A CHEMICAL AND ISOTOPIC STUDY OF GROUND WATER FROM THE TUCSON MOUNTAINS, ARIZONA

by

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ABSTRACT

The study area, located on the eastern side of the Tucson Mountains, was divided into three topographic areas: the mountains, the piedmont and the bottom-land. Chemical analyses of 54 samples were used to characterize the chemical composition of ground water from each area. Seven of the samples were analyzed for deuterium and oxygen-18. High concentrations of dissolved solids were found in samples from the mountain area.

Possible sources of dissolved solids and patterns of ground-water flow were examined in light of the chemical and isotopic data. The concentrations of bromide were used to determine that evaporite rocks are not a likely source of dissolved solids in the mountain area. Significant amounts of ground water probably do not flow from the mountain to the piedmont or bottom-land areas. The piedmont was identified as a minor recharge area.

CHAPTER 1

INTRODUCTION

Domestic wells in the Tucson Mountains (Figure 1) commonly yield water with a large concentration of dissolved solids. Wells near the Santa Cruz River channel, about three miles from the mountains, produce water that is also fairly high in dissolved solids. At the same time, wells on the piedmont between the mountains and the river, yield good quality water with a much lower concentration of dissolved solids. Chemical and isotopic information on the ground water in these three areas has been collected and analyzed in this study.

Purpose of the Investigation

The availability of, and need for, water-quality information is increasing as more houses are built in the Tucson Mountains. Many of these families depend on private wells for their domestic water supply. This study provides information on the quality of water that can be expected in different parts of the study area and may result in a wiser placement of such wells.

Furthermore, hydrochemical data can be used to analyze patterns of regional ground-water flow. Recharge and discharge areas may be identified, flow direction may be found, and the interaction of surface and ground-water system can be observed by monitoring

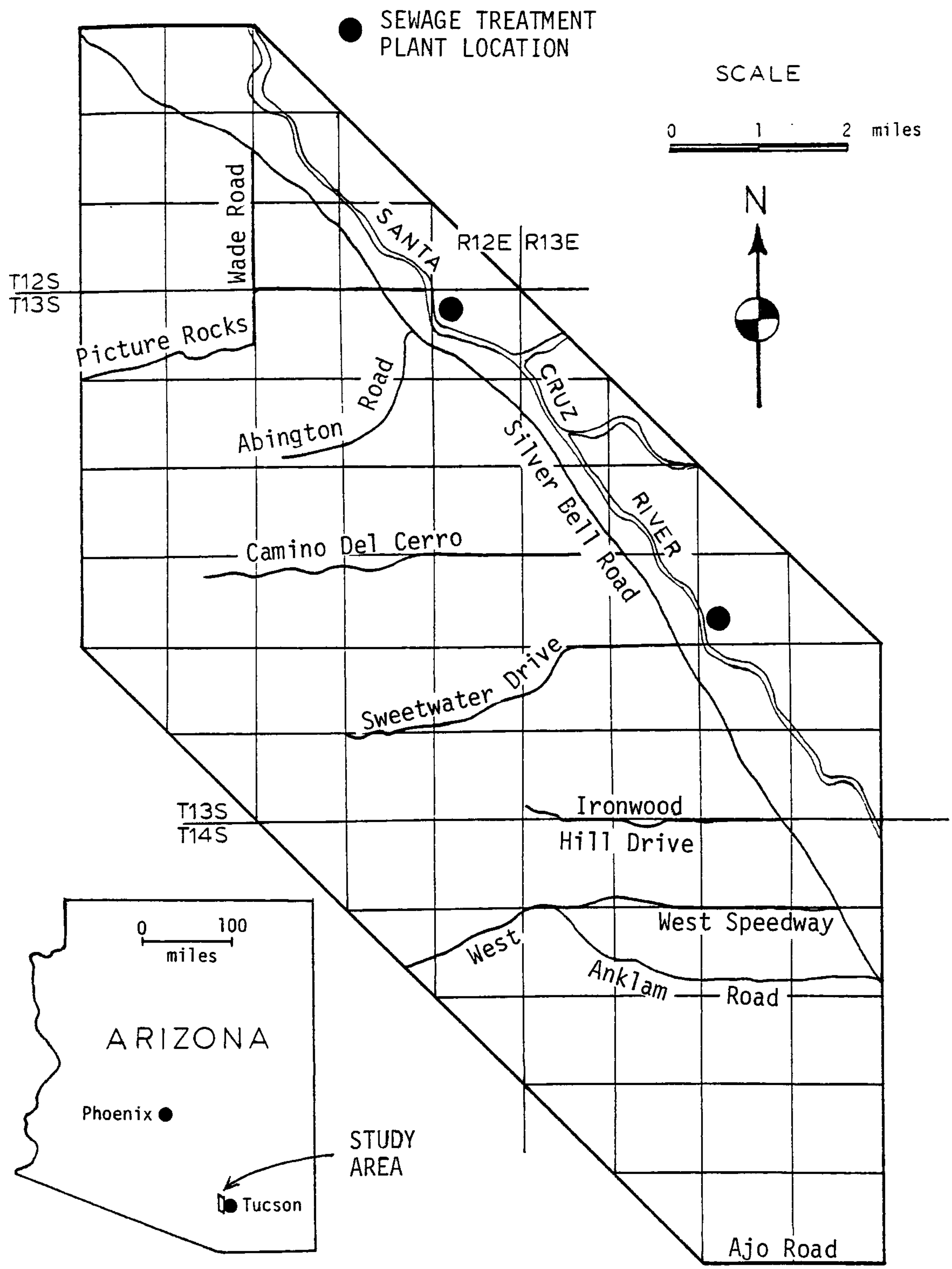

Figure 1. Location of the Study Area.

dissolved constituents and environmental isotopes. Chemical and isotopic evidence has been used in this study to develop a reasonable concept of the ground-water flow system in the Tucson Mountains. The most likely sources of dissolved solids were determined, the possibility of a hydrologic connection between the two areas of high dissolved solids was examined, and the amount of recharge contributed to Tucson basin aquifers by the Tucson Mountains was estimated.

Method of Study

The study area was divided into three parts based on topography. Chemical analyses of 24 ground-water samples, taken since 1965, were obtained from previous investigations and 30 additional wells were sampled. The quality of water from different areas was compared and maps showing the areal distribution of certain chemical constituents were made.

Four hypothetical systems of ground-water flow that could account for the observed water-quality trends are presented in the chapter entitled "Discussion". The most likely hypothesis was determined by looking at the distribution of specific chemical constituents and stable isotopes.

System for Describing Well Locations

The location of wells is described according to the U. S. Geological Survey system. The State of Arizona is divided into four quadrants. All wells in this study are in the southeast, or D quadrant. The location description begins with the letter "D" to indicate the quadrant. This is followed by the township number, the range number, the section number and three lower case letters that designate a ten acre area according to the diagram in Figure 2. For example, the well shown would be designated D 13 12 6acb.

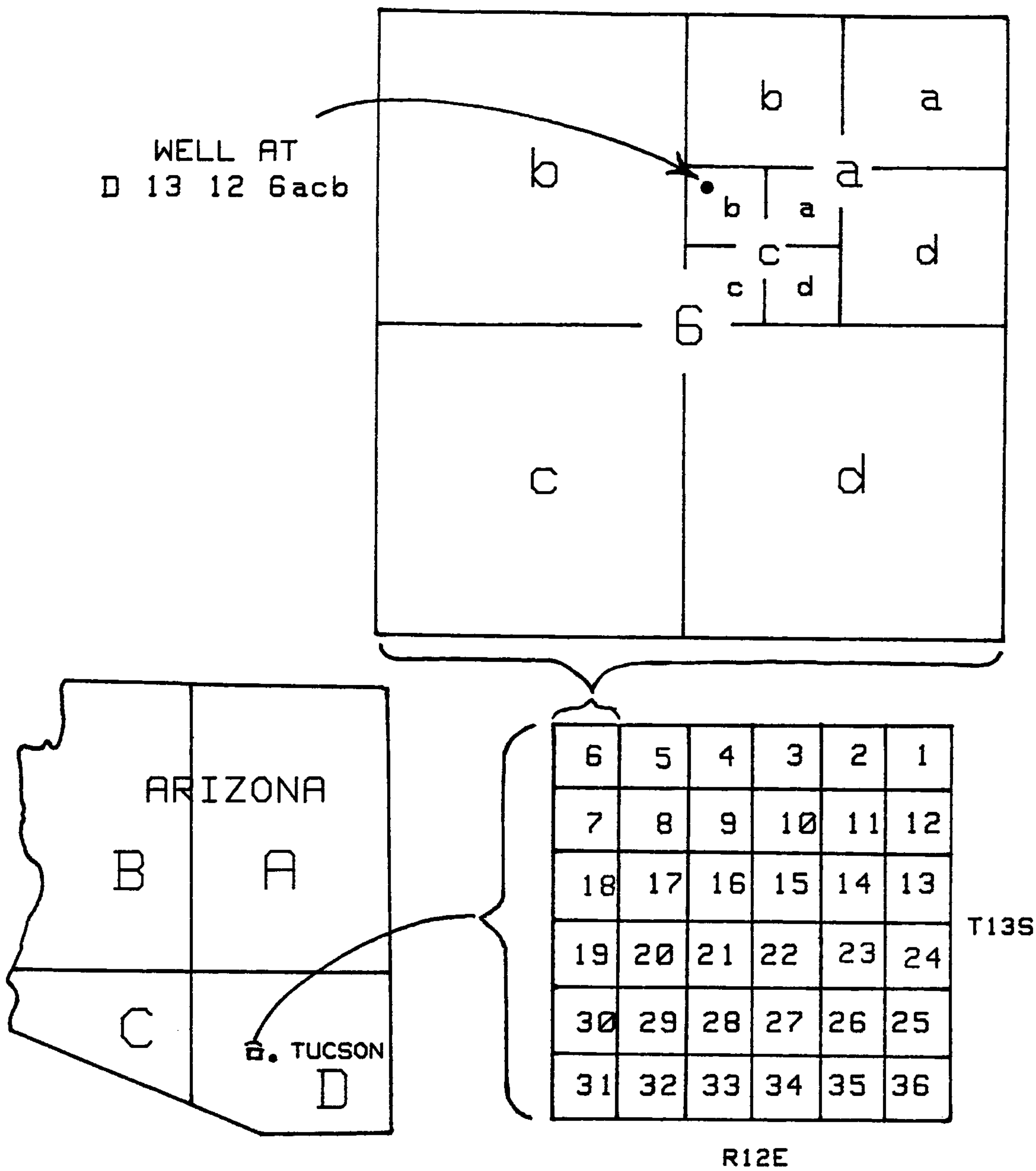

Figure 2. System for Describing the Location of Water Wells.

CHAPTER 2

DESCRIPTION OF STUDY AREA

This study is concerned with a 70-square mile area (Figure 1) encompassing the northwestern edge of the Tucson basin and the eastern slope of the Tucson Mountains. The study area is in Pima County, Arizona, near the city of Tucson.

The Tucson mountains form a ground-water divide which borders the study area on the west. The east side is bounded by the Santa Cruz River. The area extends northward to the end of the Tucson mountains. Its southern boundary is Ajo Road. However, most of the data pertains to the area north of Speedway Boulevard. Wells are scarce in the southern end of the study area.

General Features

Topography

The Tucson basin and Tucson mountains are part of the Basin and Range physiographic province. The basin floor is relatively flat and lies at an elevation of about 2,200 feet. The Tucson mountains bound the basin on the northwest and have a maximum elevation of 4,687 feet. A view of the mountains is shown in Figure 3.

The study area can be divided into three topographic areas: 1) the mountains, 2) the piedmont, and 3) the Santa Cruz bottom-land.

Figure 3. Looking West at the Tucson Mountains from D 13 14 27aaa.

Figure 4. A Domestic Well in the Mountain Area at D 13 12 9ada
Looking North.

Figure 4 shows a household well in the mountain area. Many of these wells are drilled in the dry stream beds between bedrock hills. Figure 5 shows a well on the gently sloping piedmont. A bottom-land irrigation well is shown in Figure 6.

Climate

The climate in this part of Arizona is semi-arid with mild winters and warm summers. The mean temperature is 19.7°C (67.4°F) and temperatures reach 38°C (100°F) an average of 41 days each year (NOAA, 1980).

Mean annual precipitation in Tucson is 28.2 cm (11.1 inches). Some of the higher mountain ranges in the area receive as much as 76 cm (30 inches) per year. However, the Tucson Mountains are lower and probably receive about the same amount as the basin. There is a weather station about three miles southwest of Cortaro which also reports 28.2 cm (11.1 inches) per year (Sellers and Hill, 1974). About half this rain falls during the period of July through September as a result of convective thunder storms. These storms are generally of short duration, small area extent, and high intensity. Most of the remaining precipitation results from frontal storms during the winter months. These storms produce widespread rainfall of much lower intensity than the summer storms. Average pan evaporation is about 254 cm (100 inches) per year.

Figure 5. A Domestic Well in the Piedmont Area at D 13 12 4daa Looking West.

Figure 6. View Facing North, Showing an Irrigation Well at D 13 12 2aad in the Bottom-Land Area.

Streamflow

There are no naturally perennial streams in the study area. However, the Santa Cruz River flows year-round below the two sewage treatment plants shown in Figure 1. The plants discharge about 40,000 acre-feet per year of treated effluent to the river bed. Many washes collect occasional storm runoff and carry it to the Santa Cruz River, which is the only surface water outlet from the Tucson basin. Condes de la Torre (1970) has given data on streamflow in the Santa Cruz River and its major tributaries.

Vegetation

Plants found in the study area are typical of the Sonoran desert. Phreatophytes include saltcedar, cottonwood and mesquite. These are found near the Santa Cruz River and along many of the washes. Most of the piedmont is covered by chaparral. Cacti are plentiful, especially on the lower mountain slopes (Turner, 1974).

Hydrogeology

Consolidated Rocks

The Tucson mountains are comprised of sedimentary and volcanic rocks which have been uplifted and tilted by Basin and Range faulting. There have been two periods of major volcanic activity. The first was in late Mesozoic, the second in mid-Cenozoic. The youngest volcanic formation is a basaltic andesite whose age was determined to be 19.8 million years by Damon (1968). A good review of geologic investigations of the Tucson mountains has been given by Mayo (1968).

