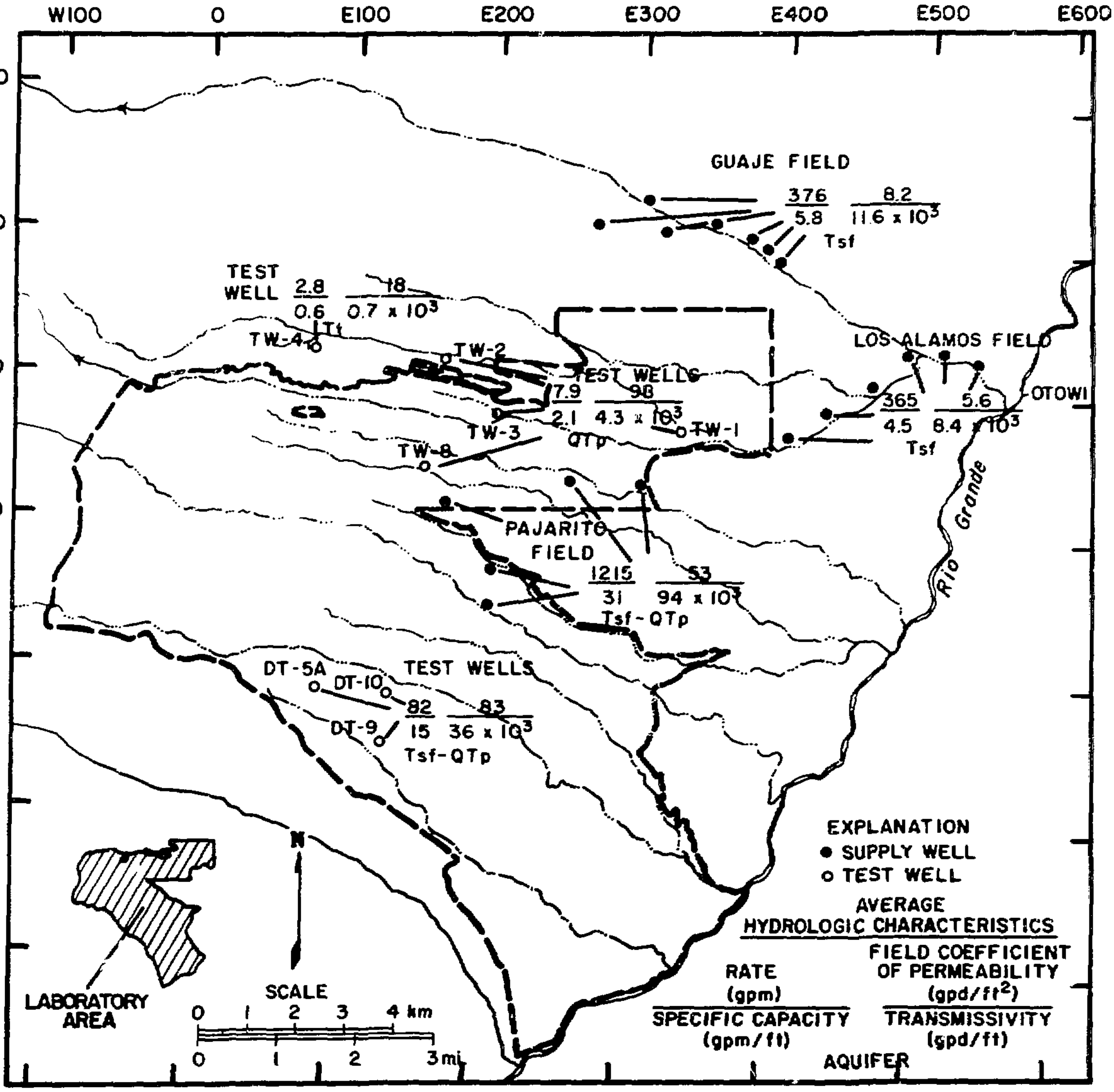

Figure 5. Hydrologic characteristics of the main aquifer.

while video logs were run in a number of wells provided details on well conditions. Some well data, mainly the depth setting of pumps, came from unpublished records of the Pan Am Utility Division.

II. WELL CONSTRUCTION AND REHABILITATION

Some of the important and unique characteristics of particular wells or groups of wells are directly dependent on the original techniques used for their construction. Much of the present understanding of well deterioration comes from observations related to well rehabilitation efforts over the years. This section provides summary descriptions of well construction techniques and rehabilitation as background to understanding subsequent discussions of individual well histories.

A. Well Construction

Three basic methods of well construction have been employed for the water production

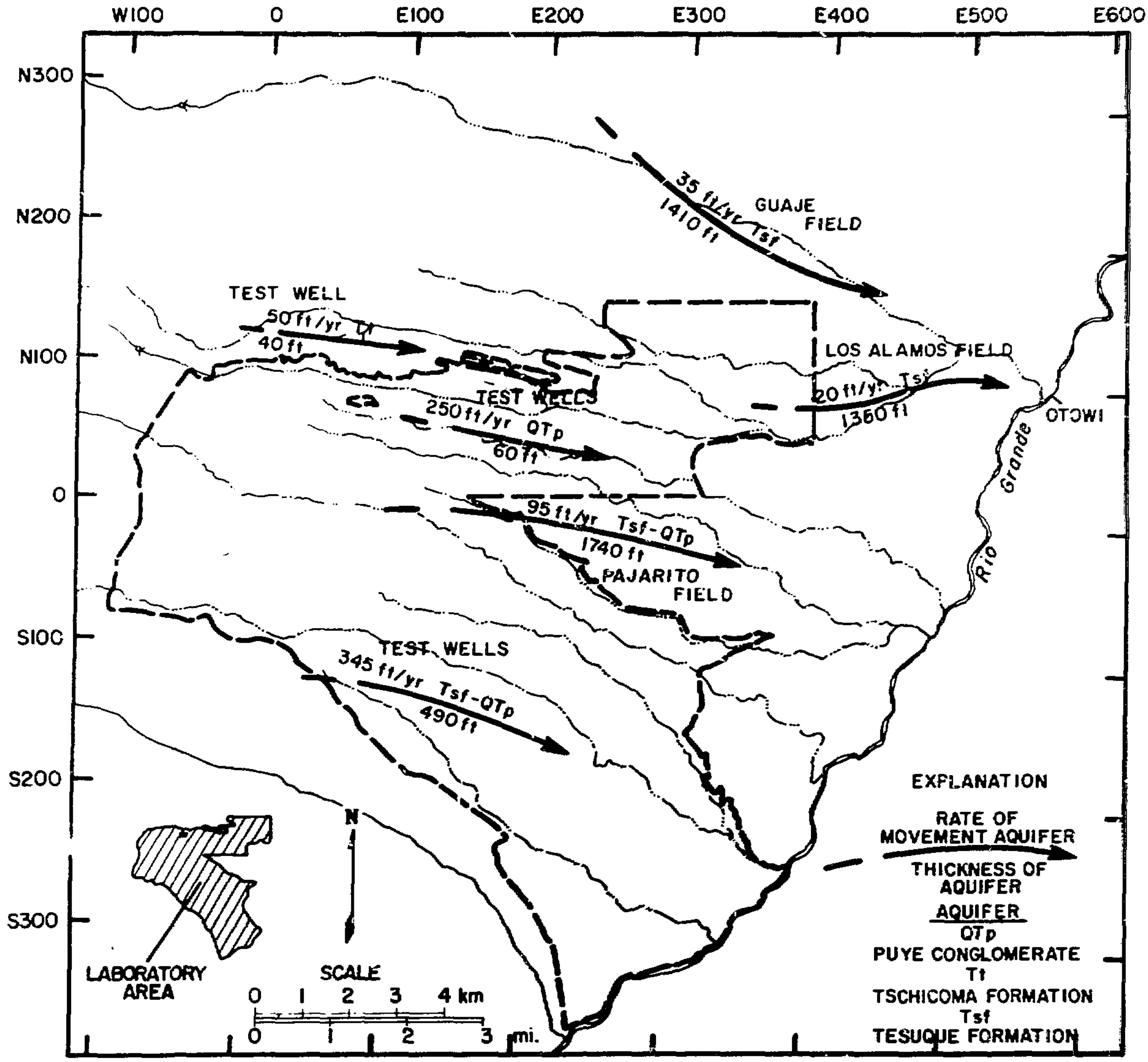

Figure 6. Rate of movement of water in the main aquifer.

wells. They generally correspond to specific time periods and reflect some evolution of understanding of the most effective methods for the local geohydrologic conditions.

Basic data on the construction of individual wells are presented in Table 1. This includes the year of completion, the total drilled depth of the pilot hole, the depth to which casing was installed, and the total length of screen or perforated casing installed. Additional information includes the most recent measurement of the depth to which sand has filled the well and the length of screen or perforations that remain uncovered. Additional detailed data on the individual well casing and screen parameters are summarized in Table 2.

Wells LA-1, -2, and -3 were constructed by drilling 16- or 19-in.-diameter holes. Geophysical logs were used to determine the depths of the most permeable zones of the aquifer. Sections of 12-in.-diameter screen were set opposite the permeable zones alternating with 10-in. slotted casing between the screen sections. The wells were gravel packed.

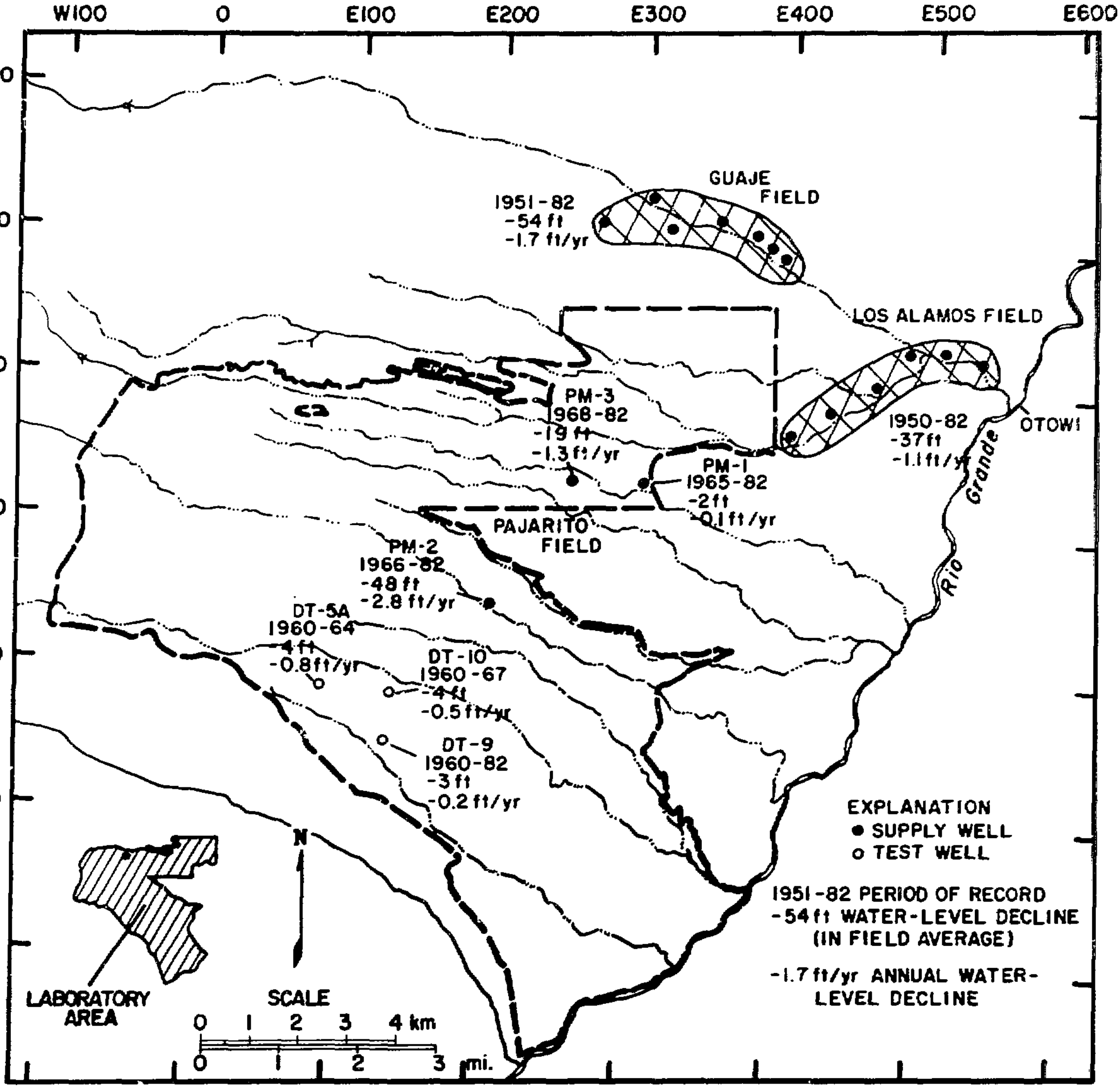

Figure 7. Water-level declines in well fields, supply, and test wells.

Wells LA-4, -5, and -6 in the Los Alamos field and wells G-1, -2, -3, -4, and -5 were started with a 20-in.-diameter surface casing (blank casing used to shut out shallow water) set and cemented in a 22-in.-diameter hole to a depth sufficient to seal out surface and near surface groundwater. Then an 11-1/2-in.-diameter pilot hole was drilled to the total depth of the well. It was reamed to 19-in.-diameter to the total depth of the pilot hole or a depth including the most permeable section of the aquifer. Selected depths opposite the most permeable zones in the aquifer were determined from geophysical logs. The intervals including these zones were underreamed to 27-in.-diameter and well screen sections placed opposite those zones. Blank casing is in the intervening zones. The wells were packed by pumping gravel through a drop line between the annulus of the hole and the casing or screen. This resulted in different thicknesses of the gravel pack in the well and is now believed to be poor design in well construction. The gravel pack will not settle and clean up during development because the gravel pack will separate in the sections of blank casing

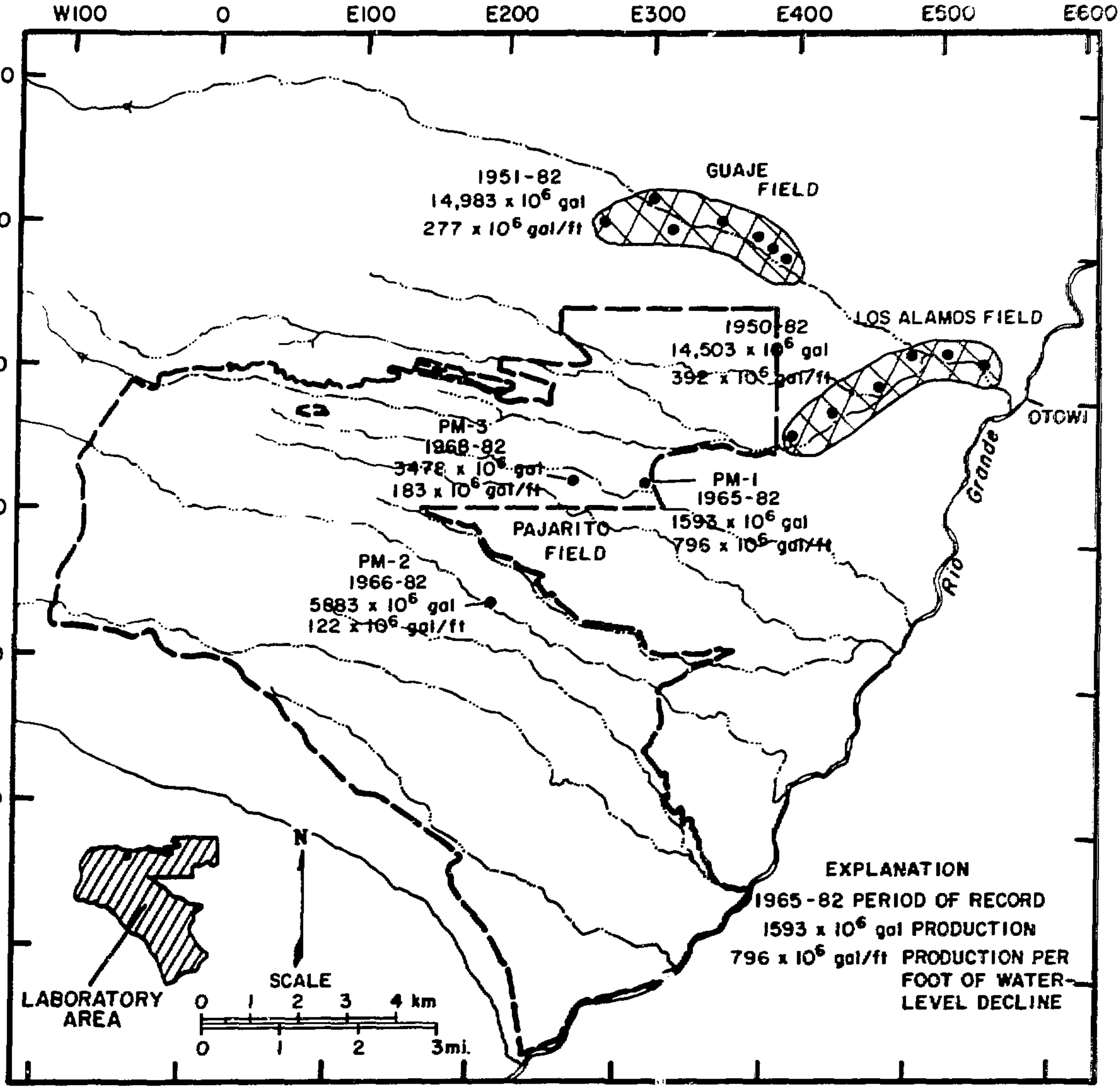

Figure 8. Water-level declines related to production from well fields and supply wells.

between sections of screen. Video logs of wells where several louvers were missing show that no gravel pack remains between the screen and hole wall. There was no apparent movement of gravel from the upper part of the well pack in the surface casing.

Well LA-1B was constructed in essentially the same fashion with two exceptions: the entire depth to be cased was reamed to 27-in.-diameter, and perforated casing was used instead of well screen.

The casing in these Los Alamos and Guaje wells is reduced from 12-in.- to 10-in.-diameter at depths well below the pump intake setting (Table 2). The 12-in.-diameter casing is necessary to allow setting of the line shaft turbine pump. Experience has shown that the intake to the pump should be set in blank casing. If the pump intake is set in the screen, the backwash from the pump, when it is shut off, will cause cavitation in the gravel pack, resulting in gravel pack separation in the screen opposite the pump intake. Formation

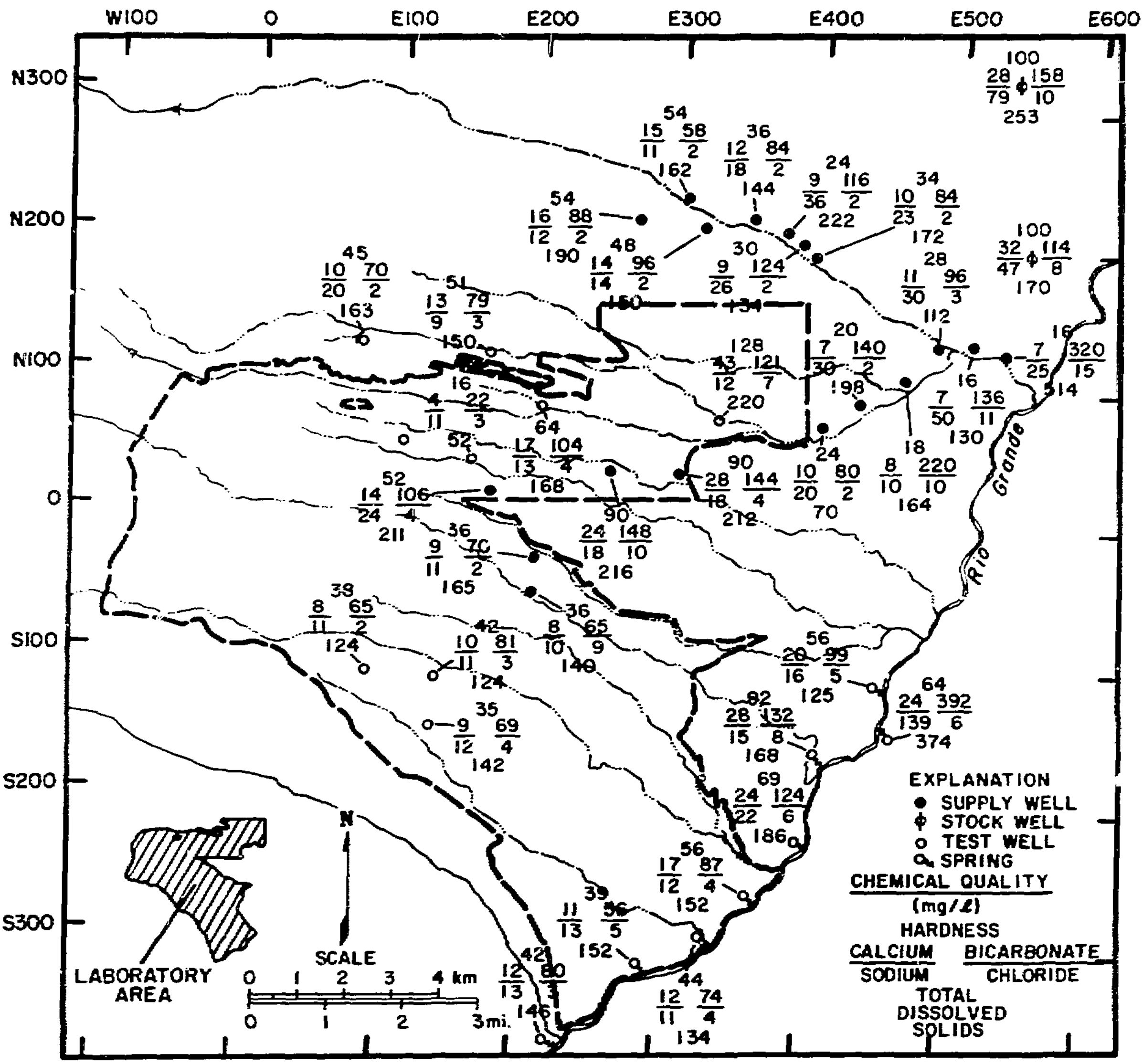

Figure 9. Chemical quality of water from springs, supply, test, and stock wells.

sand and gravel from the gravel pack will enter the well when the pump is restarted.

Well C-6 and all the wells in the Pajarito field were constructed by starting with a large diameter surface string cemented to keep out surface water. Then a 9-1/2-in.- or 11-1/2-in.-diameter pilot hole was drilled to total depth. Geophysical logs indicating permeable sections of the aquifer were used to determine completion depth of the well. The well was then reamed uniformly to completion depth to a diameter of 27-in. or 29-in. The well was cased with blank pipe to a depth of about 100 ft below the estimated pump setting. Continuous well screen was set extending to the bottom of the well. The casing and screen are uniform diameter for the entire depth, depending on the well, 12-, 14-, or 16-in.-diameter from top to bottom. The uniform thickness of gravel pack and the continuous screen in the lower part of the hole allowed better development of the wells and allows the gravel pack to move readily to fill voids. Separation of the gravel pack is less likely with this type of construction.

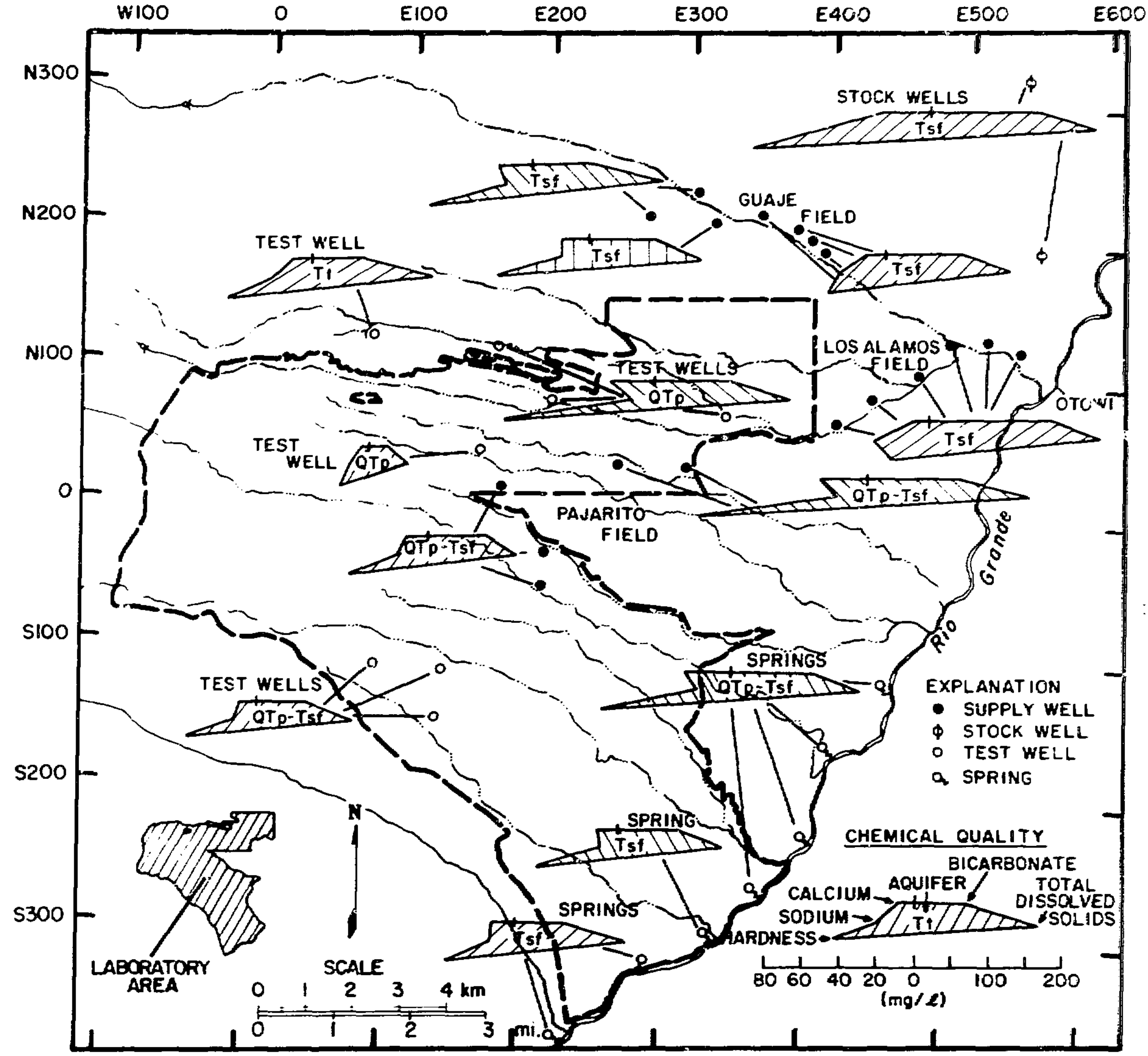

Figure 10. Graphic comparison of chemical constituents in water from springs, supply, test, and stock wells.