The older volcanic rocks have low porosity and permeability, but are reported to contribute water to a few low-yield wells (Davidson, 1973). Davidson (1973) also reported that the younger volcanics, which largely make up the northern and eastern mountain slopes, are moderately to highly permeable. However, these rocks are generally above the water table. Sandstone and limestone beds are found between the two major volcanic units. These sedimentary rocks have beed dated as Cretaceous (Damon, 1968). They may be moderately permeable, especially in areas of fracturing and faulting.

Unconsolidated Deposits

Nearly all the ground water presently recovered in the Tucson basin is found in unconsolidated to semi-consolidated basin fill deposits. The alluvium has been deposited by stream action as the surrounding mountains are uplifted and eroded. The process began in Cenozoic time and is continuing today.

The alluvium has been studied by Maddox (1960), Abuajamieh (1966), Pashely (1966), Davis (1967), and Davidson (1973). Table 1 gives a summary of the hydrogeological characteristics of the four major formations identified by Pashley (1966) and Davidson (1973).

The oldest and thickest formation is the Pantano. It is several thousand feet thick in the deepest part of the Tucson basin. Only a few wells penetrate this unit. Many more wells produce water from the Tinaja Formation, which is separated from the Pantano by an erosional unconformity. Another unconformity separates the Tinaja from the overlying Fort Lowell Formation. The Fort Lowell is currently

Table 1. Summary of Hydrogeological Characteristics of Sedimentary Formations in the Tucson Basin (after Pashley, 1966, Davidson, 1973, and Fogg et al. 1979).

Unit Name and Age	Composition (determined from well cuttings and logs and corings)	Thickness[b] (feet)	1. Porosity[c] 2. Permeability[c] 3. Transmissivity[c]/Specific Capacity	Water Quality	Comments
Pantano Formation (Type I Rillito beds)[a]	weakly to strongly cemented conglomerate, sandstone, and mudstone interbedded with volcanic flows and tuffs	0 - ?	1. .2-.27 (sandstone and gravel) 2. .5-15 ft/day 3. ?/at least 3840 ft^3/day/ft for wells tapping 500-1,000 feet of the units; up to 7700 ft^3/day/ft	TDS[d] 3000 mg/l in most wells; and 1000 in some wells flouride 1 mg/l	Yields of wells having diamteres greater than 12 inches range from approx. 300 to 5000 gpm (57,600-86,400 ft^3/day)
Tinaja beds (Types I & II - Rillito beds)[a]	sandy gravel dominant at basin margins -- grades into gypsiferous clayey silt and mudstone along central axis of basin	0 to greater than 2000 and perhaps as much as 5000	1. .26-.35 2. 1-50 ft/day 3. 1,300-20,000 ft^2/day	TDS 500 mg/l may be more than 1000 mg/l where abundant silt or fines are present	unconformably overlies the Pantano
Fort Lowell Formation (basin fill deposits)[a]	silty gravel near basin margins -- grades to a silty sand and clayey silt in the central parts; the sediment is loosely packed to weakly semented	300-400 in most places	1. .26-.34; average: .30; .50 for 4 wells in which 50% or more of material was sand and gravel 2. 20-100 ft/day 3. - /1900-19000 ft^3/day/ft	TDS 500 mg/l in general, is well suited for public supply	unconformably overlies Tinaja beds
Surficial deposits	mainly composed of gravel and gravelly sand and are fluvial in origin	5 to probably no more than 100, avg. 30; along streams 40 to 100 (avg. 50)	1. -- 2. -- 3. --	--	dry in most places

[a]Corresponding name used by Pashley (1966).

[b]Determined from formation density logs.

[c]Very rough estimate determined from aquifer test.

[d]Total dissolved solids.

the most productive formation in the basin. However, it is less than 400 feet thick, at most, and falling water levels have completely dewatered it in some places (Davidson, 1973).

Most of the aquifers in the Tucson basin appear to be unconfined and hydraulically connected. Thus, pumping from one formation affects the others. In general, porosity and permeability decrease with depth, as the amount of compaction increases. Laney (1972) has speculated that faults cause zones of increased permeability where mixing of water between the formations is more pronounced than in the rest of the basin.

Regional ground-water flow is to the northwest. Goodoff (1975) used gravity differences to show that the northwestern part of the Tucson basin is actually a separate subsurface basin. Ground water flows into this area, called the Cortaro basin, from the Tucson basin. It then continues to flow northwest and exits the basin through Rillito narrows, a natural constriction in the bedrock surface. The bedrock rises to within 1,800 feet of the surface near the southwestern entrance to Cortaro basin. The depth then increases rapidly to a maximum of about 5,000 feet. At Rillito narrows the bedrock is about 500 feet deep.

Depth of Water Table

The depth of water in the Tucson and Cortaro basins range from less than 100 feet to greater than 500 feet. The water table is generally closest to the surface near the Santa Cruz River (Martin, 1980). Water levels have declined more than 50 feet in parts of the basin during the last 30 years.

The water table becomes shallow near the mountain fronts due to the lower permeability of the shallow bedrock and the input of runoff from the mountains. In some places, water can be found at depths of a few feet in the washes draining the Tucson mountains.

Ground-Water Recharge

Ground water enters the Tucson basin as underflow from adjacent basins and as recharge from precipitation. Table 2 gives the estimated recharge from different sources. The greatest amount of mountain front recharge occurs along the mountains north and east of the basin. Recharge from the Tucson mountains is much less important because of smaller area and less precipitation. The Tucson mountains have been reported to provide about 100 acre-feet per year of water to the Tucson basin aquifers (Oskerkamp, 1973).

Infilitration in stream channels is the only other important source of recharge. Most rain falling on the basin floor evaporates or runs off. The runoff water accumulates in stream beds where sediments are coarse and permeability is relatively high. Burkham (1970) has calculated infiltration rates for all major streams in the Tucson basin.

Stream bed infiltration of another kind is important in the northern end of the basin, where large volumes of treated sewage are released to the Santa Cruz River bed. Some treated sewage is also used for irrigation in this area. The effect of these practices on the ground water has been studied by Cluff, DeCook and Matlock (1972), Schmidt (1972), Herbert (1976), Schultz et al. (1976), Wilson, Martin, and Lonergan (1977) and Martin (1980).

Table 2. Estimated Amounts of Ground-Water Recharge in the Tucson Basin (Data from Oskerkamp, 1973).

	Acre feet/year
Mountain Front Recharge	
Santa Rita Mountains	7,400
Rincon and Tanque Verde Mountains	3,800
Santa Catalina Mountains	11,700
Tortollita Mountains	7,100
Tucson Mountains	100
Sierrita Mountains	4,000
Stream Channel Infiltration	
Santa Cruz River	21,010
Canada Del Oro and tributaries	6,440
Tanque Verde Creek and tributaries	7,450
Pantano Creek and tributaries	8,660
Rillito Creek	9,670
Total Recharge	87,330

CHAPTER 3

PREVIOUS GROUND-WATER CHEMISTRY INVESTIGATIONS

Much study has been devoted to the chemical quality of ground water in the Tucson basin because of the importance of this resource. It is the only important source of water for municipal, industrial, and agricultural uses. Ground-water chemistry and stable isotopes have also been used as tools in analyzing the hydrodynamics of the basin. The University of Arizona in Tucson has provided a source of funding and personnel for much of this work.

Tucson Basin Water Quality

An Overview

Water samples from the basin were analyzed for chemical constituents at the University of Arizona before the turn of the century (Collingwood, 1891). Later studies by Skinner (1903), Catlin (1926), Smith et al. (1949), and Dutt and McCreary (1970) have presented the results of analyses of numerous ground-water samples from throughout the state. Feldman (1966) compared ground-water chemistry in different parts of the basin and attempted to relate the differences to geology. He concluded that, "The very good chemical quality areas are associated with the gneissic material from the mountains to the northeast. The poorest quality water generally comes from the Pantano beds." He also noted that water from the Santa Cruz bottom-land west of Tucson was of poor quality and that better quality water could be found between the river and the Tucson Mountains. No wells in the mountains were used in his study.

Smoor (1976) used chemical analyses from more than 100 city-owned wells in a multivariate statistical analysis. He examined quality changes as ground water moves through the Tucson basin. In contrast to Feldman, Smoor found the basin-fill lithology was a less important factor than the amount of recharge and conditions at the recharge site. He gave a detailed discussion of calcite equilibrium, but was unable to make any conclusions about the process in this area.

Laney (1972) has probably given the most comprehensive report on ground-water quality in the Tucson basin. He described water below 700 feet as coming from the deep aquifer. This includes the Pantano Formation and lower Tinaja beds. Water above this level comes from the shallow aquifer, mainly the upper Tinaja beds and Fort Lowell Formation. Water with total dissolved solids (TDS) concentration between 500 and 3000 mg/l was found in parts of the deep aquifer. This water comes from fine grained sediments of the Pantano Formation which contains gypsiferous mudstone and is dominated by calcium, sodium and sulfate ions. Chloride concentrations of more than 500 mg/l are common. Other parts of the deep aquifer are composed of coarse grained sediments and yield water with 300 to 500 mg/l TDS. This water is dominated by sodium and bicarbonate. Water from the deep aquifer is characterized by high levels of flouride. Concentrations greater than 1 mg/l are common and some samples have 5-10 mg/l (Laney, 1972).

Water from the shallow aquifer is of good quality in most areas. TDS are less than 500 mg/l with calcium, sodium and bicarbonate being the dominant ions. Laney (1972) described some areas where the shallow ground water is of anomalously poor quality. These were attributed to the upward movement of ground water along fault zones from fine grained deposits in the deep aquifer. One such area is along the Santa Cruz River on the west side of the basin. Laney also suggested that poor quality ground water along stream channels may be the result of dissolution of relic salts that were deposited by evaporation when the water table was higher.

The Cortaro Area

Investigations of ground-water chemistry have been particularly intensive in the Cortaro basin. Most authors have been concerned with changes in water quality down-gradient from the two sewage treatment plants in the area.

Davis and Stafford (1966) conducted a survey of ground-water quality in the vicinity of Tucson City's Rodger Road treatment plant. They sampled 105 wells between the plant and the town of Marana, about 14 miles away. Many of the wells contained high levels of nitrate and chloride. Alkyl benzene sulfonate, present in laundry detergents at that time, was found in several of the wells near the channel of the Santa Cruz River. Data from 1929, 1944 and 1966 were used to show that water quality had changed significantly since 1944.

Other sampling programs were reported by Cluff, DeCook, and Matlock (1972), and Matlock, Davis, and Roth (1972). These studies verified the presence of high nitrate and chloride ground water near the river channel and near fields that had been irrigated with effluent. However, many of the nitrate concentrations were not found to be as high as reported in 1966. High concentrations of boron were also found along the river. Boron concentration is normally low in the shallow aquifers of the Tucson basin. Therefore, this was taken as an indication of sewage effluent, which contains large amounts of boron.

Schmidt (1972, 1973) monitored nitrate and chloride concentrations in 26 irrigation wells during the 1971 and 1972 growing seasons. He found high nitrate concentrations mainly on the west side of the river. He reasoned that good quality water was moving into the area from the recharge area near the Santa Catalina mountains. Water temperature was found to be relatively cool for the high nitrate water. This could indicate recent infilitration.

Water quality maps were prepared by Schultz et al. (1976) in order to examine the movement of infiltrated sewage effluent. This study relied mainly on the data gathered by Matlock et al. (1972). The presence of trichlorofluoromethane (Freon 11) was noted. This compound has been introduced to the environment by man and indicates that water has been recharged to the aquifer since about 1930.

Monitoring of ground-water quality has continued with the work of Wilson, Martin and Lonergan (1977), and Martin (1980). Figure 7 shows changes in nitrate and chloride concentrations for three wells affected by sewage effluent irrigation. The concentration of these ions probably started to decrease in about 1970, when effluent irrigation was largely stopped. However, the concentrations of nitrate and

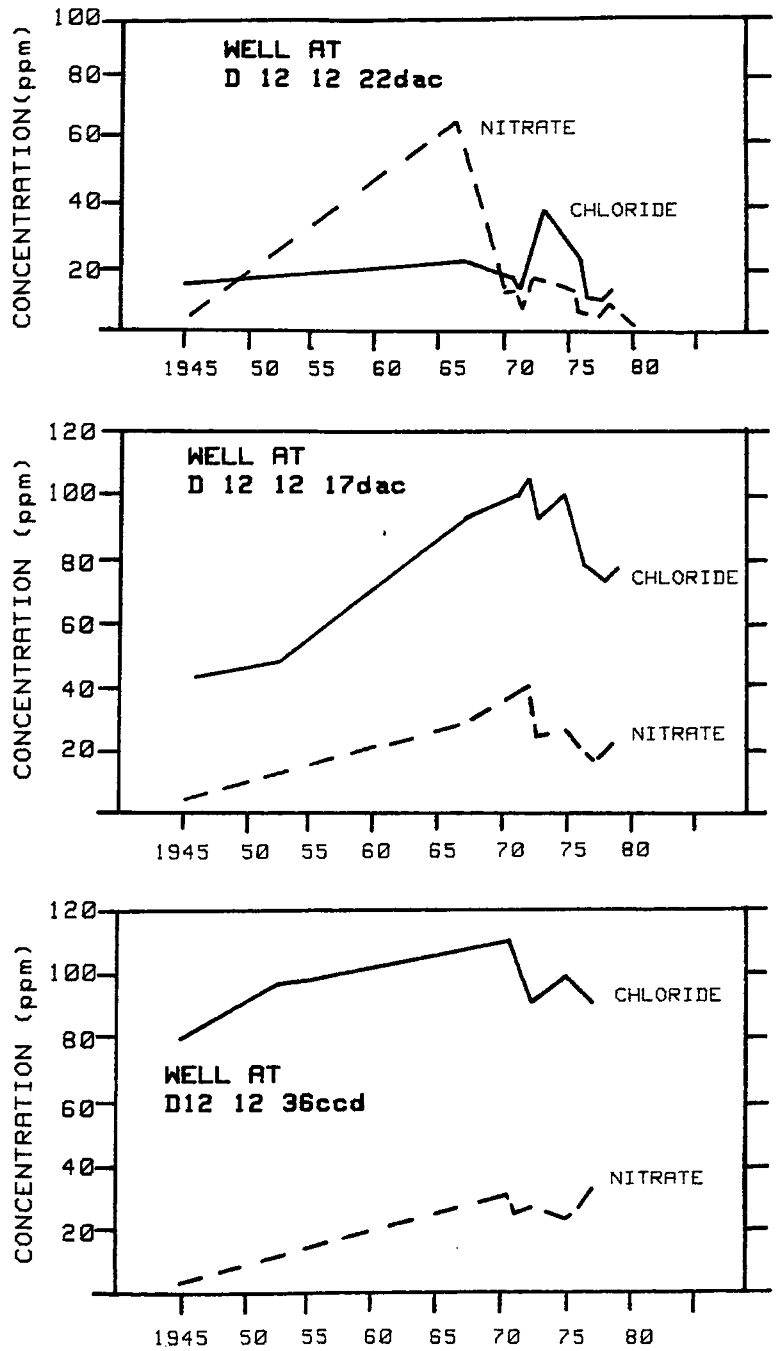

Figure 7. Changes in Nitrate and Chloride During the 34 Year Period 1944-1978 for Wells at D 12 12 22dac, 17dac and 36ccd (Martin, 1980).

chloride are still generally higher than they were in 1944, and some areas are actually increasing because of increased sewage discharged to the river bed. Martin (1980) gave the results of nitrogen isotope studies carried out in an attempt to identify the source of the nitrate. He concluded that the samples taken below the treatment plant are isotopically heavy and this indicates that sewage effluent is the probable source of contamination.

The Tucson Mountains

In contrast with the adjacent Cortaro area, quality of ground water from the Tucson mountains is virtually unstudied. Some analyses have been reported from piedmont wells and the good quality water in that region has been noted (Feldman, 1966).

Davidson (1973) reported that a few wells produce small amounts of water from the volcanic rocks in the Tucson Mountains. The older volcanic rocks and tightly cemented sedimentary layers yield water mainly from fractures. This water generally is good chemical quality according to Davidson. Where they are saturated, the younger volcanics yield water from fractures and vesicular spaces. These rocks are moderatley to highly permeable and yield water which is low in dissolved solids. But they generally lie above the water table (Davidson, 1973).

Stable Isotope Studies

Development

Techniques for measuring the isotopic composition of water were deveolped in the early 1950's. Since then the study of stable isotopes has become an important aspect of ground-water hydrology. The isotopes of hydrogen and oxygen make good ground-water tracers because they are not sorbed by the aquifer matrix and, at low temperatures, they do not react with other chemicals in the water (Brown et al. 1972).

The most abundant isotopic form of water is $H_2{}^{16}O$. There are two other stable species which are of interest in hydrology. They are $H_2{}^{18}O$ and $HD^{16}O$ where D represents the hydrogen isotope, deuterium. The isotopic ratios, D/H and $^{18}O/^{16}O$, of a water sample are expressed in terms of per mille difference (δ°/oo) with respect to mean ocean water (Craig, 1961a). For example, water with $\delta^{18}O$ = +5°/oo has an oxygen-18 content 5°/oo higher than mean ocean water.

This mass difference between isotopes of the same element results in a slight difference in their physical and chemical properties. Therefore, when a substance containing different isotopes undergoes a partial phase change, the isotopic composition of the substance remaining in the original phase is slightly different from that of the new phase. This process is called isotopic fractionation.

Precipitation results from partial evaporation of a water body followed by partial condensation in a cloud. Therefore, rainfall is usually isotopically lighter than ocean water and heavier than the vapor in the cloud. The degree of fractionation depends upon climatic conditions at the time of evaporation and condenstation, the amount of precipitation already released from the cloud and the isotopic composition of the original water body. These factors cause variations in the isotopic composition of precipitation according to season, latitude and altitude which can be used to trace ground-water movement (Ehalt et al. 1963; Woodcock and Friedman, 1963; Dansgaard, 1964; Friedman et al. 1964).

Stable isotopes can also be used to determine if a water sample has been subject to evaporation under non-equilibrium conditions. Craig (1961b) showed that the deuterium and oxygen-18 content of precipitation (Figure 8) are related by the expression:

$$\delta D^{\circ}/_{oo} = 8\delta^{18}O^{\circ}/_{oo} + 10.$$

This relationship holds whenever the evaporation and condensation process take place at equilibrium. If evaporation takes place under non-equilibrium conditions, the deuterium versus oxygen-18 point will fall to the right of this line. The samples from closed basins plotted in Figure 8 have been subject to non-equilibrium evaporation.

Tucson Basin Studies

Stable isotopes have been used to determine whether summer or winter rainfall contributes the most recharge to Tucson basin aquifers (Simpson, Thorud, and Friedman, 1970; White, 1976). Both these studies found winter recharge to be most important.

More recently, Turner (1979) has collected and analyzed precipitation samples from 28 different storms in the Tucson basin. He related the oxygen-18 content of these samples to factors such as season, rainfall intensity, temperature and humidity. The variability in stable isotope composition is illustrated by Figure 9. In general, summer convective storms are isotopically heavy because of greater evaporation as the rain falls (Turner, 1979).

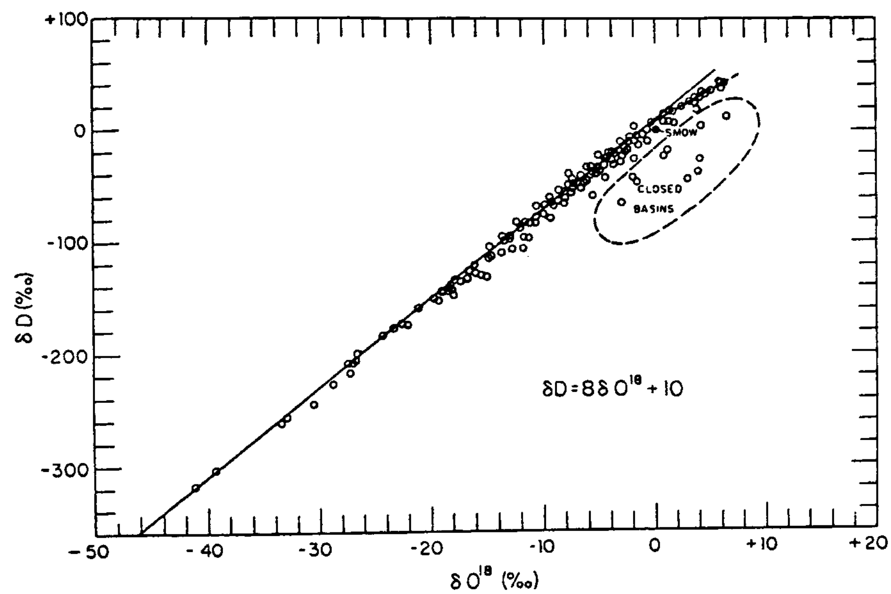

Figure 8. Deuterium and Oxygen-18 Correlation in Meteoric Waters (Craig, 1961b).

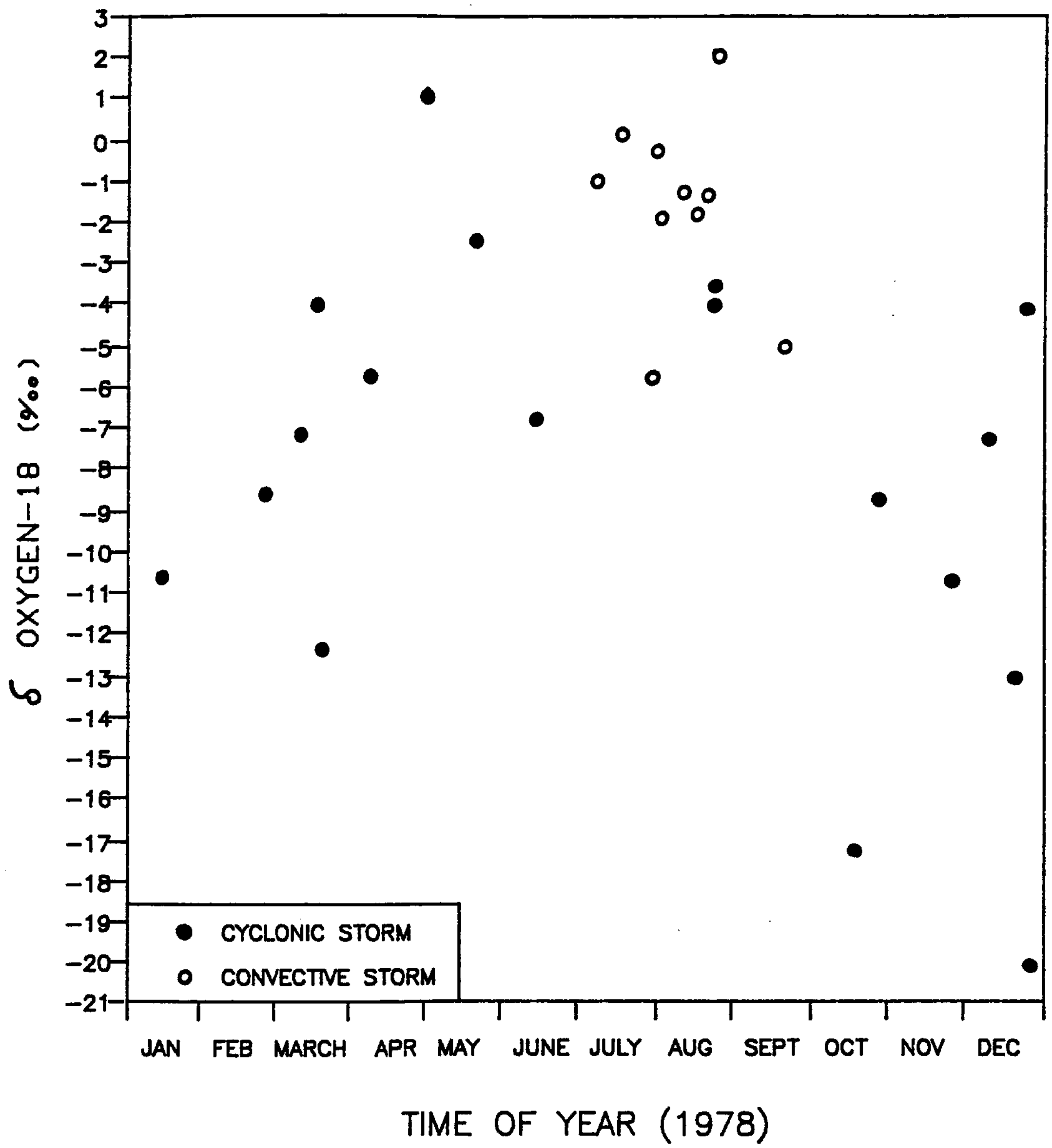

Figure 9. Seasonal Variation in the Oxygen-18 Content of Precipitation from the Tucson Basin (data from Turner, 1979).

The distribution of oxygen-18 in ground water from the Tucson basin was used by Gallaher (1979) to identify recharge areas. He maintained that the isotopic gradient is high where recharge water is being mixed with stored water of a different isotopic composition. Winter precipitation was again found to be the predominant source of recharge water. The perimeter of the Santa Catalina Mountains and the area along the Santa Cruz River were found to be the most active recharge areas (Gallaher, 1979).

CHAPTER 4

RESULTS OF THE STUDY

This chapter gives an overview of the chemical and isotopic composition of ground water from the study area. Particular attention has been given to differences in composition between wells in different topographic areas and to constituents which might indicate the source of dissolved solids.

Water samples were collected from 30 wells and analyzed for major ionic constituents and some secondary and minor constituents. Analyses for another 24 samples were obtained from previous studies. The locations of the sample points are shown in Figure 10. Table 3 gives a summary of the chemical results. The results of chemical analyses for each sample are given in Appendix A. Appendix B gives isotopic data used in the study. Descriptions of the analysis methods and sample points used in the study are provided in Appendices C and D.