Well G-6 and all the wells in the Pajarito field are constructed with a 5 ft length of blank casing welded to the bottom of the screen. The end of the pipe is welded closed with a steel plate. At least 30 ft of sediments and scale should be left in the well to prevent the sand pump or bailer from damaging or separating the casing by bumping the steel plate.

B. Well Deterioration and Rehabilitation

Well yields decline over a period of time for various reasons. Chemical precipitation, especially calcium carbonate, in the gravel pack and screen tend to restrict the entrance of water into the well. The calcium carbonate formation in the

Table 1. Well Construction

	Completion Year	Depth of Pilot Hole (ft)	Cased Depth (ft)	Length of Screen or Perforation (ft)	Depth Open (ft)	Length of Screen or Perforation Open (ft)	Percentage of Screen or Perforation Open (%)
Los Alamos Field							
Well LA-1	1946	1001	870	805	598 (60)	538 (60)	67
LA-1B	1960	2256	1750	591	1655 (83)	576 (83)	97
LA-2	1946	882	870	760	878 (62)	568 (63)	75
LA-3	1947	910	870	760	816 (83)	701 (83)	92
LA-4	1948	2019	1964	400	1907 (88)	378 (87)	95
LA-5	1948	2024	1750	400	1954 (62)	400 (62)	100
LA-6	1948	2030	1710	400	1200 (76)	210 (76)	53
Guaje Field							
Well G-1	1950	2002	2000	490	1750 (62)	420 (62)	86
G-1A	1954	2071	1519	563	1500 (73)	553 (73)	98
G-2	1951	2006	1970	425	1707 (81)	385 (81)	91
G-3	1951	1997	1792	400	1238 (88)	280 (87)	70
G-4	1951	2002	1930	360	1172 (81)	180 (81)	50
G-5	1951	1997	1840	400	703 (86)	100 (86)	25
G-6	1964	2005	1530	825	1480 (79)	790 (79)	96
Pajarito Field							
Well PM-1	1965	2501	2499	1549	2479 (73)	1534 (73)	99
PM-2	1965	2600	2300	1291	2280 (87)	1276 (87)	99
PM-3	1966	2552	2552	1591	2552 (66)	1591 (66)	100
PM-4	1981	2920	2875	1594	2875 (81)	1594 (81)	100
PM-5	1982	3120	3093	1632	3093 (82)	1532 (82)	100

Note: Numbers in parentheses indicate year of measurement.

Table 2. Well Casing and Screen

	Casing and Screen Diameter	Depth to Pump Intake Setting (ft)	Depth to Top of Upper Screen (ft)	Depth to Bottom of Lowest Screen (ft)	Location of Pump Intake Setting
Los Alamos Field					
Well LA-1	12-in. to 465, alternate 10" and 12" to 870	--	60	865	--
LA-1B	12-in. to 650 ft; 10-in. to 1750 ft	360	326	1694	Blank
LA-2	12-in. to 495, alternate 10" and 12" to 870	380	105	865	Screen
LA-3	12-in. to 445, alternate 10" and 12" to 870	340	105	865	Screen
LA-4	12-in. to 754 ft; 10-in. to 1965 ft	460	754	1964	Blank
LA-5	12-in. to 580 ft; 10-in. to 1750 ft	500	440	1746	Blank
LA-6	12-in. to 600 ft; 10-in to 1790 ft	300	420	1778	Blank
Guaje Field					
Well G-1	12-in. to 490 ft; 10-in. to 2000 ft	465	490	1980	Blank
G-1A	12-in. to 663 ft; 10-in. to 1519 ft	496	563	1513	Screen
G-2	12-in. to 600 ft; 10-in. to 1970 ft	500	425	1960	Blank
G-3	12-in. to 695 ft; 10-in. to 1792 ft	500	400	1785	Blank
G-4	12-in. to 720 ft; 10-in. to 1930 ft	610	360	1925	Blank
G-5	12-in. to 739 ft; 10-in. to 1840 ft	600	400	1830	Blank
G-6	12-in. to 1530 ft	710	825	1525	Blank
Pajarito Field					
Well PM-1	12-in. to 2499 ft	900	945	2494	Blank
PM-2	14-in. to 2300 ft	950	1004	2295	Blank
PM-3	14-in. to 2552 ft	830	956	2547	Blank
PM-4	16-in. to 2875 ft	1150	1260	2854	Blank
PM-5	16-in. to 3093 ft	1384	1440	3072	Blank

Note: Screen or perforated sections in wells in Los Alamos and Guaje fields (except G-6) are located at select depth intervals opposite permeable section of the aquifer; wells in the Pajarito field and well G-6 contain screen through the aquifer.

gravel pack and screen is probably enhanced because of the pressure drop as the water enters the well. Sand moving into and lingering in the gravel pack also restricts the movement of water into the well. In some wells sand is carried through the gravel pack into the pump. This tends to wear the pump out. Other sand pulled through the gravel pack falls to the bottom of the well covering screens that reduce the amount of water entering the well. Some restoration of yield in older wells can be accomplished by rehabilitation.

Three methods of well rehabilitation have been used at Los Alamos to try to improve the yield of the older wells. These methods are: (1) brushing and swabbing the casing and screen to remove scale and to rework the gravel pack, (2) using a sand pump to remove scale and sand covering screen at the bottom of the well, and (3) an underwater explosive detonation technique in screened sections to remove scale and work the gravel pack, combined with sand pump removal of scale and sand, from the bottom of the well.

The working of the well with a brush and using the brush as a swab to create pressure differences to pull sand through the gravel pack in a screen section has been used on most of the wells. The brush dislodges chemical precipitate scale that has accumulated on the interior of the well screen and casing. This type of rehabilitation is followed by use of a sand pump to remove the sand and scale from the bottom of the well. In some cases a sand pump alone may be used to produce some swabbing effect and remove accumulations from the well. In general these simple rehabilitation measures increase the yield from the well for a short time and then the yield again declines. However, these methods can also cause additional deterioration of performance by physically damaging the well screens, especially in older wells. Older wells are more susceptible to damage because of corrosion weakening the screens. The use of a heavy wire brush in one of the older wells (LA-4) apparently damaged the screen, breaking out louvers in the screen, so that the sand entrance into the well could not be controlled.

A proprietary technique employing small explosive charges detonated in screened sections to break loose and remove scale and work or loosen up the gravel pack was employed in 1987 in one of the older wells (G-3, completed in 1951). The overall effect on the well was adverse as a number of louvers were broken from the screen by the detonations. Additional louvers were broken by subsequent use of a sand pump to remove sand and scale from the bottom of the well. The broken screen permits significant amounts of formation sand and gravel pack to enter the well, restricting yield and precluding further use in the water supply system.

However, this experience provided some of the most revealing information on the possible condition of many of the oldest wells in the Guaje and Los Alamos well fields. A small bucket was suspended below each section of explosive charges. The bucket caught some of the louvers broken from the screen as well as the scale, sand, and some of the gravel pack from the screen. The condition of the louvers indicated that the sections were almost completely rusted through, showing little or no competent metal remaining. The louvers were essentially cemented in place only by the chemical precipitates. The louvers were encrusted and cemented with the gravel, also indicating that the gravel pack itself is probably partially cemented by the formation of calcium carbonate in the gravel pack. Because of the extensive metal corrosion, use of acid to remove calcium carbonate deposits will probably result in complete failure of the screen and casing. The casing and screen in the older wells have been so weakened by rusting and corrosion that severe well damage is likely to result from any further attempts at rehabilitation.

Damaged screen and casing can sometimes be repaired by running a liner through the damaged section. This was done on well G-4 in 1976. The liner was set below the reduction of the casing from 12-in. to 10-in. As the well continued to produce sand with the pumpage, the liner lost its effectiveness within a short time.

Rehabilitation efforts of these older wells are only a short-term correction of well problems. The yields can be increased for only short periods of time before the yields continue their declines. The weakening of the well screens by corrosion and rust precludes any further rehabilitation in most of the wells in the Los Alamos and Guaje fields. Deterioration of casing and screen that allows sand to enter the well results in excessive wear on the pump, thus shortening the life of the pump.

III. HISTORIES OF THE WELL FIELDS

A. General Production and Performance Data

The total use of water for the Laboratory and the community increased by 230 x 10^6 gal. in 1976. Water use in 1977 declined to about 1500 x 10^6 gal. and has varied since 1977 from about 1450 x 10^6 gal. in 1979 to 1625 x 10^6 gal. in 1985 (Fig. 11). The decline in 1977 was attributed largely to a rate increase for water used in the community. A trend line projection of future water demands was made in 1985 based on water use data from 1977 through 1985. The projection suggested an annual increase of about 17 x 10^6 gal. The 1986 production fell below the projected production by about 105 x 10^6 gal. (Fig. 1) (Purtymun 1987).

The cumulative contribution to water production for each well through 1986 and cumulative totals for each well field are presented in Table 3. The annual production from each well field is charted in Fig. 12. Since the mid-1960s, production from the Los Alamos and Guaje fields has generally declined, while production from the Pajarito field has increased. Production from the Los Alamos field has decreased most rapidly in the last several years because of well deterioration and because it has the largest energy cost.

Changes in performance characteristics of individual wells give an indication of well condition and the degree of deterioration that has occurred with time. Data on pumping rates and specific capacities were presented for each well at the time it was completed and in 1986 (Table 4). The pumping rate is influenced by several factors including the proportion of the well screen that is open, the well's specific capacity, the aquifer drawdown, and the need to throttle the well because of snagging. The pumping rate, in turn, strongly influences the cost of producing water from a given well. The specific capacity is often an important indicator of well deterioration. It is an indicator of the pressure difference needed to move water from the aquifer into the well and is influenced by the amount of chemical precipitation and cementation in the gravel pack and the well screen.

The condition of the aquifer in the vicinity of each well is indicated by the change in nonpumping water levels presented in Table 5. These values indicate the ability of the aquifer to recover from pumpage and suggest the amount of water that has been "mined" from the vicinity of each well.

Particularly significant data will be highlighted in subsequent discussions of individual well histories.

B. History of the Los Alamos Well Field

The Los Alamos field is the oldest well field consisting of seven wells (Fig. 1). In 1986, the field produced 179 x 10^6 gal. or about 12% of

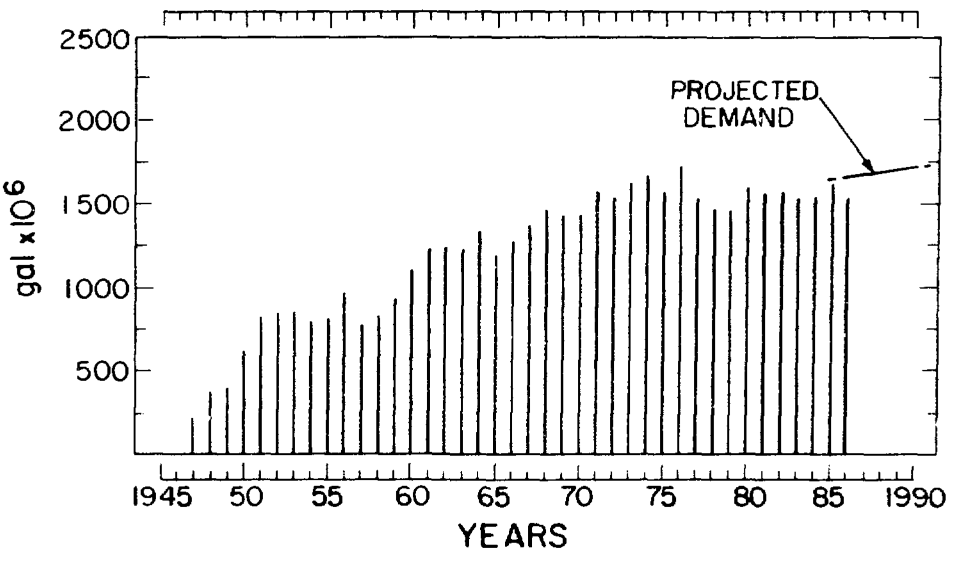

Figure 11. Water production 1947 to 1986 and projected demand 1986 to 1990 (Purtymun 1987).