A Survey of Well Logs

Well logs from each of the three areas were examined in order to determine which formations were yielding water and how water-table elevations compare. Figure 11 shows typical well logs for each area. Nearly all the wells in the piedmont and bottom-land areas were drilled exclusively in alluvial sediments. The logs list alternating layers of

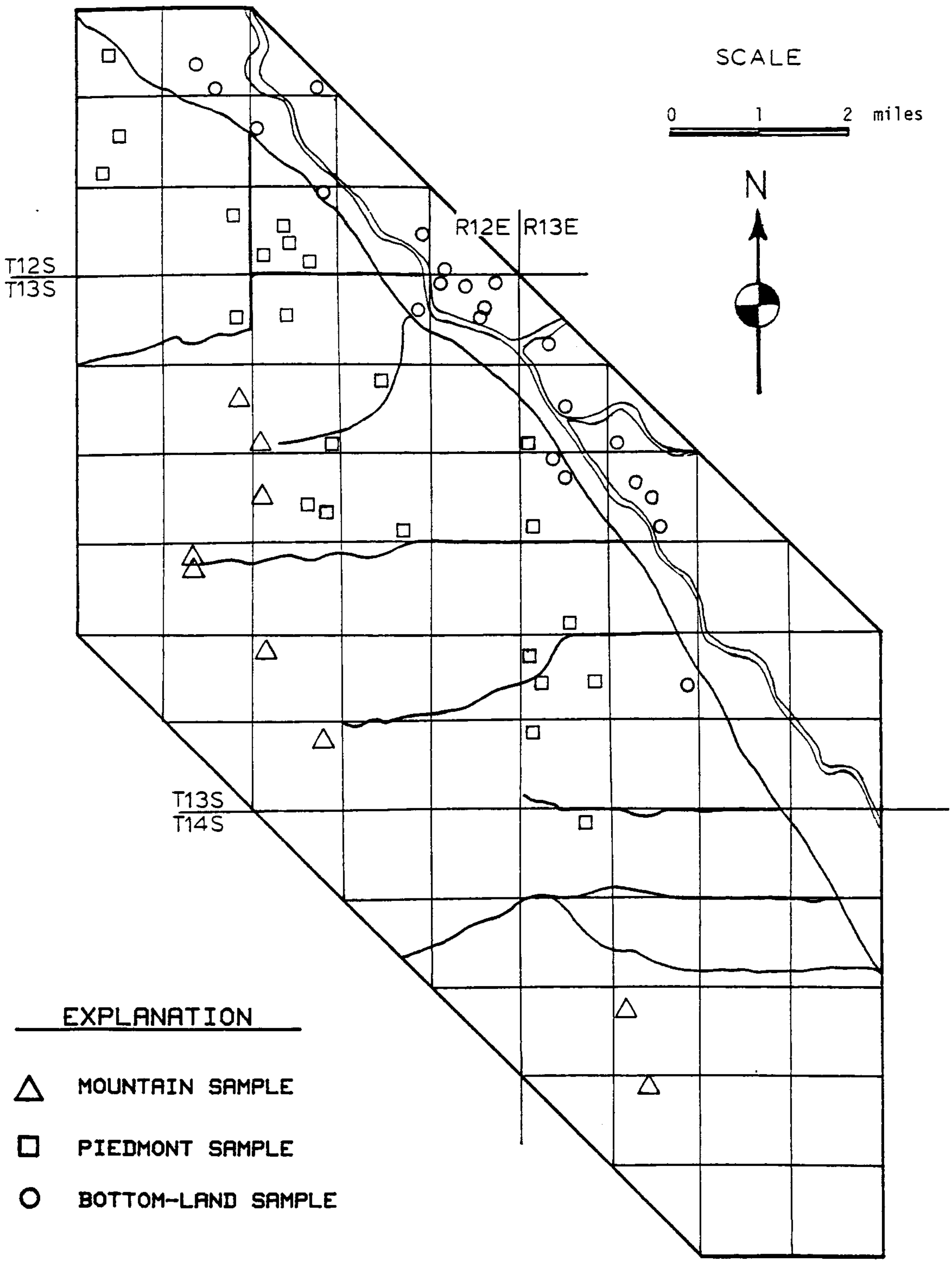

Figure 10. Location and Classification of Sample Points in the Study Area.

Table 3. Summary of the Results of Chemical Analyses of Samples from the Study Area.

	Mountain Wells			Piedmont Wells			Bottom-Land Wells		
	No. of Samples	Range (ppm)	Average (ppm)	No. of Samples	Range (ppm)	Average (ppm)	No. of Samples	Range (ppm)	Average (ppm)
Calcium	9	44 - 242	134	23	4 - 112	57	22	58 - 162	108
Magnesium	9	13 - 78	37	23	0 - 30	12	22	7 - 36	15
Sodium	9	50 - 645	197	23	32 - 166	71	22	25 - 173	118
Potassium	9	2.0 - 7.8	4.5	21	0.8 - 5.4	3.1	20	2.1 - 5.7	3.5
Sulfate	9	18 - 544	218	23	14 - 285	71	22	100 - 340	200
Bicarbonate	9	272 - 449	360	23	63 - 356	235	22	142 - 371	292
Chloride	9	20 - 817	233	23	15 - 170	56	22	39 - 140	81
Fluoride	9	0.60 - 2.71	1.20	23	0.35 - 2.0	1.06	22	0.40 - 1.98	0.87
Bromide	9	0.18 - 3.75	2.15	17	0.17 - 0.85	0.41	3	0.34 - 0.45	0.38
Nitrate	9	2.2 - 31.4	11	22	1.8 - 22.1	9	20	2 - 44	18
Silica (SiO_2)	9	29 - 60	46	22	11 - 65	39	20	12 - 45	27

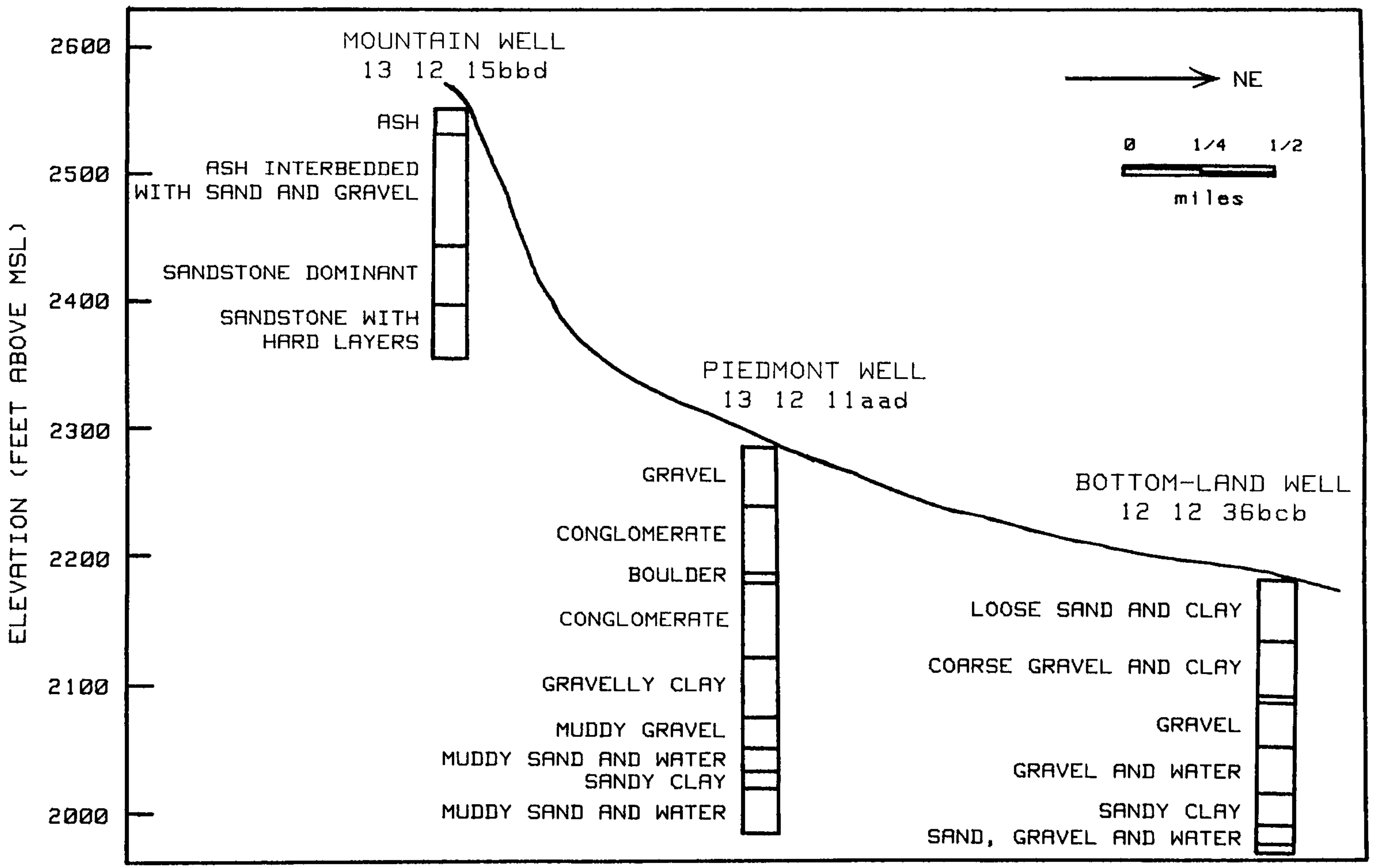

Figure 11. Diagram of Typical Driller's Logs from the Mountain, Piedmont and Bottom-Land Areas (data from University of Arizona, 1981).

clay and conglomerate. Deposits of sand and gravel are encountered in wells near the river.

Wells in the mountain area are commonly drilled in washes where recent stream deposits are found. However, these deposits are usually only 10 to 20 feet deep. Well logs show little or no water in most of the stream deposits. A red volcanic rock, probably part of the youngest volcanic sequence, underlies the alluvium in many of the valleys in the Tucson Mountains and can be seen in outcrops. The thickness of this formation varies from place to place. Water is obtained from fractures in these rocks in a few places. Most of the mountain wells go through this red rock and into sedimentary deposits below. The sedimentary formation is described as sandstone, sand, gravel, or congolmerate, and contains thin beds of shale. Most of these deposits are saturated and seem to be the major source of water for most mountain wells (University of Arizona, 1981).

Water-table elevations (Figure 12) are lower in the piedmont than in adjacent bottom-land wells. But the elevation difference is not as great today as it was 20 years ago. Water levels are falling at a much faster rate in areas near the river. The water table is generally highest in mountain wells. However, data are scarce and the water level varies from one well to another, depending on which formation is yielding water.

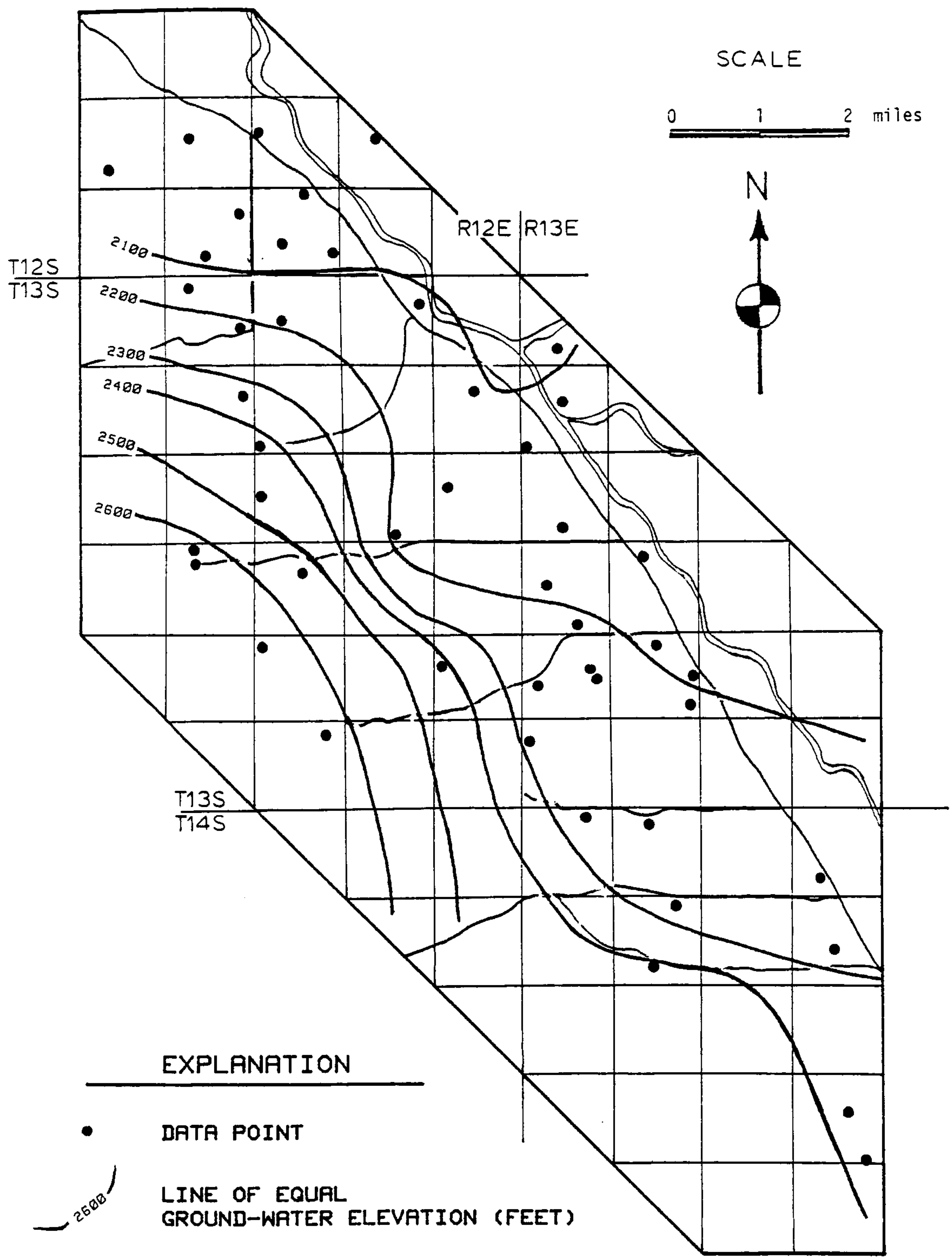

Figure 12. Map of Water-Table Elevation in the Study Area.

Observed Water-Quality Patterns

Total Dissolved Solids

The specific electrical conductance of each sample was measured. These readings were then used to estimate the total dissolved solids (TDS) concentration of each sample. Multiplying the specific conductance in micromohos/cm by 0.7 gives a rough approximation of TDS in parts per million (ppm) (Davis and Dewiest, 1966). A map showing lines of equal TDS is given in Figure 13. The lowest TDS values are found in piedmont wells. Some of the mountain wells had very high TDS and the bottom-land wells contained moderate concentrations.

Major Constituents

Chloride. Lines of equal chloride concentration are shown in Figure 14. The distribution is similar to that of TDS. The average concentration in mountain wells was 233 ppm, whereas, the averages in piedmont and bottom-land wells were 56 ppm and 81 ppm, respectively one sample from the mountain area had a chloride concentration of 817 ppm. This is more than twice the next highest concentration. Moreover, the highest concentrations of sodium and nitrate were also found in this well. Local contamination may be indicated because nitrate concentrations are generally low in mountain wells. Septic tank drainage may be the source of contamination. The house near this well has a water softner that could be putting a large amount of sodium chloride into the septic tank. The average chloride concentration is 160 ppm in mountain samples, if this sample is disregarded.

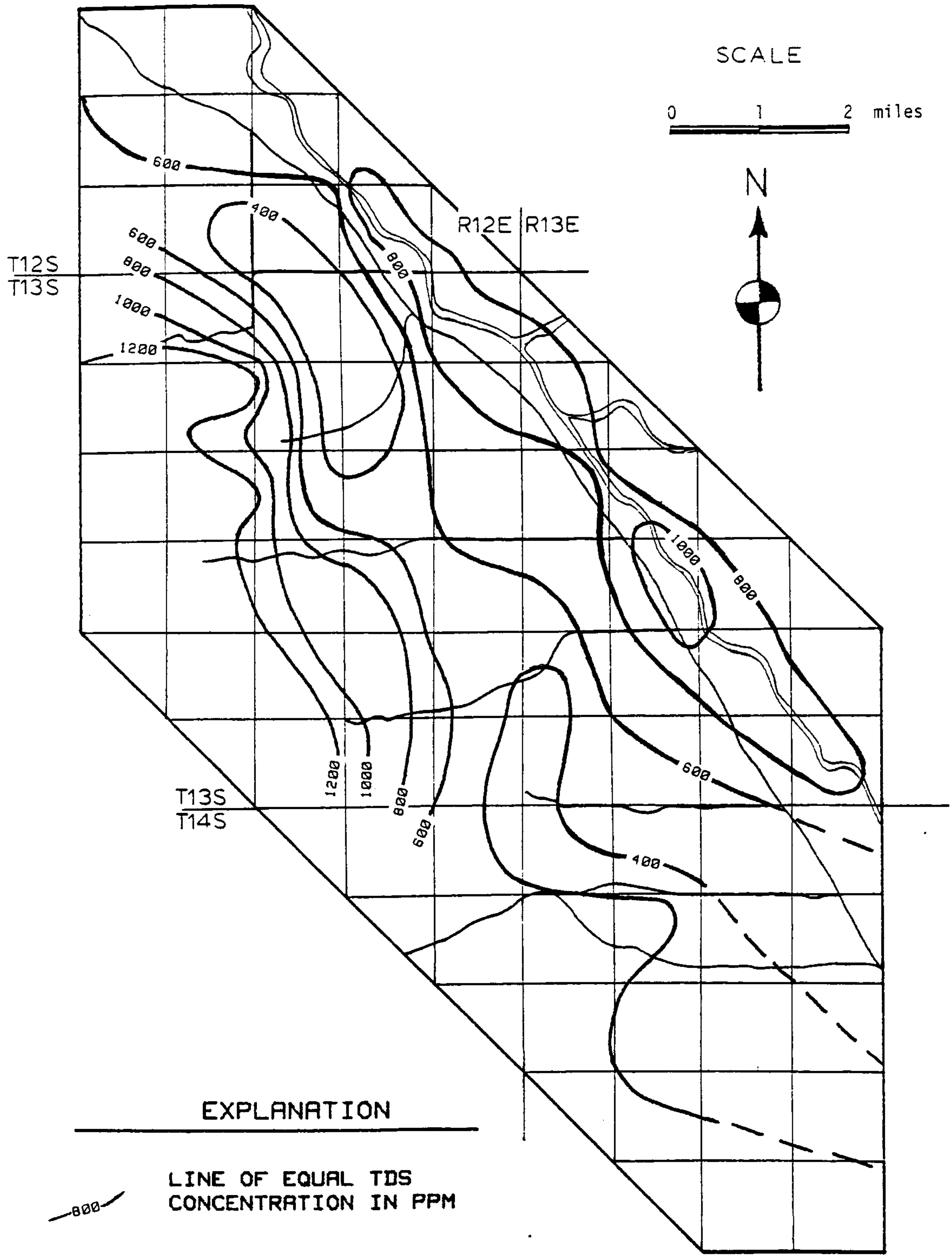

Figure 13. Map Showing the Distribution of Total Dissolved Solids in the Study Area.

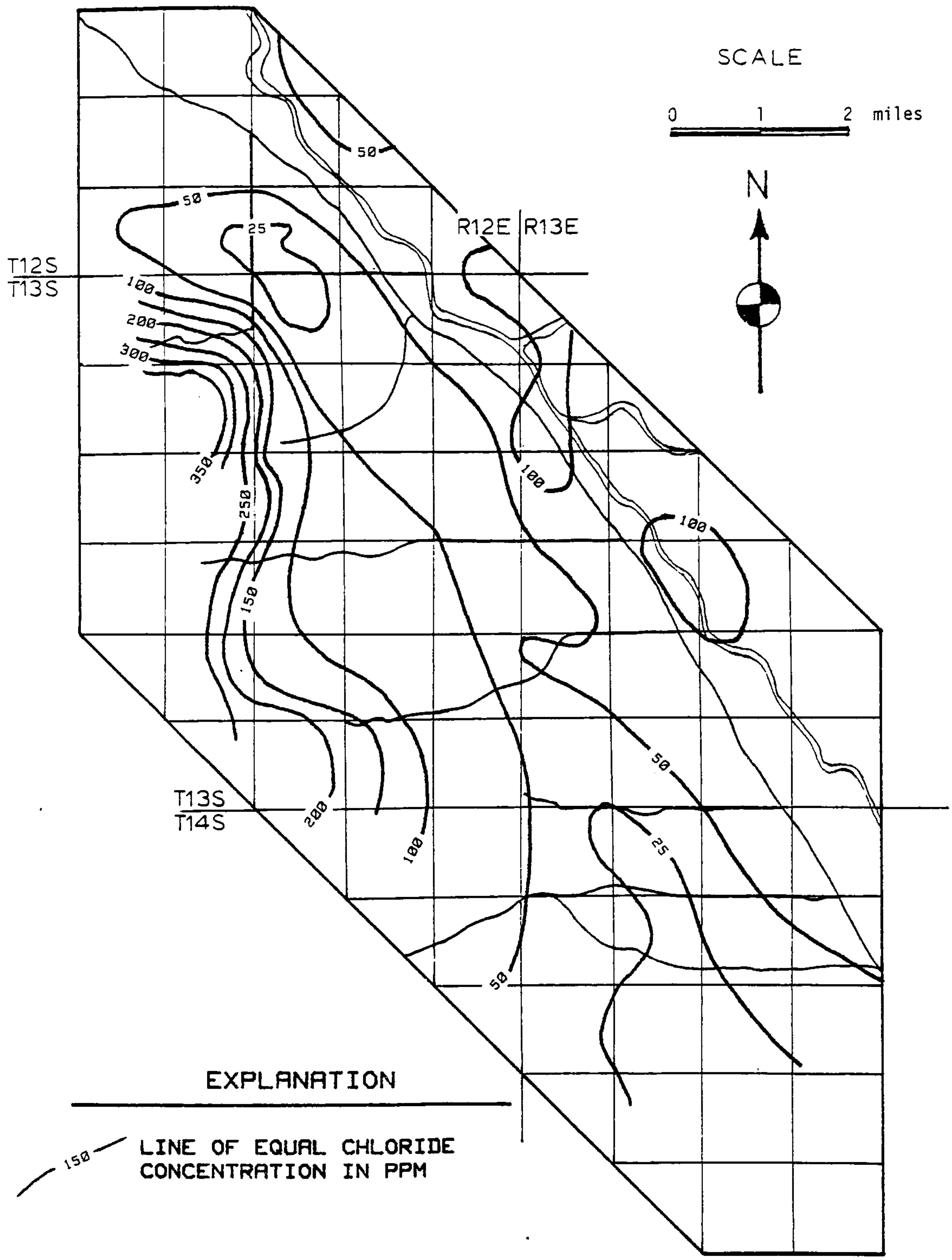

Figure 14. Map Showing the Distribution of Chloride in the Study Area.

Sulfate. High concentrations of sulfate were found in both mountain and bottom-land wells. However, surprisingly low values were found in a few of the mountain wells. Mountain samples had an average of 208 ppm. The average concentration in piedmont samples was 71 ppm. The average for the bottom-land wells was 200 ppm. Lines of equal sulfate concentration are shown in Figure 15.

Bicarbonate. The concentration of bicarbonate was not as variable as most of the other ions. Over 75% of the wells had between 200 and 350 ppm. Concentrations followed the same general pattern, with highest values in the mountain. But the difference in concentration between different areas was not as great as that displayed by other constituents.

Calcium. The average calcium concentration follows the trend of other major ions. However, the variation from one well to another in the same area is greater. For example, the highest concentration found in a piedmont sample was 112 ppm and the lowest from the same area was 4 ppm. The highest concentraton in a mountain sample was 242 ppm and the lowest was 44 ppm. Samples from the bottom-land area were less variable than mountain or piedmont samples.

Magnesium. The average magnesium concentration found in mountain ground water was 37 ppm. The samples from piedmont and bottom-land wells had 12 and 15 ppm, respectively. The ratio of magnesium/calcium is nearly the same for mountain and piedmont samples Whereas, the average magnesium/calcium ratio is about half as high for bottom-land wells.

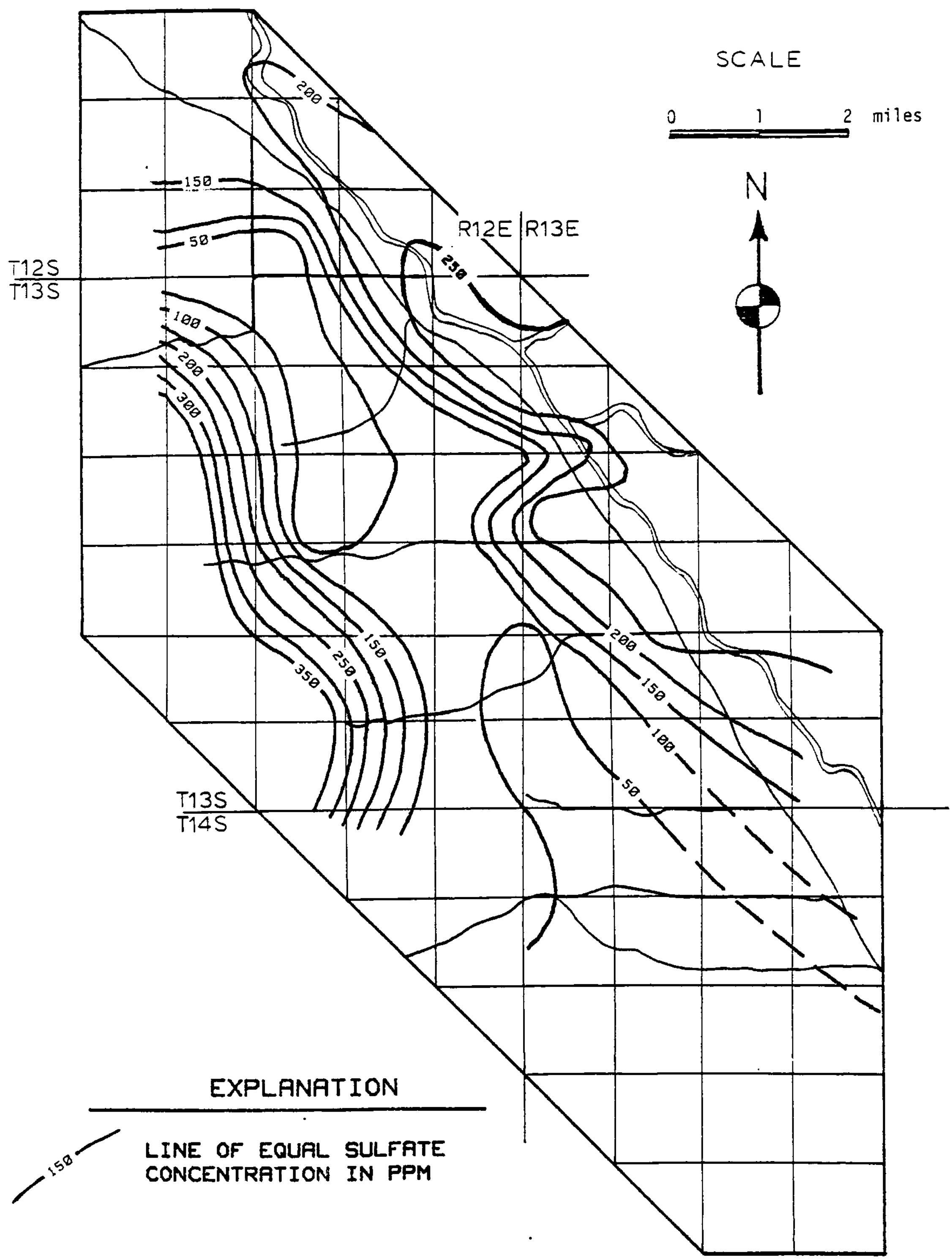

Figure 15. Map Showing the Distribution of Sulfate in the Study Area.

Sodium. A few of the mountain wells and one bottom-land well had anomalously high sodium concentrations. The sodium concentration is highly variable within each area.

Silica. The concentrations of silica found in mountain and piedmont wells were nearly the same. Samples from the bottom-land wells were significantly lower in silica. The average concentrations in mountain and piedmont wells were 46 and 39 ppm, respectively. The average in bottom-land wells was 27 ppm. Silica was generally less variable than most constituents and there is little correlation between high concentrations of silica and high concentrations of other constituents. However, samples with a pH of 7.5 or higher tended to have lower silica concentrations.

Some Secondary and Minor Constituents

Potassium. Concentrations of chemical constituents other than silica and nitrate were generally highest in mountain wells and lowest in piedmont wells. This was true for potassium. The differences, however, were not as pronounced as those found for other constituents. Water from the mountain wells contained about 50% more potassium than piedmont samples. By comparison, the sodium concentration is nearly 200% greater in the mountain wells.

Nitrate. The concentration of nitrate varies among wells in the same area, but was highest in bottom-land wells. Concentrations exceeding the U. S. Environmental Protection Agency's maximum contaminant level of 45 ppm for public water supplies have been reported in some wells near the Santa Cruz River (Matlock et al., 1972).

Moderately high levels (over 20 ppm) were found in some of the mountain and piedmont wells. High nitrate concentrations may be an indication of local contamination from septic tanks or stock corrals.

Fluoride. The highest level of fluoride was 2.7 ppm found in one of the mountain wells. However, the average concentration was about the same in all three areas. The average concentration found in the study area was about 1 ppm. Figure 16 shows the distribution of fluoride.

Bromide. Bromide concentrations were measured for the 24 samples. Bromide/chloride ratios were then determined for these wells and compared to the ratio found in sea water. The bromide concentration was much greater for mountain wells with an average of 2.2 ppm, than for piedmont wells with 0.4 ppm on the average. However, the average bromide/chloride ratio was nearly the same for these two areas. The ratio was about 0.009 in these wells compared to 0.0034 for sea water (Horne, 1969).