Table 3. Production 1947-1986 and 1986

		1947-1986		1986	
		Pumpage x 10^6 gal	Percent of Total	Pumpage x 10^6 gal	Percent of Total
Los Alamos Field					
Well	LA-1	154	<1	0	0
	LA-1B	2,196	5	55	4
	LA-2	1,484	3	24	2
	LA-3	1,745	4	27	2
	LA-4	3,777	8	39	3
	LA-5	3,290	7	34	2
	LA-6	2,884	6	0	0
	Total	15,530	33	179	13
Guaje Field					
Well	G-1	2,630	6	30	2
	G-1A	3,380	7	130	9
	G-2	2,770	6	109	7
	G-3	2,183	5	27	2
	G-4	1,350	3	34	2
	G-5	3,082	6	52	4
	G-6	1,300	3	77	5
	Total	16,695	36	459	31
Pajarito Field					
Well	PM-1	1,941	4	74	5
	PM-2	6,330	14	84	6
	PM-3	4,429	10	246	16
	PM-4	1,539	3	307	20
	PM-5	149	<1	147	9
	Total	14,388	31	858	56
	Grand Total	46,613	100	1,496	100

the total well field production of 1,496 x 10^6 gal. (Table 3). The pumpage from the field from 1947 through 1986 has been 15,530 x 10^6 gal. At this writing, November 1987, production is from only three of the wells. Well LA-1 was abandoned in 1956 due to sand problem. Wells LA-4 and -5 are down for repairs. Damage to the screens of LA-4 may prevent the well from ever being put back on the line. Well LA-5 should be restored to production after the pump is repaired. Well LA-6 was taken out of active production in 1976 as the water from the well could no longer meet drinking water standards for arsenic content.

1. **Well LA-1.** Well LA-1 was used from 1947-1952 and again in 1955 and 1956, with a production of 154 x 10^6 gal. The well, completed in 1946, had large amounts of sand produced with the pumpage. The sand wore the pump out and reduced the pumping rate by covering the screen at the bottom of the well. Rehabilitation of the well has included reworking the gravel pack by

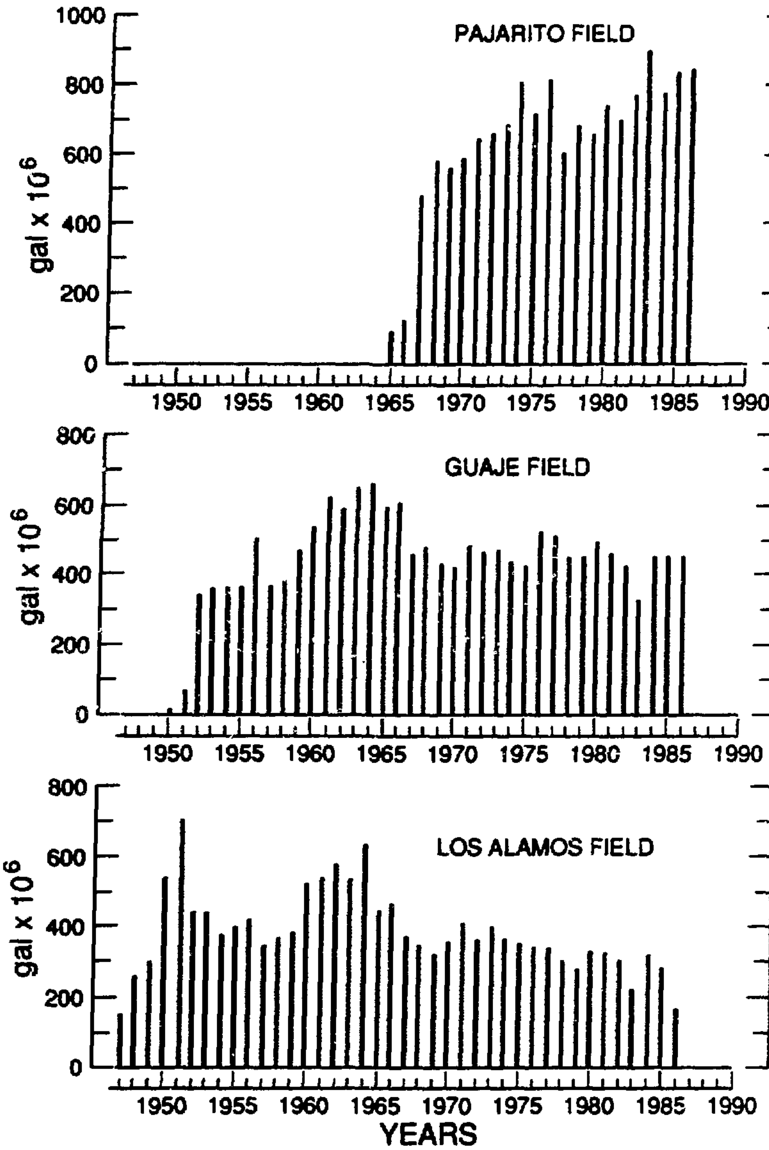

Figure 12. Annual production from Pajarito, Guaje, and Los Alamos fields.

swabbing the well and a reported treatment of acid to dissolve the scale. The acid not only removed the scale, but probably enlarged the screen openings and broke down the formation, which increased the sand content with the pumpage. The pump was pulled from the well in the late 1950s. It was open to 598 ft with only 67% of the 805 ft of screen open. Since that time, the well has been used only as an observation well to monitor the water level changes in the upper part of the aquifer in the lower part of the Los Alamos field. The water level fluctuations in the well reflect the pumpage from LA-1B. The condition of the well precludes its use for part of the water supply.

2. Well LA-1B. Well LA-1B, drilled to replace LA-1, is located about 150 ft northeast of LA-1. The pumpage from the well from 1960-1986 has been 2,196 x 10^6 gal. When the well

Table 4. Comparison of Pumping Rate and Specific Capacity

	Pumping Rate (gpm)			Specific Capacity (gpm/ft drawdown)		
	Completion	Current	Change (±)	Completion	Current	Change (±)
Los Alamos Field						
Well LA-1	260 (47)	--	--	--	--	--
LA-1B	558 (61)	573 (86)	+15	5.6 (61)	4.8 (86)	-0.8
LA-2	423 (50)	312 (86)	-111	1.9 (50)	1.8 (86)	-0.1
LA-3	345 (50)	338 (86)	-7	2.6 (50)	2.0 (86)	-0.6
LA-4	631 (50)	552 (86)	-79	8.4 (50)	5.9 (86)	-2.5
LA-5	535 (50)	419 (86)	-116	4.4 (50)	2.9 (86)	-1.5
LA-6	623 (50)	--	--	11.8 (50)	--	--
Guaje Field						
Well G-1	538 (50)	249 (86)	-289	5.0 (50)	1.5 (86)	-3.5
G-1A	577 (55)	468 (86)	-109	11.3 (55)	11.4 (86)	+0.1
G-2	550 (52)	382 (86)	-168	11.5 (52)	14.7 (86)	+3.2
G-3	458 (52)	196 (86)	-262	9.5 (52)	1.9 (86)	-7.6
G-4	395 (52)	211 (86)	-184	3.9 (52)	1.2 (86)	-2.7
G-5	477 (52)	394 (86)	-83	8.2 (52)	9.6 (86)	+1.4
G-6	392 (64)	293 (86)	-99	5.0 (64)	3.8 (86)	-1.2
Pajarito Field						
Well PM-1	600 (65)	578 (86)	-22	15.0 (65)	26.3 (86)	+11.3
PM-2	1425 (66)	1359 (86)	-66	22.6 (66)	21.2 (86)	-1.4
PM-3	1342 (68)	1397 (86)	+55	47.9 (68)	58.2 (86)	+10.3
PM-4	1460 (82)	1305 (86)	-155	35.6 (82)	37.3 (86)	+1.7
PM-5	--	1199 (86)	--	--	--	--

Note: Numbers in parentheses are year of measurement.

Table 5. Comparison of Nonpumping Water Levels

	(ft)		
	Completion	Current	Change (± ft)
Los Alamos Field			
Well LA-1	F (46)	34 (86)	-34
LA-1B	+34 (60)	25 (86)	-59
LA-2	F (46)	74 (86)	-74
LA-3	F (47)	88 (86)	-88
LA-4	189 (48)	284 (86)	-95
LA-5	71 (48)	168 (86)	-97
LA-6	2 (48)	92 (85)	-90
Guaje Field			
Well G-1	192 (51)	279 (86)	-87
G-1A	265 (55)	310 (86)	-45
G-2	279 (52)	369 (86)	-90
G-3	310 (52)	375 (86)	-65
G-4	357 (52)	396 (86)	-39
G-5	417 (52)	453 (86)	-36
G-6	576 (64)	576 (86)	0
Pajarito Field			
Well PM-1	746 (65)	748 (86)	-2
PM-2	826 (66)	851 (86)	-25
PM-3	743 (68)	763 (86)	-20
PM-4	1050 (82)	1084 (86)	-34
PM-5	--	--	--

Note: Numbers in parentheses are year of measurement; F indicates flowing well while +34 indicates flowing well (water level above land surface).

was completed, it was artesian with a head of about 34 ft. Pumpage has reduced the artesian pressure and the nonpumping water level had declined to 25 ft below land surface in 1986 or a total decline of about 59 ft (Table 5). The well was logged with the downhole video camera in 1983. At that time the well was open to a depth of 1,655 ft with 576 ft or 97% of the 591 ft of perforation open. The lower 95 ft of the well was filled with sand that had moved through the gravel pack and perforations into the well. The well pumping at 573 gallons per minute (gpm) has about 119 ft of drawdown and there is little, if any, sand produced with the pumpage. The video tape of the hole revealed a slight bend in the casing at a depth of 385 to 405 ft as indicated by the roll of the camera. The casing reduces in size from 12-in. to 10-in. at a depth of 650 ft (Table 2). As the well is cased with wrought iron pipe, no attempt should be made to bail or remove sand from the bottom of the well. Overall, the well is considered to be in fair condition and is likely to be usable for as much as 20 years more.

3. **Well LA-2.** The pumpage from well LA-2 from 1947-1986 was 1,484 x 10^6 gal. The well when completed was artesian. The nonpumping water level declined from flowing in 1946 to a depth of 76 ft below land surface. The pump was last removed from the well in 1962 and 1963. The well had accumulated little or no sand during the

one year of pumping. It appears that the well makes very little sand; however, the pumping rate must be held around 300 gpm with limited pumping time, 12 hours or less, or the pumping level will decline to the level of the pump intake. The well is considered to be in only fair condition and is likely to be usable for no more than another 10 years.

4. **Well LA-3.** The pumpage from well LA-3 from 1947-1986 was 1,745 x 10^6 gal. The pumping rate and the specific capacity have not changed significantly. The well was artesian when completed with nonpumping water level declining to about 88 ft below land surface in 1986. The pump was removed from the well in 1983. At that time, the well was open to a depth of about 816 ft; about 92% of the 760 ft of perforations was open. The scale was removed from the casing and perforations with a wire brush. The well produces sand with the pumpage at high discharge rates. The pumping rate should be maintained around 300 gpm, which will result in a drawdown of less than 150 ft. A drawdown greater than 150 ft will result in water and sand cascading into the well, which will cause excess wear on the pump and will decrease the well efficiency by sand accumulating and covering up the perforations. The well is considered to be in fair condition and is likely to be usable for no more than another 10 years.

5. **Well LA-4.** The pumpage from well LA-4 from 1948-1986 was 3,777 x 10^6 gal. The pumping rate decrease, the specific capacity decline from 8.6 to 5.9 gpm/ft of drawdown, and the 95 ft nonpumping water level decline indicate some deterioration of the well. The line shaft turbine pump failed in early 1987 and was pulled and replaced with a submersible. The hole was logged with the downhole video camera in July 1987 and was found open to 1,921 ft. A heavy wire brush was used to clean scale off the casing and screen. The scale and formation sand were removed to a depth of 1,942 ft in late July. The new pump was run in the hole, but testing indicated that the pumpage contained large amounts of sand. The well was shut down and several tests were run at discharge rates ranging from 351 to 525 gpm. The tests ranging from 2 to 4.5 hours indicated little or no sand in the pumpage. The well was put back on the line at about 525 gpm; however, after several hours of pumping, a large amount of sand occurred in the discharge. To prevent damage to the new pump and the pumps in the booster station the well was again taken off the line. The future action to be taken with the well has not been decided. Before removal of the pump early in 1987, the pumpage from the well contained little or no sand at a high pumping rate. The video log of the well in April 1987, before rehabilitation, indicated no damage to the casing or screen. The presence of large amounts of sand occurring periodically in the pumpage indicates that the casing, screen, or the reduction between the 12-in. and 10-in. was ruptured during the rehabilitation of the well.