Bromide results were available for only three of the bottom-land wells. These measurements indicated a somewhat lower bromide/chloride ratio of 0.007 for this area. However, the ratios are still much higher than that found in sea water.

Stable Isotope Results

Stable isotope samples were collected from three wells in the mountain area, three in the piedmont area and one in the bottom-land area. The deuterium and oxygen-18 content of these samples was measured. Figure 17 shows the results of the analyses and the sample locations.

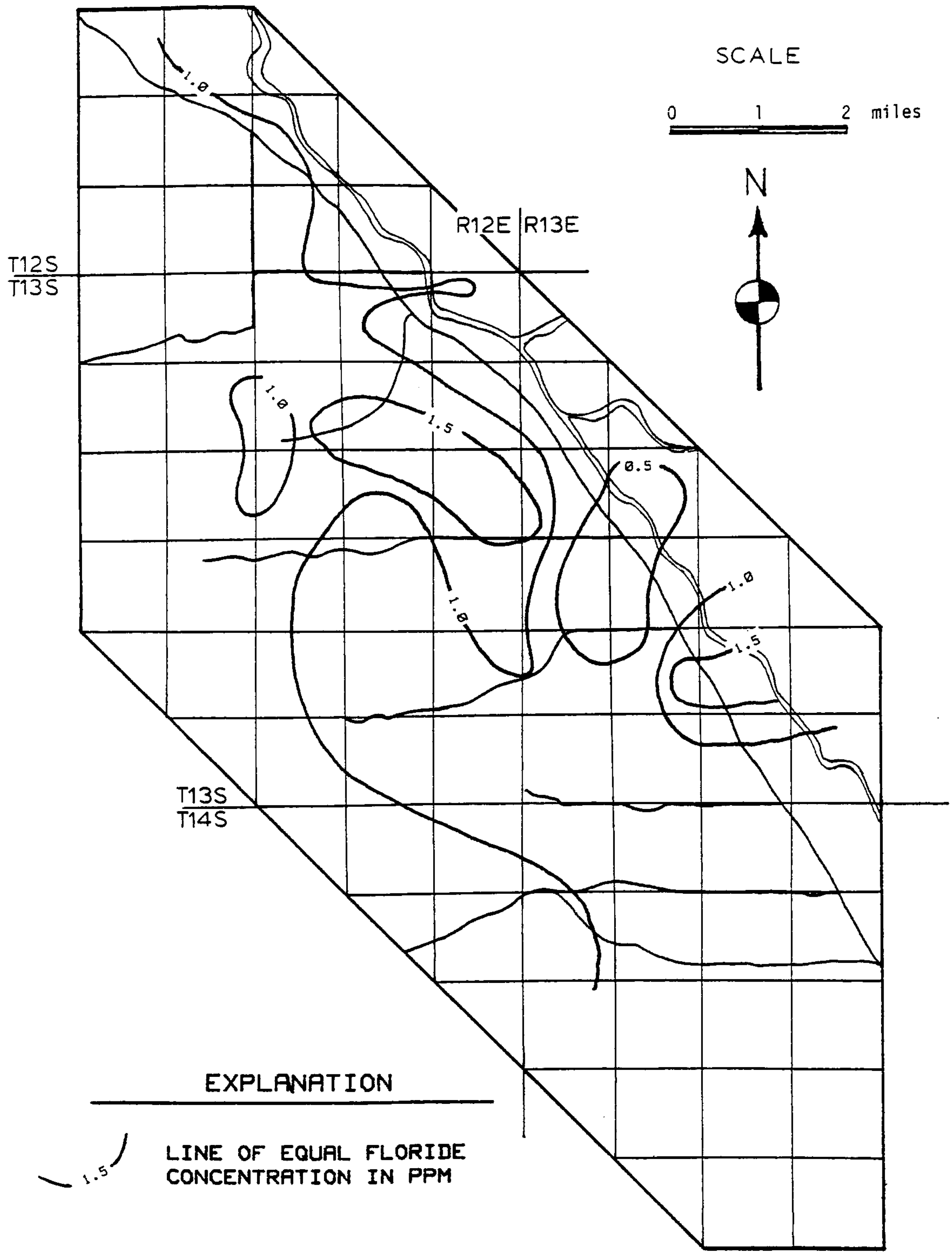

Figure 16. Map Showing the Distribution of Fluoride in the Study Area.

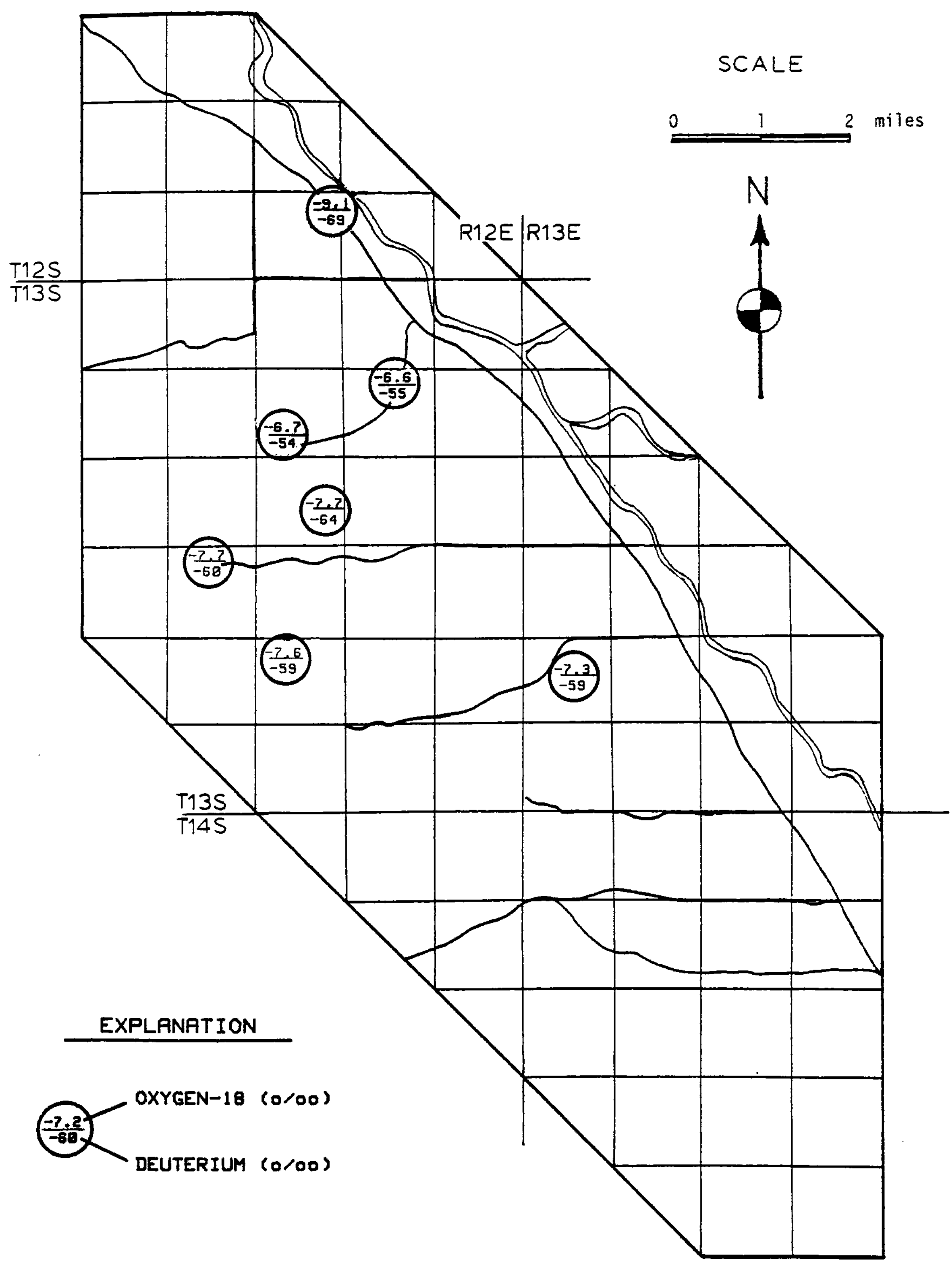

Figure 17. Map Showing the Results of Deuterium and Oxygen-18 Analyses.

The isotopic composition of mountain ground water was nearly identical to that found in the piedmont area. The average deuterium value was -58°/oo in the mountain area and 59°/oo in the piedmont area. The average oxygen-18 value was -7.3 in the mountain area and -7.2 in the piedmont area. The single bottom-land sample was significantly lighter than the others with -69°/oo deuterium and -9.1°/oo oxygen-18. However, all samples had oxygen-18 values in the range found for Tucson basin precipitation by Turner (1979). The implication of the stable isotope results will be discussed in the next chapter.

CHAPTER 5

DISCUSSION

Ground water from the piedmont area has been shown to contain a much lower concentration of dissolved solids than ground water from the mountain or bottom-land areas. This was unexpected because increases in the concentration of major ions normally occur as ground water moves along a flow path. The elevation of water in wells is generally higher in the mountains; therefore, ground water from this area might be expected to flow into the piedmont aquifer. Four possible flow systems that could account for the observed TDS distribution will be examined in light of the hydrochemical and isotopic data that have been presented.

Possible Systems of Ground-Water Flow

Old Water in Sedimentary Rocks

The sedimentary rocks which are between the two volcanic sequences in the Tucson Mountains may contain old water that was present when the youngest volcanics were deposited. These sediments could be bounded by nearly impermeable rocks that allow very little flow from this area into the basin fill aquifers. The rocks may contain brine from a sea or lake, or they may contain interstitial salts. Volcanic gases could also have added dissolved solids to the water. Precipitation falling on the mountains could flow into the piedmont area as surface runoff and recharge the aquifer in the area. High levels of TDS in the bottom-land area could be explained by a separate source, such as the dissolution of relic salts along the river channel (Laney, 1972) or recharge of treated sewage effluent (Martin, 1980)

High Evapotranspiration

Another explanation of large salt concentrations in mountain ground water could be a high rate of evapotranspiration. Slow recharge and a shallow water table would contribute to this mechanism. As water is evaporated from the aquifer, salts from precipitation and dry fall-out would be left. Over a long period of time, with sufficiently little flow through the aquifer, appreciable concentrations of dissolved solids could be built up.

Mountain Evaporites

Evaporites may be present in the sedimentary rocks of the mountain area. Deposits of gypsum or halite could contribute large amounts of sodium, calcium, chloride and sulfate to ground water. The good quality of water in the piedmont aquifer might be explained again by a lack of underflow from the mountains to the piedmont and an independent source of dissolved solids in the bottom-land area.

Mountain Evaporites and Flow Under the Piedmont

If evaporites are the source of dissolved solids in mountain ground water, then substantial volume of water may be flowing through the mountain aquifer. This low-quality water could flow under the piedmont in a deep aquifer that is separated from the basin fill by a volcanic tuff or some other low permeability formation. Low-quality water might then empty into the basin fill aquifer near the Santa Cruz River channel and contribute dissolved solids to the ground water in that area.

The Major-Ion Evolution Sequence

The chemical composition of ground water depends primarily on the availability and solubility of minerals. More minerals become available as water moves through the subsurface. Therefore, the TDS concentration generally increases along a flow path. The TDS would remain constant if no soluble minerals were encountered, the ground water was already saturated with the available constituents, or the addition of fresh recharge water balanced the increases in dissolved solids. TDS concentration could decrease along a flow path if constituents were precipitating from super-saturated water, being sorbed on the mineral matrix or if a sufficient volume of relatively fresh water were recharging the aquifer.

Chebotarev (1955) observed that the dominant anionic species changes as ground water moves on a regional scale. The change generally follows the sequence:

$$HCO_3^- \rightarrow HCO_3^- + SO_4^{2-} \rightarrow SO_4^{2-} + HCO_3^- \rightarrow SO_4^{2-} + Cl^- \rightarrow Cl^- + SO_4^{2-} \rightarrow Cl^-$$

Bicarbonate (HCO_3^-) is more widely available in recharge areas but has lower solubility than sulfate (SO_4^{2-}) or chloride (Cl^-). Whereas, chloride has a very high solubility, but is usually not present in recharge areas because it has already been dissolved and transported. The major-ion evolution sequence shown above is therefore a symptom of the availability and solubility of minerals (Freeze and Cherry, 1979). If water is recharged in an area where sodium chloride is available, the dominant anion will be chloride. Also, if water dominated by chloride or sulfate is joined by a larger volume of fresh recharge water the dominant anion may evolve to bicarbonate. Therefore, the specific geochemistry and hydrology of the aquifer must be know to predict the actual evolution of dominant ions.

The composition of each sample was plotted on a trilinear diagram in order to compare the proportions of major ions. Ground water in the mountain area (Figure 18) has about equal numbers of chloride, sulfate and bicarbonate ions. Bicarbonate is the dominant anion in the piedmont area (Figure 19). This suggests that the piedmont is a recharge area. If a significant amount of ground water flows from the mountain area to the piedmont it must be diluted by a large volume of bicarbonate type water.

Samples from the bottom-land area (Figure 20) are dominated by sulfate and bicarbonate anions. Chloride is less prevalent than in the mountain wells. Therefore, the source of dissolved solids in the two areas is probably different. If chloride-rich water flows from the mountain area to the bottom-land area through a deep aquifer, there must be another source of sulfate ions in the bottom-land aquifer.