The pump was pulled from the well in January 1988. Two video logs were run of the well. The log of February 3, 1988, was to the total depth of the well at 1 907 ft. The second log was run March 1, 1988, to a depth of about 780 ft. The logs indicated that the casing has separated at a depth of about 750 ft where the casing reduces from 12-in. to 10-in. diameter. It may be possible to repair the separation if the condition of the casing has not deteriorated because of corrosion and can stand the pressure of swedge inserted between the 12-in. and 10-in. diameter.

During 38 hours of pumping, including testing, during August 1987, about 35 ft of sediment had accumulated in the well. The depth of the well was reduced from 1942 ft to 1907 ft. The accumulation of sand in the well over a short period of pumping indicates the serious nature of the separation.

6. **Well LA-5.** The pumpage from well LA-5 from 1948-1986 was 3,290 x 10^6 gal. The well was sounded in 1962 (the last time the pump was removed from the well) at a depth of 1,954 ft. It was apparent that the pilot hole below the bottom of the casing was open for more than 200 ft. The pumping rate declined from 535 gpm in 1950 to 419 gpm in 1986 and the specific capacity decline from 4.4 to 2.9 gpm/ft of drawdown showed deterioration in the efficiency of the well. The nonpumping level declined about 97 ft from 1950 to 1986. The well produces little or no sand with the pumpage. The well is equipped with a line-shaft turbine pump, but needs a larger line-shaft to keep the pump in adjustment. In the summer of 1987, the line shaft separated. The well

is currently down for repairs. The well is considered to be in fair condition and is likely to be usable for no more than another 10 years.

7. Well LA-6. The production from well LA-6 was 2,884 x 10^6 gal. from 1948-1976. The well was taken off line in 1976 because of excessive arsenic in the water. The concentration of arsenic in the water had increased over time so that it could no longer be diluted with pumpage from other wells in the field to meet Federal Drinking Water Standards. During 1976, sand was used to pack off sections of the well from the bottom up to test various zones in an attempt to determine the source of the high arsenic concentrations (Purtymun 1977a). During this work, the tail pipe of a pump was lost in the sand at a depth of about 1,200 ft and, subsequently, a "fishing tool" and cable was lost at that depth trying to remove the tail pipe. The well had 400 ft of perforations or screen of which 210 ft or 53% of the perforations are above the tail pipe and fishing tool. Before these problems occurred, the well had been a good producer. The pumping rate declined only modestly and the specific capacity actually increased. With the effective depth of the well reduced to 1,200 ft, the well could sustain a pumping rate of about 580 gpm with a drawdown of about 60 ft. The well flowed water under artesian pressure at one time during construction. At the present time the well is not used in the system, nor are there any future plans to use the well because of the water quality.

C. History of the Guaje Well Field

The Guaje field consists of seven wells (Fig. 1). Wells G-1, -2, -3, -4, and -5 were completed in 1950-1951. Well G-1A was added in 1954 and G-6 was added in 1964 to offset the declining production of the other wells in the field. The production from the field during 1950-1986 was 16,695 x 10^6 gal. In 1986 the field produced 460 x 10^6 gal. or about 31% of the total well field production of 1,496 x 10^6 gal.

1. Well G-1. The pumpage from well G-1 was 2,630 x 10^6 gal. from 1950-1986. The well was last sounded in 1962 and was open to a depth of 1,750 ft with 576 ft or 86% of the screen open. No rehabilitation was undertaken at that time. The considerable decline in both pumping rate and specific capacity indicates significant deterioration of the well. The deterioration is probably a combination of scale forming on the screen, deterioration of the gravel pack, and sand covering the screen openings in the bottom of the well. The nonpumping water level declined from 192 ft in 1951 to 279 ft in 1986 or about 87 ft (Table 5). The well is considered to be in fair condition, but because of limited yield is likely to be usable for no more than 10 years.

2. Well G-1A. Well G-1A was drilled in 1954 to supplement the declining production of the five original wells in the well field. The well produced 3,380 x 10^6 gal. from 1954-1986 or about 20% of the total field production (Table 3). The pump was removed in 1973 and sediments were cleaned out of the well to a depth of 1,500 ft. The sediment left in the well covered only 10 ft of the 563 ft of screen in the well. The pumping rate has declined only modestly and the specific capacity has remained about constant. Overall, the well is considered to be in fair condition and is likely to be usable for as much as 20 years more.

3. Well G-2. The production from well G-2 was 2,770 x 10^6 gal. or about 17% of the total pumpage from 1950-1986. The pump was removed in 1981 for the first time since it was installed in 1950. During rehabilitation, the scale was removed from the casing and screen using a wire brush. The sand in the well was removed to a depth of 1,707 ft. A section of 1/2-in.-airline in the well prevented the removal of sand to the total depth of the well. Of the 425 ft of screen in the well, 385 ft or 91% of the screen was open. A video log was made of the well, which contained some interesting views of the screen and aquifer. The bore hole log showed water cascading through screened sections at depths of 285 to 295 ft, 300 to 310 ft, and 320 to 330 ft. The water level on December 18, 1981, was at 355 ft and on January 11, 1982, was at 333 ft. The water level in G2 fluctuates due to pumping of well G-1A about 1250 ft to the southwest. The pumping rate has declined from 550 gpm in 1952 to 382 gpm in 1986. The specific capacities appear to have increased from 11.7 gpm/ft of drawdown in 1952 to 14.7 gpm/ft of drawdown in 1986. The apparent increase is due to heavy pumpage of the well that does not allow the nonpumping level to make a complete recovery and does not accurately measure well efficiency. The nonpumping water level has declined from 279 ft in 1953 to 382 ft in 1986. Overall, the well is considered to be in fair condition but because of declining yield is likely to be usable for no more than about 10 years.

4. **Well G-3.** The pumpage from well G-3 was 2,183 x 10^6 gal. from 1952-1986. Several attempts have been made to rehabilitate the well since 1975 to increase the yield. The rehabilitation efforts have failed to increase the yield. The pumping rate has declined from 458 gpm in 1950 and 196 gpm in 1986. The specific capacity of the well declined from 9.5 gpm/ft of drawdown in 1950 to 1.9 gpm/ft of drawdown in 1986 indicating significant well deterioration. During well rehabilitation in the winter of 1975-1976, the depth sounded was 1,558 ft. After the scale was removed from the casing and screen, the well was swabbed to try to work the gravel pack free of possible formation of calcium carbonate. The well was cleaned out to a depth of 1,601 ft before the pump was replaced in the well.

The pump was again removed from the well in January 1984, and the well was found to be filled with sediments to a depth of 1,304 ft. After rehabilitation, the sand and scale were removed from the well to a depth of 1,631 ft. The pumping rate and specific capacity declined rapidly from 1984-1986. The pump was removed from the well in June 1987. The well was logged to a depth of 1,492 ft. A proprietary explosive technique was tried to develop and rehabilitate the well. Small explosive charges were set off in 22 sections of screen to a depth of 1,492 ft. The well was examined with the downhole camera. The explosive shock waves had dislodged louvers leaving holes in the screen at 527, 757, 893, 957, and 1117, and in the section from 1,220 to 1,230 ft. Scale, formation sand, and gravel pack had entered and filled the hole to a depth of 1,431 ft. The well was developed by running a bailer up and down the hole to remove the remaining scale from the casing and screen as well as to move and open the gravel pack. At the end of 6 hours of development the hole was filled to a depth of 1,384 ft. After several days of additional development using a sand pump as a swab, the depth was at 1,238 ft. At that time only 280 ft of the 400 ft, or 70%, of screen in the well remained open. The sand and gravel pack were entering the hole faster than it could be removed. Further development and bailing of sand and gravel pack were terminated and the pump was replaced for further testing to assess the results of the explosive type of rehabilitation and development. Initial testing at a low discharge rate, 200 gpm, indicated that the well was making a large amount of sand. Additional testing is planned for late winter or early spring 1988. Depending on the amount of damage to the well screen, it may be that the well will no longer be usable.

5. **Well G-4.** Pumpage from well G-4 was 1,350 x 10^6 gal. from 1952-1986. The pump was removed from the well in 1981. The depth was at 1,172 ft. No rehabilitation was attempted. Only 100 ft or 25% of the 400 ft of screen in the well was open. Significant declines in both the pumping rate and the specific capacity of the well indicate serious deterioration (Table 4). The nonpumping water level declined from 357 ft in 1952 to 396 ft in 1986. The distance between G-4 and G-5 is about 2,500 ft; however, the pumping of one well affects the water levels in the other.

The well was badly damaged during construction. After completion in 1952, low yield from the well indicated well damage. The pump was pulled and a caliper log run of the well indicated that it was open to a depth of 1,381 ft. The caliper indicated no detectable breaks or holes in the screen or casing above 1,381 ft. An obstruction in the well prevented any removal of sediments below 1,381 ft. The pump was pulled from the well in February 1974, and the well was only open to a depth of 750 ft indicating that 1,215 ft of sediment had collected in the bottom of the well. Sediments were cleaned out to a depth of 1,185 ft when a sand pump was lost in the well. A video log of the hole was run to a depth of 1,167 ft and showed a few louvers out of the screen at a depth of about 765 ft. The sand pump was recovered and the well was cleaned out to a depth of 1,756 ft. A number of louvers, scrap iron, rags, and gloves were recovered at about 1,380 ft, the depth of the obstruction noted in 1952. A second run with the video log was made to a depth of 1,492 ft (limit of the equipment) that showed well screen damage from 1,270 to 1,290 ft, 1,312 to 1,332 ft, and 1,383 to 1,393 ft. It was quite evident that during construction and emplacement of the gravel pack, the drop lines with external couplings feeding the gravel into the annulus between the casing and the hole wall tore the louvers from the screen. A slotted liner was run into the well to compensate for the damaged section. The liner, "belled-out" at the top, was 7-1/2 in. o.d. and was about 536 ft long. The bottom of the liner was set at 1,750 ft with the "belled-out" end set in the blank casing of the well at a depth of 1,214 ft. The yield of the well initially increased from about 280 gpm to around 400 gpm. At the higher yield, the well produced sand with the pumpage. The pump was pulled in 1981. Sand containing some gravel pack had accumulated to a depth of 1,150 ft. The well was cleaned out to a depth of 1,172 ft and the pump was replaced in the well. The pump failed and was pulled for repairs in 1985. The depth of the well was about 1,123 ft. No rehabilitation was attempted. The well is considered to be in poor condition and is unlikely to be usable for more than 10 years.

6. Well G-5. The pumpage from well G-5 was 3,082 x 10^6 gal. or 18% of total field production from 1952-1986 (Table 3). No major changes have occurred in the pumping rate, specific capacity, or nonpumping water level. The line shaft turbine originally installed in the well was replaced with a submersible in 1958. At that time the well was open to a depth of 673 ft. In 1975 the pump was removed for repairs and the sediments were removed to a depth of 912 ft. No attempt was made to remove sediments from the well below 912 ft because of significant well screen damage between 700 and 912 ft. The well bore filled with sand and gravel faster than it could be bailed from the hole. There were two badly damaged sections of screen at 710 to 714 ft and 738 to 740 ft. Large cobbles, 4 to 6-in. in diameter could be seen outside the casing with no gravel pack remaining in back of the damaged screen. The pump has been removed several times since 1975; however, due to the damage to the casing below 700 ft, no rehabilitation of the well has been undertaken other than removing scale for the screen and casing above the reduction in the casing at 700 ft. Sediments and sand had accumulated in the well to a depth of about 700 ft when the wells was measured again in 1979.

The damage to the casing probably occurred when the well was constructed or when the test pump was dropped into the well during testing in 1950. The pump was fished out of the well. Although only 100 of the 400 ft of screen in the well are above the 700 ft depth, the well has been and has continued to be one of the best and most reliable wells in the field (18% of total production from the field). However, because of its age and the damaged screen, the well is considered to be in poor condition and it is unlikely that it will be usable for more than 10 years.

7. Well G-6. Well G-6 was added to the well field in 1964 to replace the declining production from the other wells in the field. Since 1964, the production through 1986 was 1,300 x 10^6 gal. The pump was removed in April 1979 for repairs and the sand was removed from the well to a depth of 1,510 ft. In December of 1979, the pump was again removed for adjustment and the hole was open only to 1,480 ft. The pumping rate and the specific capacity have declined significantly. These changes and the amount of sand production indicates that considerable well deterioration has occurred in the past few years. At startup the pumpage contains excessive amounts of sand and gravel pack. The discharge is pumped to waste for the first few minutes to keep part of the sand and gravel pack out of the distribution system. The continued deterioration of the well, as shown by production characteristics, indicates that it should be replaced within 10 years.

D. History of the Pajarito Well Field

The Pajarito field consists of five wells (Fig. 1). The field was developed from 1965-1982. The field was developed to meet a small increasing demand for water and to supplement the declining production from the Los Alamos and Guaje fields. The production from the field from 1965-1986 was 14,388 x 10^6 gal. or 31% of all production (Table 3). Four of the wells in this field are considered high yield wells (pumping rates in excess of 1,000 gpm).

1. Well PM-1. The pumpage from well PM-1 was 1,941 x 10^6 gal. from 1965-1986. The pump was pulled in 1973 and was open to a depth of 2,479 ft. Only about 1% of the 1,549 ft of screen was covered with sediments. There was no rehabilitation of the well. The pump was repaired and replaced in the well. The pumping rate has declined slightly and the specific capacity has increased from about 15 gpm/ft of drawdown in 1965 to 26.3 gpm/ft of drawdown in 1986. The increased specific capacity results from further developing the well by setting the gravel pack, as well as cleaning the gravel pack and aquifer of residual drilling muds. The further development of the well is also evident from the insignificant 2 ft change of the nonpumping water level (Table 5). The well produces sand in the pumpage at the start. A sand separator is used to remove sand from water as there is usage before the first storage tank, which separates the sand from the water. The well is considered to be in good condition and is likely to be usable for 20 to 30 years.

2. Well PM-2. The pumpage from well PM-2 was 6,330 x 10^6 gal. from 1966-1986. The pump was pulled for rehabilitation in 1987. The well was open to a depth of 2,283 ft. The blank casing and screen were worked over using a bailer or sand pump. This removed the outer scale from the casing and screen and reworked the gravel pack. The pumping rate, specific capacity, and nonpumping water level have only declined slightly. The well is a high-yield well and had a pumping rate of over 1,350 gpm in the fall of 1987. The well has produced more water than any other well in the three well fields. The well is considered to be in good condition and is likely to be usable for 20 to 30 years.

3. Well PM-3. Pumpage from well PM-3 was 4,429 x 10^6 gal. from 1966-1986. The pumping rate and the specific capacity have increased slightly since completion. The nonpumping water level has declined only 20 ft. The well has the lowest amount of drawdown and largest specific capacity of any well in the three well fields. Well PM-3 is a high-yield well with the production second highest of any well in the three fields. The pump, a line shaft turbine, has not been removed from the well since it was installed in 1966. The well is considered to be in good condition and is likely to be usable for 20 to 30 years.

4. Well PM-4. Well PM-4 is a relatively new well that was added to the field in 1982. The well produced 1,539 x 10^6 gal. from 1982-1986. The well is equipped with a line shaft turbine driven by a natural gas engine. A slight change in engine performance readily affects the pumping rate. The pumping rate declined from about 1,460 gpm in 1982 to about 1,305 gpm in 1986. This decline may have been caused by engine performance. This decline in gpm does not reflect well deterioration as the specific capacity increased slightly from 35.6 gpm/ft of drawdown to 37.3 gpm/ft of drawdown in 1986. The nonpumping water level declined from 1,050 ft to 1,084 ft during the same period. The well is considered to be in good condition and is likely to be usable for 30 years.

5. Well PM-5. Well PM-5 was the last well added to the system. The well was completed in 1982 and placed on line in 1985. The production from the well from 1985-1986 was 149 x 10^6 gal. The pumping rate is about 1,200 gpm. Due to the presence of drilling mud in the access line for the transducer, no water levels have been recorded since the well was tested. At that time the water level was about 1,210 ft below the surface of the mesa. The well is considered to be in good condition and is likely to be usable for 30 years.

IV. WELL FIELD PRODUCTION CAPACITIES

Well field and transmission system capacities limit the ability to meet peak demand requirements. Peak demand typically occurs during the summer months when temperatures and landscape irrigation requirements are highest. Current maximum production capabilities are only slightly greater than the historic maximum peak demand period. Maximum well field yields are given as the total of all wells in a field pumping at their rated current yields. Firm yield is taken to be the maximum yield reduced by the yield of the largest producing well in that field. Maximum yield and firm yield are over a 24-hour period. For the Los Alamos and Guaje lines, maximum transmission system capacities are determined by assuming all pumps in the booster stations are functioning. Firm transmission system capacity is the maximum reduced by the rated capacity of the largest pump. The Pajarito field can supply water to different parts of the distribution system, and transmission system capacity cannot be readily defined.

The maximum yield from the Los Alamos field in 1986 was 1,610 gpm or 2.32 million gallons per day (mgd), whereas the firm yield was 1,040 gpm or 1.50 mgd (Table 6). The booster capacity to transfer water through the four pumping stations into storage in the Laboratory and townsite has a maximum capacity of 3,000 gpm or 4.32 mgd, and a firm capacity of 2,000 gpm or 2.88 mgd (Table 6). The maximum and firm yield from the well field is much less than the maximum and firm capacity of the booster stations. The maximum yield from the Los Alamos well field could be nearly doubled to use maximum booster capacity. The increase cannot be accomplished by the rehabilitation of the present wells; it could be realized by the addition of new wells constructed with the latest methods.

The maximum yield for the Guaje field in 1986 was 2,000 gpm or 2.88 mgd, whereas the firm yield was 1,530 gpm or 2.20 mgd (Table 7). The four booster stations that transfer water from the field to the Laboratory and townsite have a maximum capacity of 3,000 gpm or 4.32 mgd, and a firm capacity of 2,000 gpm or 2.88 mgd (Table 7). The maximum yield from the well field could be increased by about 50% to make full use of the maximum booster capacity. This cannot be accomplished by well rehabilitation because of the current conditions of the wells, but it must be accomplished by addition of new wells to the field.

The maximum yield for the Pajarito field in 1986 was 5,845 gpm or 8.42 mgd, whereas the firm yield is 4,445 gpm or 6.40 mgd (Table 8). Wells PM-1 and -3 pump water to the community of White Rock or into storage that serves White Rock and Pajarito Acres. If necessary, water from storage can also be pumped into the next series of boosters, which will distribute the water to storage in the townsite area and the Laboratory. Wells PM-2, -4, and -5 pump to booster station 2, which backflows water for distribution in White Rock and Pajarito Acres or can pump it to Pajarito Booster 3 and then into storage for the Laboratory or townsite.

Table 6. Los Alamos Field

	Summary Well Capacity			
	Maximum Yield (1986)		Firm Yield (1986)	
Well	gpm	mgd	gpm	mgd
LA-1[a]	0	0	0	0
LA-1B	570	0.82	--	--
LA-2	300	0.43	300	0.43
LA-3	340	0.49	340	0.49
LA-4[b]	0	0	0	0
LA-5[c]	400	0.58	400	0.58
LA-6[d]	0	0	0	0
Total	1610	2.32	1040	1.50

[a]Well abandoned.
[b]Well damage; probably will never be placed back on line.
[c]Well down for repairs (November 1987).
[d]Standby - chemical problem.

Summary Booster Capacity

Maximum Booster Capacity - 3000 gpm: 4.32 gpd
Firm Booster Capacity - 2000 gpm: 2.88 gpd

Table 7. Guaje Field

	Summary Well Capacity			
	Maximum Yield (1986)		Firm Yield (1986)	
Well	gpm	mgd	gpm	mgd
G-1	250	0.36	250	0.36
G-1A	470	0.68	--	--
G-2	380	0.55	380	0.55
G-3[a]	0	0	0	0
G-4	210	0.30	210	0.30
G-5	395	0.57	395	0.57
G-6	295	0.42	295	0.42
Total	2000	2.88	1530	2.20

[a]Well damaged; probably never will be placed back on line.

Summary Booster Capacity

Maximum Booster Capacity - 3000 gpm: 4.32 gpd
Firm Booster Capacity - 2000 gpm: 2.88 gpd

Table 8. Pajarito Field

	Summary Well Capacity			
	Maximum Yield (1986)		Firm Yield (1986)	
Well	gpm	mgd	gpm	mgd
PM-1	580	0.83	580	0.83
PM-2	1360	1.96	1360	1.96
PM-3	1400	2.02	--	--
PM-4	1305	1.88	1305	1.88
PM-5	1200	1.73	1200	1.73
Total	5845	8.42	4445	6.40

Table 9. Peak Demand Periods - 1976
(June 11 - July 12)

No. of Days	32
Total Production	299×10^6 gal.
Average Daily Production	9.3×10^6 gal.

No. of Days Exceeding (gal.)	Days
10×10^6	14
9×10^6	9
8×10^6	4
7×10^6	3
$<7 \times 10^6$	2

Maximum and Firm Yield - 1986

Field	Maximum ($\times 10^6$ gpd)	Firm ($\times 10^6$ gpd)
Los Alamos	2.32	1.50
Guaje	2.88	2.20
Pajarito	8.42	6.40
	13.62	10.10

V. PEAK DEMAND

The historical maximum peak demand period occurred during the summer of 1976. The peak demand period was 32 days, from June 11 through July 12. During that time, 299×10^6 gal. was pumped or an average of 9.3×10^6 gpd. Fourteen days exceeded 10×10^6 gpd (Table 9).

The daily maximum yield from the three well fields in 1986 was 13.62×10^6 gal. and the firm yield was 10.1×10^6 gal. Thus, the system could probably meet a peak demand period similar to the one that occurred in 1976 if all major producing wells in the three fields are operating. However, the maximum and firm yields from the three fields can be expected to continue to decline as the older wells deteriorate. At present, six wells (LA-1, 2, -3, -4, -5, and -6) in the Los Alamos field and six wells in the Guaje field (G-1, -2, -3, -4, -5, and -6) will have to be replaced in the next 10 years to meet present and future demands.

VI. PUMPING SCHEDULE

The cost of operating various wells and well fields differ based on power consumption, which, in part, is based on yield and location. A detailed pumping schedule has been designed to minimize the cost of well field operations (Foreman 1985). The schedule does not consider the present well characteristics or conditions (1987). In general, when a well pumping rate falls below 300 gpm, it is excessively expensive to operate. The schedule is an idealized guideline; it can be modified as needed to accommodate the actual demand and to account for equipment down for maintenance or repair.

The schedule for operation of the wells (in hours/month) is detailed in Table 10. Pumping times for each well are based on expense of operation modified by considerations of controlling water quantity.

Table 10. Monthly Pumping Schedule (in hours) for Individual Wells[a]

Los Alamos Field

Wells LA-1B, -2, -3, -4, and -5 are to be pumped 18 hours monthly

Guaje Field	G-1	G-1A	G-2	G-3	G-4	G-5	G-6
January	36	350	350	200	200	350	350
February	36	300	300	100	100	300	160
March	36	300	300	100	100	300	160
April	36	400	400	200	200	400	355
May	36	400	400	200	200	400	355
June	36	400	400	200	200	400	355
July	36	400	400	200	200	400	355
August	36	400	400	200	200	400	355
September	36	400	400	200	200	400	355
October	36	300	400	200	200	400	355
November	36	300	400	200	200	400	355
December	36	300	300	100	100	400	160

Pajarito Field	PM-1	PM-2	PM-3	PM-4	PM-5
January	50	180	300	240	100
February	50	180	300	170	100
March	50	180	300	170	100
April	50	300	300	240	100
May	300	350	550	500	450
June	300	350	550	500	450
July	250	320	500	500	450
August	150	280	480	500	450
September	100	220	480	300	450
October	50	180	225	210	100
November	50	180	300	210	100
December	50	180	300	170	100

[a]Summary reference (Foreman 1985); at present time (1987) wells LA-4 and G-3 are not in use due to well damage.

The Los Alamos field is the most expensive to operate. Wells in this field need to be pumped a minimum of about 4 hours a week to prevent bacterial growth. They are pumped more than four hours a week just to meet actual demand or maintain fresh water in the lines.

The Guaje field is more cost effective to operate. Well G-1 is the most expensive well in the field and needs to be run 8 hours per week to prevent bacterial growth in the well and lines. All other wells in the Guaje field are generally not pumped more than the number of hours shown in Table 10 for each month. If circumstances require that some wells are used more than the ideal amount, then use in future months should be reduced so that the total number of pumping hours over the year is not exceeded.

The Pajarito field includes the highest yielding wells. Wells PM-1 and -3 are used mainly to serve White Rock and Pajarito Acres, with water being pumped to Pajarito Booster 2 only when absolutely necessary. The schedule indicates that most of the water used in White Rock and Pajarito Acres is pumped from PM-3 as it is less expensive to operate than PM-1. Water from wells PM-2, -4 and -5 is generally not directed to the White Rock tank unless that is the only way to meet actual demand in White Rock and Pajarito Acres. Wells PM-2 and PM-4 are located close to each other and excessive pumping in one well may affect the water level in the other well. Thus, the recommended total pumpage from the two wells is not normally exceeded.

VII. DEVELOPMENT OF ADDITIONAL WATER SUPPLY

Replacement of wells in the Los Alamos and Guaje fields and additions to the Pajarito field will be necessary to meet the current demand as well as the projected future demand. The status of all the existing wells is summarized in Table 11. The deterioration of the wells in the two older well fields will gradually reduce the yield until current demand cannot be met. As discussed in the section on well field histories, it is likely that at least six wells in the Los Alamos field and six wells in the Guaje field will have to be replaced in the next 10 years (Table 11).