Cations are less dependable as tracers of ground-water flow than anions because they are more affected by adsorption and ion exchange. However, the diagrams show that the mountain samples and some of the

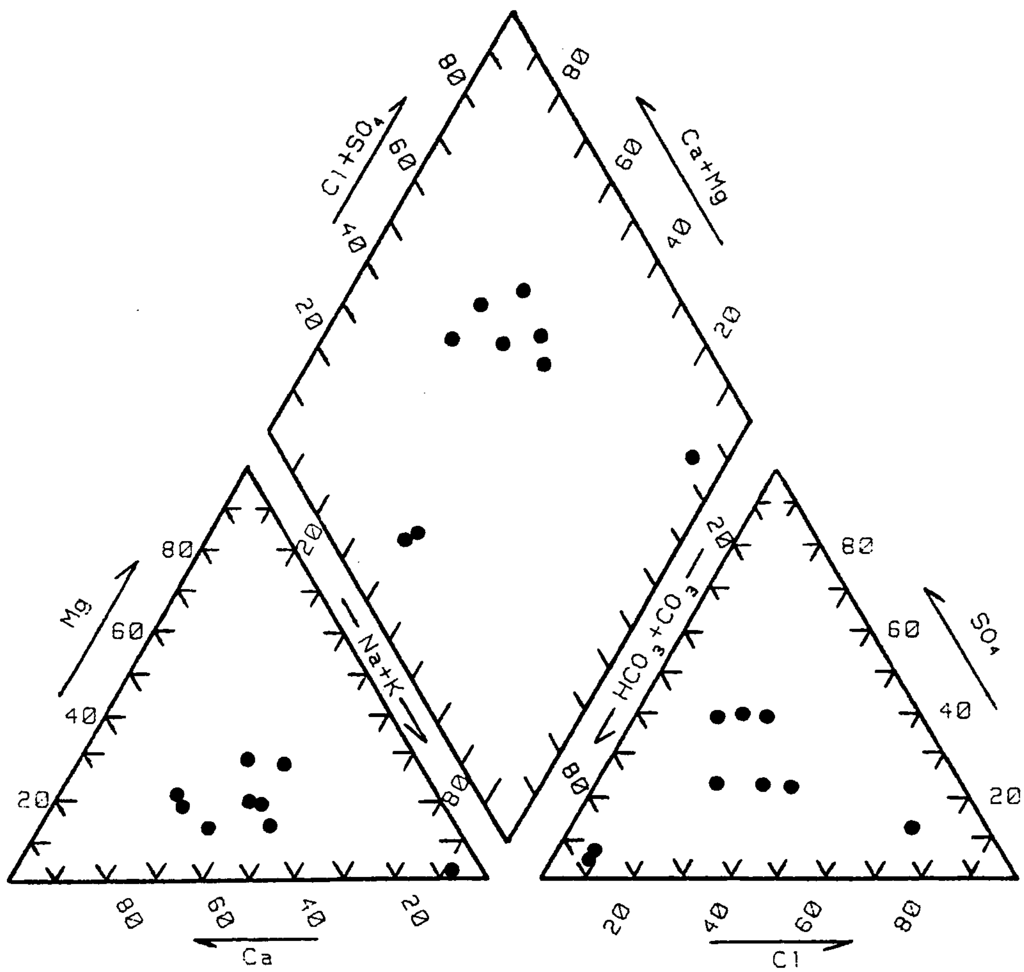

Figure 18. Trilinear Diagram Showing the Percentage of Major Cations and Anions in Mountain Samples.

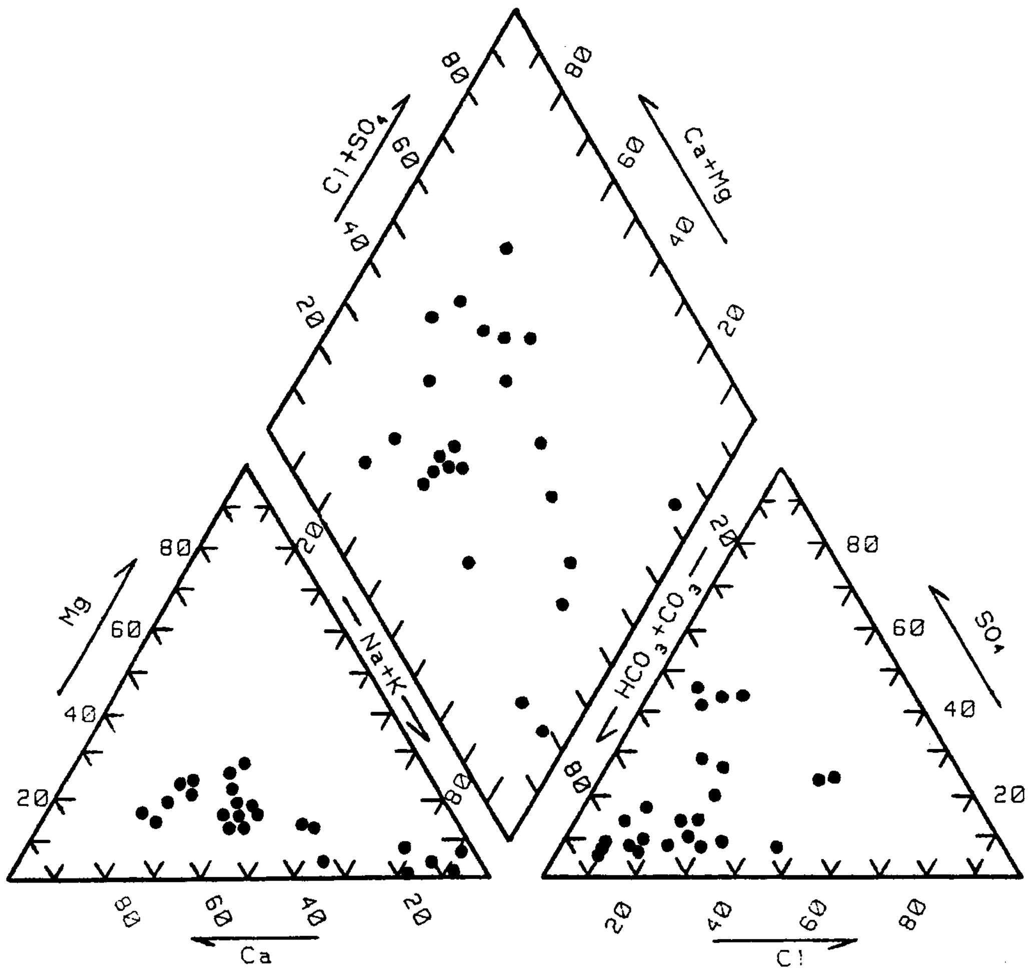

Figure 19. Trilinear Diagram Showing the Percentage of Major Cations and Anions in Piedmont Samples.

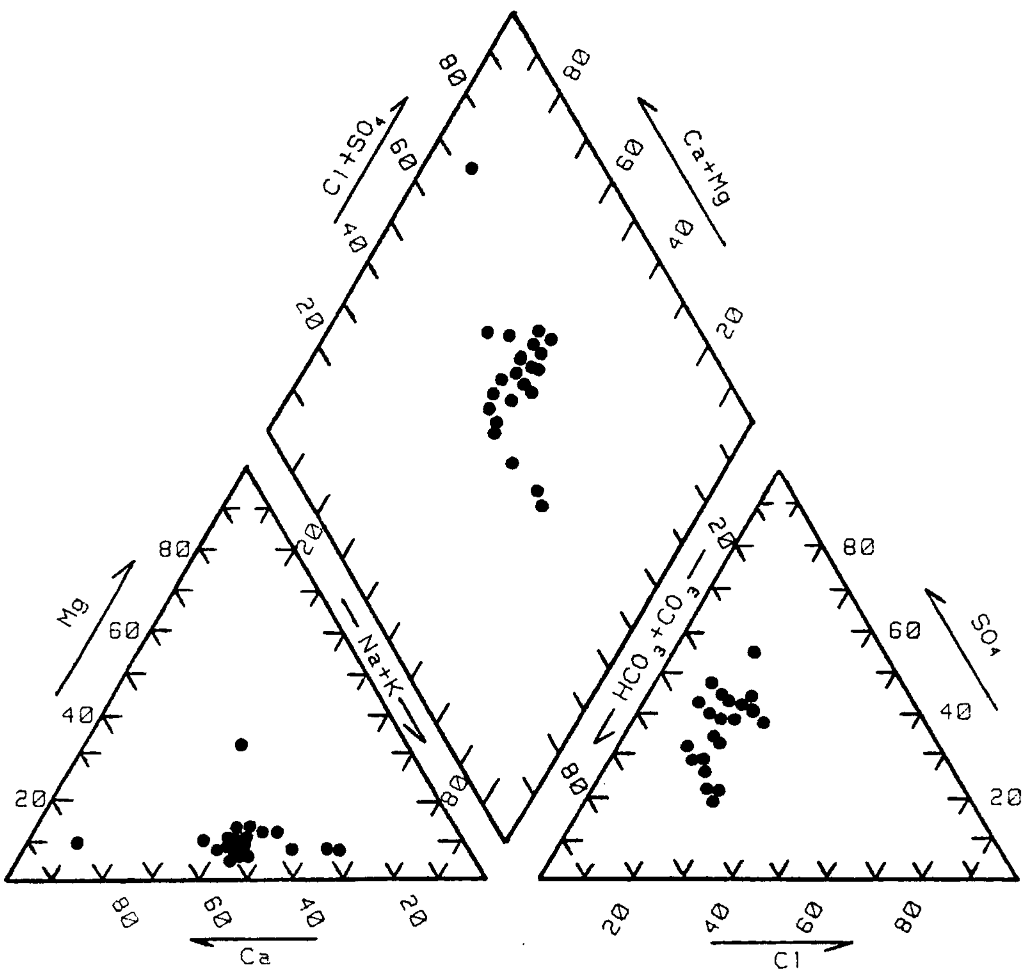

Figure 20. Trilinear Diagram Showing the Percentage of Major Cations and Anions in Bottom-Land Samples.

piedmont samples have a greater proportion of magnesium than those from the bottom-land area. This may be due to the large amount of magnesium in minerals in the volcanic rocks.

Clues from Specific Constituents

Chloride

Chloride is useful in studing the flow of water in an aquifer because it has a very high solubility and is relatively unaltered by any chemical reactions which might take place (Feth, 1981). Wells in the mountain area are high in chloride while those in the piedmont are very low in chloride. Therefore, if any ground water flows from the mountain aquifer to the piedmont, it must be diluted by at least 10 times as much recharge water containing less than 10 ppm chloride. Relatively high chloride is also found in bottom-land wells. A connection between the two areas might be indicated. However, as noted in the last section, the proportion of chloride relative to the other anions differs in the two areas. A likely source of chloride in bottom-land wells is sewage effluent (Martin, 1980).

Chloride found in mountain wells may come from precipitation and dry fallout, evaporite deposits, other minerals containing chloride, volcanic gases, residual brines, or a combination of these sources. Some of the mountain wells may also receive chloride from localized sources of contamination, such as a septic tank. Contamination is not, however, a likely explanation for the high chloride levels in most mountain wells.

Precipitation in the Gila River drainage basin, which includes the Tucson Mountains, was reported to contain an average of 0.15 ppm chloride (Junge and Werby, 1958). This figure is based on one year of sampling at widely scattered stations and should be regarded as only an approximation. It does not include the contribution of dry fallout, as no data are available on the amount of chloride contributed by dry fallout in the Tucson area. Studies in other places have indicated that an additional 20% to 200% of the chloride carried in by precipitation may be contributed by dry fallout (Feth, 1981). A reasonable approximation of the concentration of total atmospheric chloride in precipitation falling on the study area is 1 ppm. A very large amount of evaportranspiration would, therefore, be required to account for high chloride concentrations in mountain ground water.

Volcanic rocks generally contain only minor quantities of chloride and are not likely sources. Sedimentary rocks, on the other hand, may contain chloride minerals as dispersed crystals or in beds of evaporite (Hem, 1970). Water in the sedimentary rocks of the Tucson Mountains may contain chloride from a residual brine or from the hydrochloric acid commonly found in volcanic gases. The concentrations of other constituents are useful in determining the likely sources of chloride.

Bromide

This memeber of the halogen group is sometimes useful in determining the source of chloride in ground water (Rittenhaus, 1967). When sodium chloride precipitates, forming an evaporite bed, the bromide is left in solution. Therefore, a high bromide/chloride (Br/Cl) ratio may indicate the presence of residual bitterns remaining after precipitation. Ratios much lower than that of sea water would suggest that an evaporite may be the source of chloride.

The Br/Cl ratios of most samples in this study were about 0.01 (Figure 21). Sea water has a Br/Cl ratio of about 0.003. Therefore, an evaporite is probably not the source of chloride in the mountain wells. The average of the three Br/Cl ratios determined in the bottomland area was 0.007. This is higher than sea water, but not quite as high as most mountain and piedmont samples. Precipitation is reported to have a higher Br/Cl ratio than sea water (Hem, 1970). This may account for the observed data, although no specific information on the bromide concentration of precipitation in the study area is available. Other possible explanations for the high Br/Cl ratios include the presence of a residual brine in sedimentary units or water containing chloride and bromide derived from volcanic gases.

Fluoride

Another halogen, fluoride, is of interest because high concentrations of this ion are associated with poor quality water from the Pantano Formation (Laney, 1972). Most of the wells in the study area yield water with 0.5 to 2.0 ppm. Comparing Figures 13 and 16 shows that areas of high fluoride do not correspond with areas of high TDS in the mountain area. Therefore, the Pantano Formation is not indicated as a source of high TDS.