The large number of wells in the Los Alamos vicinity and the long production histories provide a solid basis for recommendations for location and development of new and replacement wells. The recommendations in this report are elaborations of basic concepts presented in a previous report, "Hydrologic Characteristics of the Main Aquifer in the Los Alamos Area: Development of Ground Water Supplies" (Purtymun 1984a). That report contains sections describing drilling conditions, geologic and geophysical logs, and well construction techniques applicable in the Los Alamos area that should aid in the construction of new or replacement wells.

A. Geologic and Hydrologic Consideration

The main aquifer extends from the Rio Grande westward beneath the Pajarito Plateau and rises stratigraphically through the Tesuque Formation into the lower part of the Puye Conglomerate. The Puye Conglomerate is an important part of the main aquifer. The coarse volcanic debris within the conglomerate yields water readily to wells and, in part, allows the development of high-yield, low-drawdown wells in the area. The conglomerate attains its greatest thickness in a north-south trending basin beneath the central part of the plateau as shown in Fig. 13. The Tesuque Formation beneath the plateau is saturated and is the main source of water supply. The sediments of the Tesuque Formation become coarser westward from the Rio Grande; the upper beds become younger with the westward dip. This coarse sediment aids in the development of high-yield wells in the same general area.

The locations of future wells in this area must be chosen carefully because wells placed too far west will encounter hard volcanic rocks of the Tschicoma Formation, which do not yield water readily. A well that is completed in or near the outcrop of Tschicoma would not yield an appreciable amount of water because the rocks are relatively impermeable and they form a barrier to the east and southeast movement of groundwater in the main aquifer. Wells placed too far to the east encounter thick basalts, which constitute difficult drilling and may not yield water readily. The siltstones and fine-grained sandstones of the Tesuque Formation do not yield water as well as the coarser sediments found further to the west.

Proposed locations and staging for new and replacement wells in each of the three fields are discussed in the next three sections.

Table 11. Well Characteristics

Field and Well	Age	Yield (gpm)	Yield[a]	Well Condition[b]	Maximum Remaining Life	Remarks
Los Alamos Field						
LA-1	41	0	None	Poor	0	
LA-1B	27	573	Adequate	Fair	20	
LA-2	41	312	Adequate	Fair	10	
LA-3	40	338	Adequate	Fair	10	
LA-4	39	0	None	Poor	0	
LA-5	39	419	Adequate	Fair	10	Pump failure (1987)
LA-6	37	0	None	Poor	0	Arsenic above MPC[c]
Guaje Field						
G-1	37	249	Marginal	Fair	10	
G-1A	33	468	Adequate	Fair	20	
G-2	36	382	Adequate	Fair	10	
G-3	36	0	None	Poor	0	
G-4	36	211	Marginal	Poor	10	
G-5	36	394	Adequate	Poor	10	
G-6	23	293	Marginal	Poor	10	
Pajarito Field						
PM-1	22	578	Adequate	Good	20	
PM-2	22	1359	High	Good	30	
PM-3	21	1397	High	Good	30	
PM-4	6	1305	High	Good	40	Gas power
PM-5	5	1199	High	Good	40	

[a] Yield: Marginal - <300 gpm, expensive to operate; Adequate - 300-1000 gpm; and High - 1000+ gpm.

[b] Well Condition: Poor - damage to casing and screen; Fair - well deterioration due to corrosion and sanding; and Good - little, if any, well deterioration. Wells equipped with electric motors except PM-4.

[c] Maximum permissible concentrations for drinking water standards.

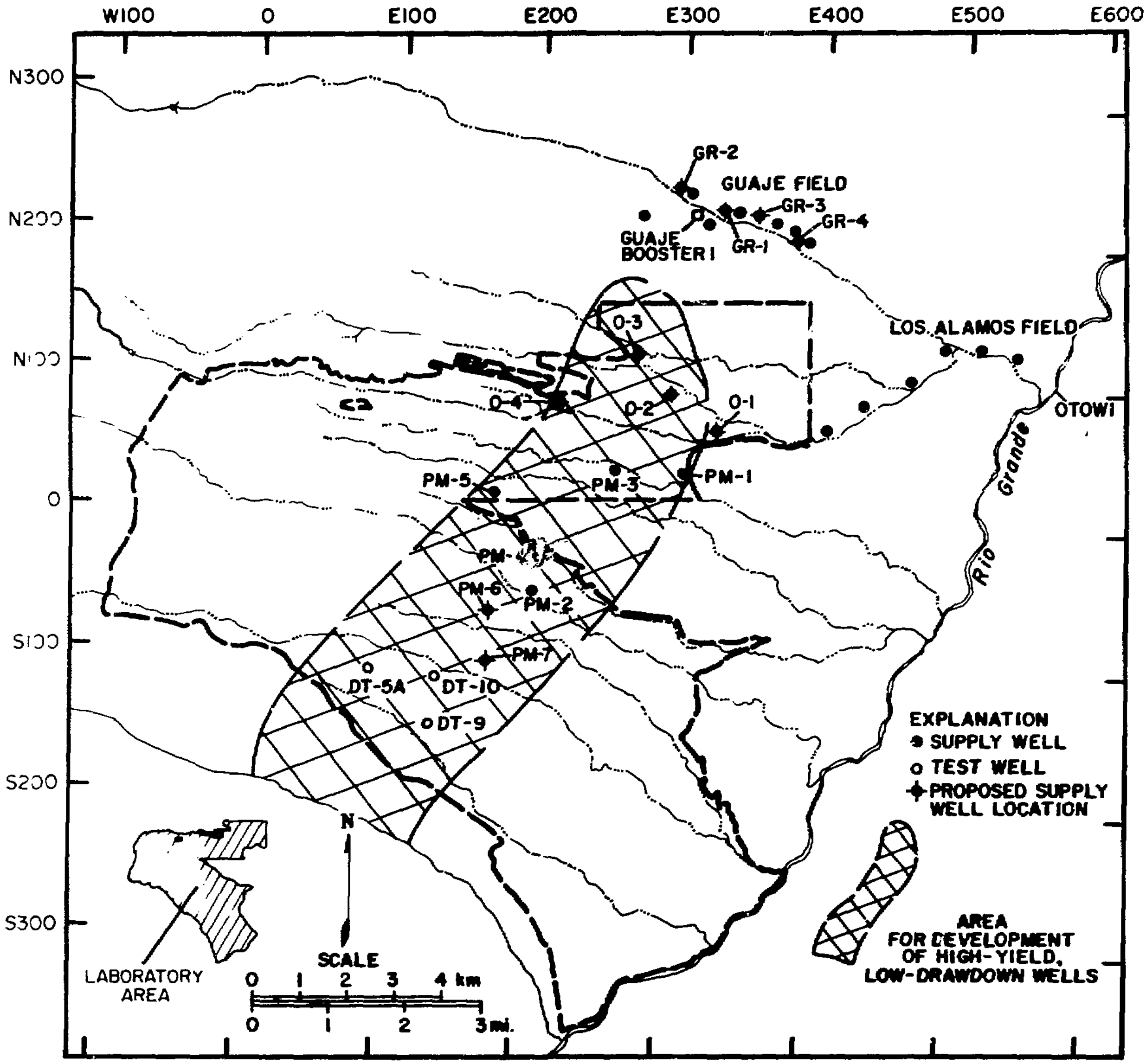

Figure 13. Proposed location for supply wells and areas for development of high-yield, low-drawdown wells.

B. Los Alamos Field

Within the next 10 years most, if not all, of the wells in the Los Alamos field will have to be replaced or relocated. The Los Alamos field is located east of Los Alamos in Santa Fe County on the San Ildefonso Pueblo Grant. The aquifer in this area is composed of siltstones and fine grained sandstones of the Tesuque Formation. Only low- to moderate-yield wells (300 to 500 gpm) can be located in this area. There has been some problem with the water quality; well LA-6 has been placed on standby because of arsenic concentrations in excess of standards for municipal use.

Location and development of additional wells for the Los Alamos field should be west of the present well field (Fig. 14). This is in an area where high yield and low drawdown (1,000 gpm with less than 100 ft drawdown) can be developed. The proposed location is on land controlled by the Department of Energy (Otowi Section). In this

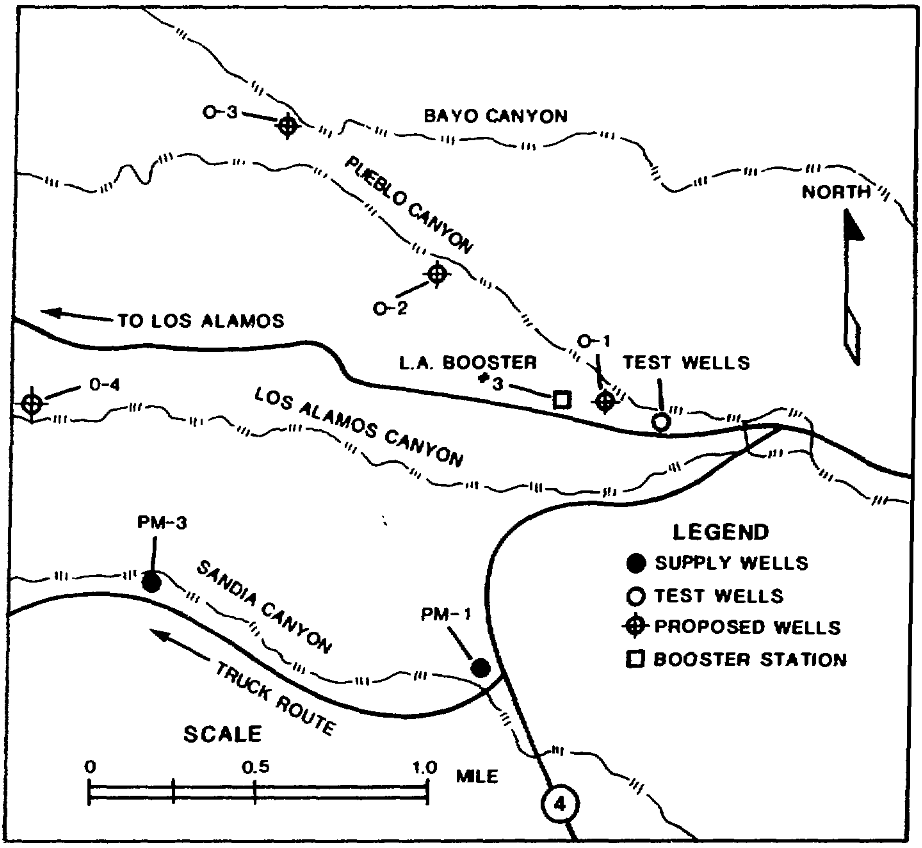

Figure 14. Proposed location for supply wells in the Otowi section.

area, the lower part of the Puye Formation is saturated and coarser sediments in the upper part of the Tesuque Formation are within the main aquifer (Table 12). Three wells could be developed in this area of lower Pueblo and adjacent to Los Alamos Canyon with adequate spacing so that cones of depression caused by pumping of the wells will not overlap. The wells should be drilled in sequence as shown (Otowi-1, -2, and -3 in Fig. 12) at about 3500 ft spacing. The well field could take advantage of the existing booster stations and water line from the Los Alamos field. Combined production rates from the three wells are expected to be at least 3,000 gpm, which will match the capacity of the booster stations. The quality of water from the wells is expected to be similar to that of well PM-1.

An alternate location for a well (Otowi-4) near the Otowi section would be in Los Alamos Canyon below TA-53 (Mason facility). The anticipated geologic log of the well is shown in Table 13. The chemical quality of water in the aquifer would be similar to the other wells in the Otowi section. The well could be used to supply TA-53 to the south or pumped into the Los Alamos line to the north at Booster No. 4 (Figs. 13 and 14).

C. Guaje Field

Within the next 10 years, six of the wells in the Guaje field should be replaced (Table 11). The five wells (G-1 through G-5) located in Guaje Canyon did not meet their full potential for yield and production due to well damage and poor construction. It is now known that screens in wells G-4 and G-5 were damaged during construction. The method of well construction in all five wells (underreaming opposite permeable sections of the aquifer and setting screen opposite the underreamed section) did not develop the wells to their full potential yield. Setting blank casing below the pump intake and screen to the bottom of future

Table 12. Anticipated Geologic Log of a Supply Well in Lower Pueblo Canyon

Elevation: 6400 to 6600 ft above sea level
Depth of Pilot Hole: 2500 ft
Hydrologic Data:
Depth to Water: 600 to 750 ft
Yield: Estimated 1000 gpm
Drawdown: Estimated 100 ft or less
Aquifer: Puye Conglomerate and Tesuque Formation

Stratigraphic Unit	Thickness (ft)	Depth (ft)
Alluvium		
Gravels and boulders	20	20
Puye Conglomerate		
Conglomerate	60	80
Basaltic Rocks of Chino Mesa		
Basalts and interflow breccia, may contain perched water, at a depth of 210 to 260 ft	205	285
Puye Conglomerate		
Conglomerate	165	450
Basaltic Rocks of Chino Mesa		
Basalts and interflow breccias	100	550
Puye Conglomerate		
Conglomerate	250	800
Tesuque Formation		
Siltstone, sandstone, and conglomerate with occasional basalt flow in upper 1200 ft of formation	1700	2500

well would allow better well development with higher resulting yields. The hydrologic characteristic of the aquifer indicates that wells with a moderate yield and low drawdown (500 to 1,000 gpm with about 100 ft of drawdown) can be developed within the present well field (Table 14).

Four wells could be developed that would replace the yield of the six wells (G-1 through G-6). The replacement wells should be spaced in a manner to cause minimum interference between the wells as they are pumped. The additional wells should not be located northwest or west of the existing wells because of the outcrop of Tschicoma in the area. The land is east of well G-1 within the San Ildefonso Pueblo Grant so the replacement well should be between G-1 and east of the Tschicoma outcrop near G-6.

The location of the wells should allow maximum spacing between the wells (Fig. 15). Construction should be done in a specific sequence with the hydrologic data collected during construction and testing evaluated to confirm the proposed location of the next well. The proposed sequence of construction would be Guaje replacement well 1 (GR-1) located about halfway between wells G-3 and G-4; a Guaje replacement

Table 13. Anticipated Geologic Log of O-4 (Otowi-4) in Los Alamos Canyon Below TA-33

Elevation: 6625 ft above sea level
Depth of Pilot Hole: 2800 ft
Hydrologic Data:
Depth to Water: 750 ft
Yield: Estimated 800-1500 gpm
Drawdown: Estimated 100 ft or less
Aquifer: Lower Puye Conglomerate and Tesuque Formation

Stratigraphic Unit	Thickness (ft)	Depth (ft)
Alluvium	20	20
Bandelier Tuff		
Ashflows and pumice	160	180
Puye Conglomerate		
Conglomerate	100	280
Basaltic Rocks of Chino Mesa		
Basalts and interflow breccia	80	360
Puye Conglomerate		
Conglomerate	500	860
Tesuque Formation		
Siltstone, sandstone, and conglomerate with possible basalt flows	1940	3800

well 2 (GR-2) located 150 ft from well G-5; Guaje replacement well 3 (GR-3) located midway between G-2 and G-3, and Guaje replacement well 4 (GR-4) located near well G-1. The existing wells with yields at or about 300 gpm should be left on the line as the replacement wells are drilled. The chemical quality of the replacement wells will be similar to the existing wells.

D. Pajarito Field

The Pajarito field is composed of five wells; four are developed as high yield wells (Table 11). The age and present condition of the wells suggest that there is no need for replacement in the next 20 years. New wells may be needed if additional water production is required to supplement the production from the three fields.

The Pajarito field north and west of PM-2, -4, or -5 cannot be expanded and still remain in the area where high-yield wells can be developed. Also, space is unavailable in Sandia Canyon for additional wells if space is maintained between wells to reduce interference or overlapping drawdown.

The suggested location for additional wells in the Pajarito field is southwest of well PM-2 (Fig. 13). The locations are chosen for maximum spacing between wells to minimize the interference between wells when they are pumping and to align the wells perpendicular to the movement of groundwater in the main aquifer.

One well, Pajarito 6 (PM-6), could be located about 3500 ft southwest of PM-2 at an elevation of about 6850 ft. This well is recommended if the proposed M-Division central

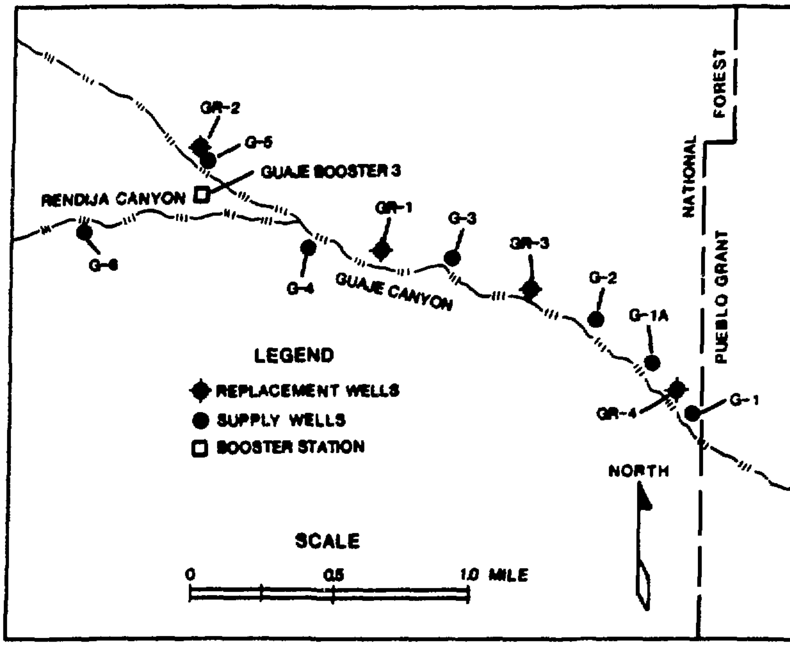

Figure 15. Proposed location for replacement wells in Guaje field.

Table 14. Anticipated Geologic Log of a Supply Well
Near Well G-4 in Guaje Canyon

Elevation: 6230 ft above sea level
Depth of Pilot Hole: 2000 ft
Hydrologic Data:
Depth to Water: 400 ft
Yield: Estimated 500 gpm
Drawdown: Estimated 100 ft or less
Aquifer: Tesuque Formation

Stratigraphic Unit	Thickness (ft)	Depth (ft)
Alluvium		
Gravels and boulders	15	15
Puye Conglomerate		
Conglomerate	105	120
Tesuque Formation		
Siltstone and sandstone	380	500
Basalt and interflow breccia	30	530
Siltstone and sandstone	330	860
Basalt and interflow breccia	75	935
Siltstone and sandstone	30	965
Basalt and interflow breccia	20	980
Siltstone and sandstone	130	1110
Basalt and interflow breccia	40	1150
Siltstone and sandstone	850	2000

Table 15. Anticipated Geologic Log of Supply Wells on the Pajarito Plateau South of Well PM-2

Elevation: 6850 ft above sea level
Depth of Pilot Hole: 2850 ft
Hydrologic Data:
Depth to Water: 950 ft
Yield: Estimated 1000 gpm
Drawdown: Estimated 100 ft or less
Aquifer: Puye Conglomerate and Tesuque Formation

Stratigraphic Unit	Thickness (ft)	Depth (ft)
Bandelier Tuff		
Ashflow tuff and pumice	650	650
Basaltic rocks of Chino Mesa		
Basalt and interflow breccia	350	1000
Puye Conglomerate		
Conglomerate	650	1650
Tesuque Formation		
Sandstone and conglomerate	400	2050
Basalt and interflow breccia	50	2100
Sandstone and siltstone	200	2300
Basalt and interflow breccia	100	2400
Siltstone and sandstone	450	2850

complex is developed; this would provide a water source for the complex and preclude pumping the water to the reservoir string and feeding it back down to R-Site. A second well, Pajarito 7 (PM-7), may be located about 7000 ft southwest of PM-2 at an elevation of about 6800 ft (Fig. 11). High-yield wells can be developed at these locations (Table 14). The water quality should be similar to that of PM-2.

REFERENCES

Black 1951: Black and Veatch, Consulting Engineers, "Report on Water Supply, Los Alamos Project, Los Alamos, New Mexico," Kansas City, MO, Admin. Rept. to United States Atomic Energy Commission (1951).

Cushman 1965: R. L. Cushman, "An Evaluation of Aquifer and Well Characteristics of Municipal Well Fields in Los Alamos and Guaje Canyons Near Los Alamos, New Mexico," U.S. Geol. Survey Water-Supply Paper 1809-D (1965).

Cushman 1975: R. L. Cushman and W. D. Purtymun, "An Evaluation of Yield and Water Relations," Los Alamos Scientific Laboratory report LA-6086-MS (1975).

Foreman 1985: Gordon Foreman, "Instructions for Pumping Schedule," Los Alamos Informal Memorandum to PAA UWGW Well Operation (1985).

Griggs 1964: R. L. Griggs, "Geology and Ground-Water Resources of the Los Alamos Area, New Mexico," U.S. Geol. Survey Water-Supply Paper 1753 (1964).

Herkenhoff 1974: Gorden Herkenhoff and Associates, Engineers and Planners, "Comprehensive Plan for Water System Improvement, Los Alamos, New Mexico," Contract at (29-1) 2201, Albuquerque, NM (1974).

Keiser 1985: Raymond Keiser, Consulting Engineers, "Long Range Utilities Plan," ENG-11, Los Alamos, New Mexico (1985).

Purtymun 1965: W. D. Purtymun and J. B. Cooper, "Locations for Five Water-Supply Wells at Los Alamos, New Mexico," U.S. Geol. Survey Open-File report (1965).

Purtymun 1969: W. D. Purtymun and J. B. Cooper, "Development of Ground-Water Supplies on the Pajarito Plateau, Los Alamos County, New Mexico," U.S. Geol. Survey Prof. Paper 650-B (1969).

Purtymun 1972: W. D. Purtymun and J. E. Herceg, Compilers, "Summary of Los Alamos Municipal Well-Field Characteristics, 1947-1971," Los Alamos Scientific Laboratory report LA-5040-MS (1972).

Purtymun 1972a: W. D. Purtymun and J. E. Herceg, "Water Supply at Los Alamos During 1971," Los Alamos Scientific Laboratory report LA-5039-MS (1972).

Purtymun 1973: W. D. Purtymun and J. E. Herceg, "Water Supply at Los Alamos During 1972," Los Alamos Scientific Laboratory report LA-5296-MS (1973).

Purtymun 1974: W. D. Purtymun and J. E. Herceg, "Water Supply at Los Alamos During 1973," Los Alamos Scientific Laboratory report LA-5636-MS (1974).

Purtymun 1975: W. D. Purtymun, "Water Supply at Los Alamos During 1974," Los Alamos Scientific Laboratory report LA-5998-MS (1975).

Purtymun 1976: W. D. Purtymun, "Water Supply at Los Alamos During 1975," Los Alamos Scientific Laboratory report LA-6461-PR (1976).

Purtymun 1977: W. D. Purtymun, "Water Supply at Los Alamos During 1976," Los Alamos Scientific Laboratory report LA-6814-PR (1977).

Purtymun 1977a: W. D. Purtymun, "Hydrologic Characteristics of the Los Alamos Well Field with Reference to the Occurrence of Arsenic in Well LA-6," Los Alamos Scientific Laboratory report LA-7012-MS (1977).

Purtymun 1978: W. D. Purtymun, "Water Supply at Los Alamos During 1977," Los Alamos Scientific Laboratory report LA-7436-MS (1978).

Purtymun 1979: W. D. Purtymun, "Water Supply at Los Alamos During 1978," Los Alamos Scientific Laboratory report LA-8074-PR (1979).

Purtymun 1980: W. D. Purtymun, "Water Supply at Los Alamos During 1979," Los Alamos Scientific Laboratory report LA-8504-PR (1980).

Purtymun 1981: W. D. Purtymun and Max Maes, "Water Supply at Los Alamos During 1980," Los Alamos National Laboratory report LA-8977-PR (1981).

Purtymun 1983: W. D. Purtymun, N. M. Becker, and Max Maes, "Water Supply at Los Alamos During 1981," Los Alamos National Laboratory report LA-9734-PR (1983).

Purtymun 1984: W. D. Purtymun, N. M. Becker, and Max Maes, "Water Supply at Los Alamos During 1982," Los Alamos National Laboratory report LA-9896-PR (1984).

Purtymun 1984a: W. D. Purtymun, "Hydrologic Characteristics of the Main Aquifer in the Los Alamos Area: Development of Ground Water Supplies," Los Alamos National Laboratory report LA-9957-MS (1984).

Purtymun 1985: W. D. Purtymun, N. M. Becker, and Max Maes, "Water Supply at Los Alamos During 1983," Los Alamos National Laboratory report LA-10327-PR (1985).

Purtymun 1986: W. D. Purtymun, N. M. Becker, and M. N. Maes, "Water Supply at Los Alamos During 1984," Los Alamos National Laboratory report LA-10584-PR (1986).

Purtymun 1986a: W. D. Purtymun, N. M. Becker, and M. N. Maes, "Water Supply at Los Alamos During 1985," Los Alamos National report LA-10835-PR (1986).

Purtymun 1987: W. D. Purtymun, A. K. Stoker, and M. N. Maes, "Water Supply at Los Alamos During 1986," Los Alamos National Laboratory report LA-11046-PR (1987).

Theis 1962: C. V. Theis and C. S. Conover, "Pumping Test in the Los Alamos Canyon Well Field near Los Alamos, New Mexico," U.S. Geol. Survey Water-Supply Paper 1619-I 1962).