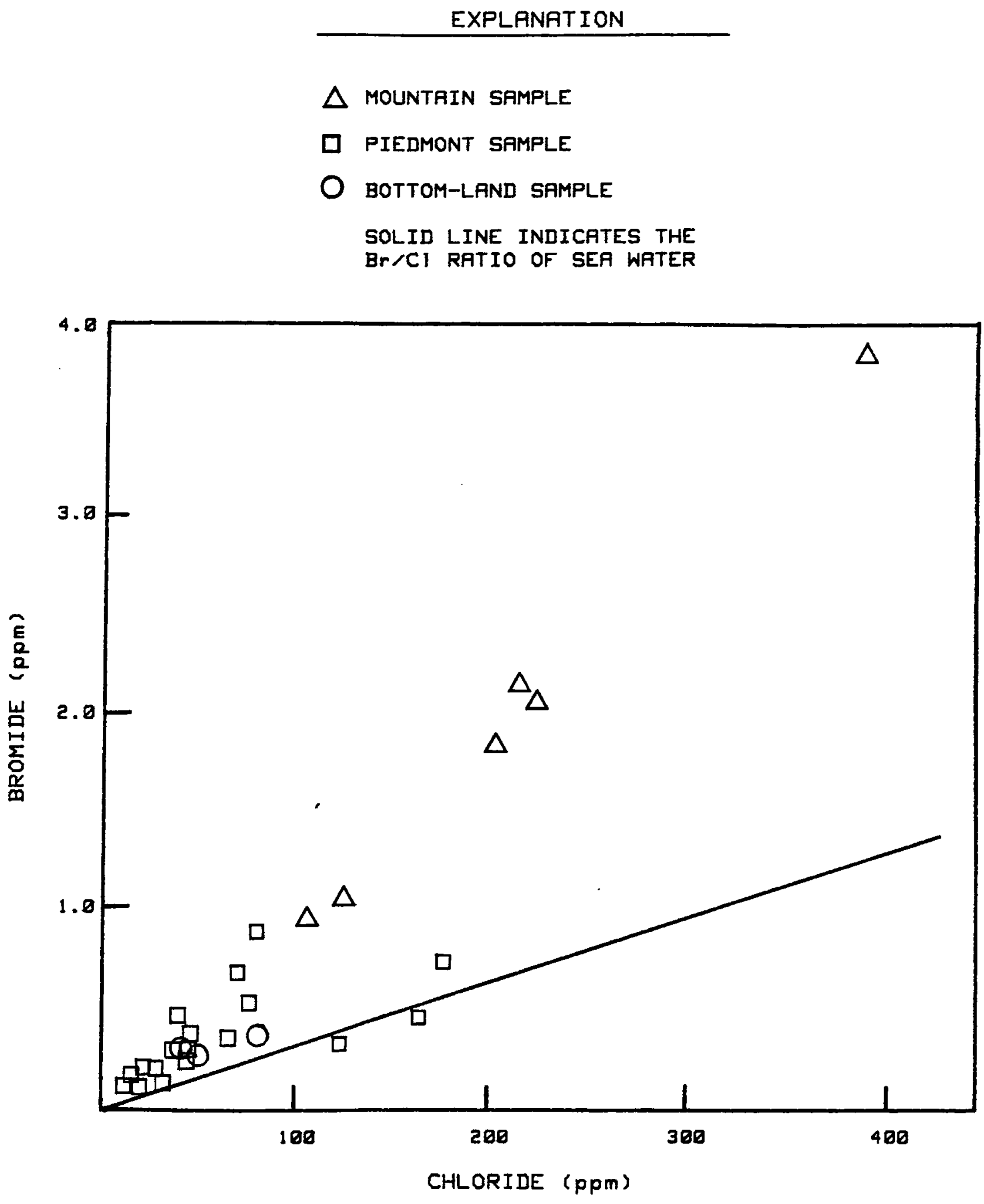

Figure 21. Bromide vs Chloride Concentrations of Ground-Water Samples from the Study Area Compared to the Bromide/Chloride Ratio of Sea Water.

Sulfate

The distribution of sulfate is similar to that of chloride. This is not surprising because most of the likely chloride sources could also be sources of sulfate. Precipitation contains a greater concentration of sulfate than chloride except near the ocean (Hem, 1970). Sulfate can also come from gypsum and anhydrite which are commonly deposited with halite. Volcanic gases may contain both sulfur and chlorine compounds. Sulfate minerals, however, have a lower solubility than sodium chloride. A diluted residual brine is not a likely source of chloride in the mountain area because sulfate would have precipitated before sodium chloride and the high concentrations of sulfate would not be observed.

Nitrate

High nitrate levels in ground water from the bottom-land area have been attributed to recharge of sewage effluent in the Santa Cruz River bed and to the leaching of nitrate from soils under irrigation (Laney, 1972 and Martin, 1980). A few of the samples from piedmont and mountain wells were also high in nitrate. This could indicate contamination from septic tanks or domestic animals. The samples were scattered rather than grouped in one area. Therefore, the nitrate source was probably localized in each case.

Calcium

Calcium found in the water samples could originate in carbonate rocks or evaporites. Calcium is also present in many minerals found in igneous rocks, but the decomposition of these minerals is very slow. Water in contact with carbonate or evaporite deposits reaches equilibrium concentrations quickly.

Limestone is present in the Tucson Mountain area both in beds and as blocks of pyroclastic material. Many of these blocks are very large and are exposed on the sides of the mountains. Freeze and Cherry (1979) showed that only a small amount of available limestone, about 0.01% by weight, must be dissolved to reach equilibrium concentrations of calcium and carbonate in a typical ground-water system.

Ground water in some parts of the study area may not be exposed to limestone or may not be exposed long enough to reach saturation. This may explain the wide range of calcium concentrations. Other factors, such as the ionic strength of the water and the partial pressure of carbon dioxide, also affect calcite equilibrium. Samples from the mountain and bottom-land areas have higher ionic strength than those from the piedmont. The equilibrium concentration of calcium is, therefore, lower in the piedmont area.

The calcium distribution is not very useful for the purpose of this study because of the discontinuous limestone found in both the mountain and piedmont areas. The ratio of calcium/sulfate (Ca/SO_4) is more interesting. Dissolution of gypsum or anhydrite would result in a Ca/SO_4 ratios of 0.42 if no calcium precipitated as calcite. In fact, calcite would slowly precipitate and cause a lower ratio. The Ca/SO_4 ratio of samples from the piedmont averages 1.43 compared to 0.56 for bottom-land samples and 0.63 for the mountain samples with high TDS.

The amount of calcium in high TDS samples from the mountain area is, therefore, higher than would be expected if an evaporite containing gypsum or anhydrite was the source of dissolved solids.

Magnesium

The igneous rocks of the Tucson Mountains are likely to contain magnesium in minerals including olivine, pyroxines, amphiboles and dark colored micas (Hem, 1970). Magnesium is commonly a major constituent of ground water from such rocks. The decomposition of these minerals is very slow, but if they have been in contact with ground water from the mountain area for a long period of time, magnesium saturation might be expected. The dominance of calcium and sodium may indicate that slow dissolution of igneous rocks is not the source of high dissolved solids in the mountain area.

At least one factor complicates the analysis given above. If the water first dissolves limestone, the solubility of magnesium compounds is significantly reduced by the common-ion effect of calcium (Freeze and Cherry, 1979). This would put the concentration of magnesium in saturated solution at about the level observed in mountain samples. Additional magnesium from the weathering of igneous rock would precipitate. The magnesium distribution, therefore, yields little solid evidence about the source of dissolved solids.

Sodium

Sodium compounds are mostly soluble and may be introduced into ground water by rain, evaporites, weathering of feldspars or saline water trapped in sedimentary deposits. Sodium is not affected by chemical reactions in most natural water, but it may be sorbed by minerals with high cation exchange capacities. The ratio sodium/chloride (Na/Cl) is interesting because a ratio higher than that caused by dissolution of sodium chloride indicates that sodium chloride is not the source of all the sodium present. A lower ratio is not as significant because some of the sodium may have been sorbed.

The Na/Cl ratio of all the bottom-land samples and 80% of the piedmont samples are much higher than that of sodium chloride. Half of the mountain samples with high TDS have a Na/Cl ratio about the same as sodium chloride and half have a slightly higher ratio. Therefore, much of the sodium in mountain ground water may be coming from a source which also provides chloride. This could be halite, rain and dry fallout, or a sodium chloride brine trapped in the sedimentary rocks. This evidence is not conclusive because the sodium and chloride in mountain ground water could be coming from separate sources.

Potassium

Potassium, like sodium, is a common constituent of igneous rocks. However, potassium minerals are more inert and potassium tends to be incorporated into clay and mica mineral structures. This explains the narrow range of potassium concentrations normally observed in natural water (Hem, 1970).

The average concentration in mountain wells is about 20% higher than the average found in the other two areas. A longer contact time with igneous or non-precipitate sedimentary rocks, which also contain substantial amounts of potassium, is suspected.

Silica

Silicon is the second most abundant element in the earth's crust. It is a major constituent of nearly all non-precipitate rocks. The concentration of silica in natural water is apparently controlled by the solubility of alumino-silicate minerals, such as fedspars and micas. Amorphous silica has a higher solubility, 115 ppm at 25°C (Morey et al. 1962), but does not influence the concentration of silica in most ground water.

Davis (1964) compared the concentrations of silica found in thousands of ground-water samples from various parts of the United States. He reported a median value of 17 ppm. Most samples ranged from 10 to 30 ppm. Samples from the study area were generally higher. The average silica concentration in the mountain area was 46 ppm. The piedmont and bottom-land areas averaged 39 ppm and 27 ppm, respectively. The average ground-water temperature in Tucson is higher than most areas of the United States. This may explain elevated concentrations of silica, because the solubilities of silica minerals are highly dependant on temperature.

Silica is so widely available that its distribution is not useful in determining the source of high dissolved solids in the mountain area. It is interesting that silica concentrations are lowest in the bottom-land area. This may be due to the fact that the volcanic rocks in the Tucson Mountains have a different mineralogy than the rocks which comprise most of the Tucson basin.

Stable Isotope Evidence

Analyses of stable isotopes show similar concentrations of deuterium and oxygen-18 in ground water from the mountain and piedmont areas. A difference might be expected if more evapotranspiration is occuring in the mountain area. This would cause mountain ground water to be isotopically heavy compared to piedmont ground water. Greater evaporation might also cause the mountain samples to be shifted farther from the meteoric line. Therefore, stable isotope evidence does not support the hypothesis of high evapotranspiration in the mountain area.

However, it is possible that salts could accumulate by evapotranspiration and not cause a difference in isotopic composition. First, the effect of falling onto a higher elevation, and thus having less evaporation during falling could offset the effect of evaporation in the soil. Second, the precipitation from many small storms could completely evaporate leaving salts in the soil, but not leaving heavy water molecules. Then a large rainfall might eventually carry these salts to the water table. Also, water that is in the soil after a rainfall experiences very little mixing and the depth of isotopic fractionation in saturated soil has been shown to be small (Zimmerman et al. 1967). Partial evaporation of soil moisture could therefore occur without causing significant isotopic fractionation in the ground water.

The single isotope sample collected from the bottom-land area has a lighter isotopic composition than any of the mountain or piedmont samples. Gallaher (1979) gave the oxygen-18 content of six additional

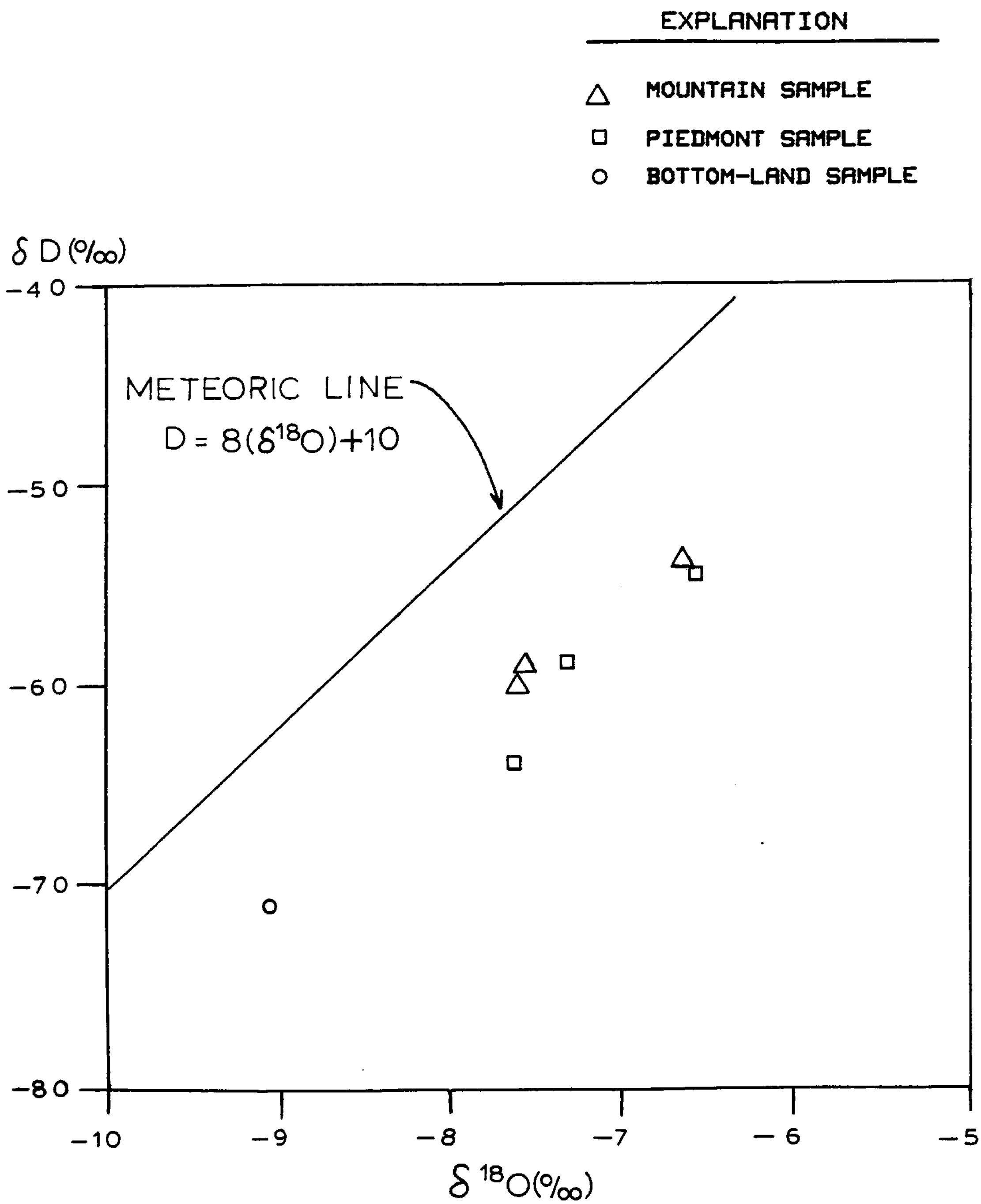

Figure 22. Deuterium vs Oxygen-18 Content of Samples from the Study Area Compared to the Meteoric Line.

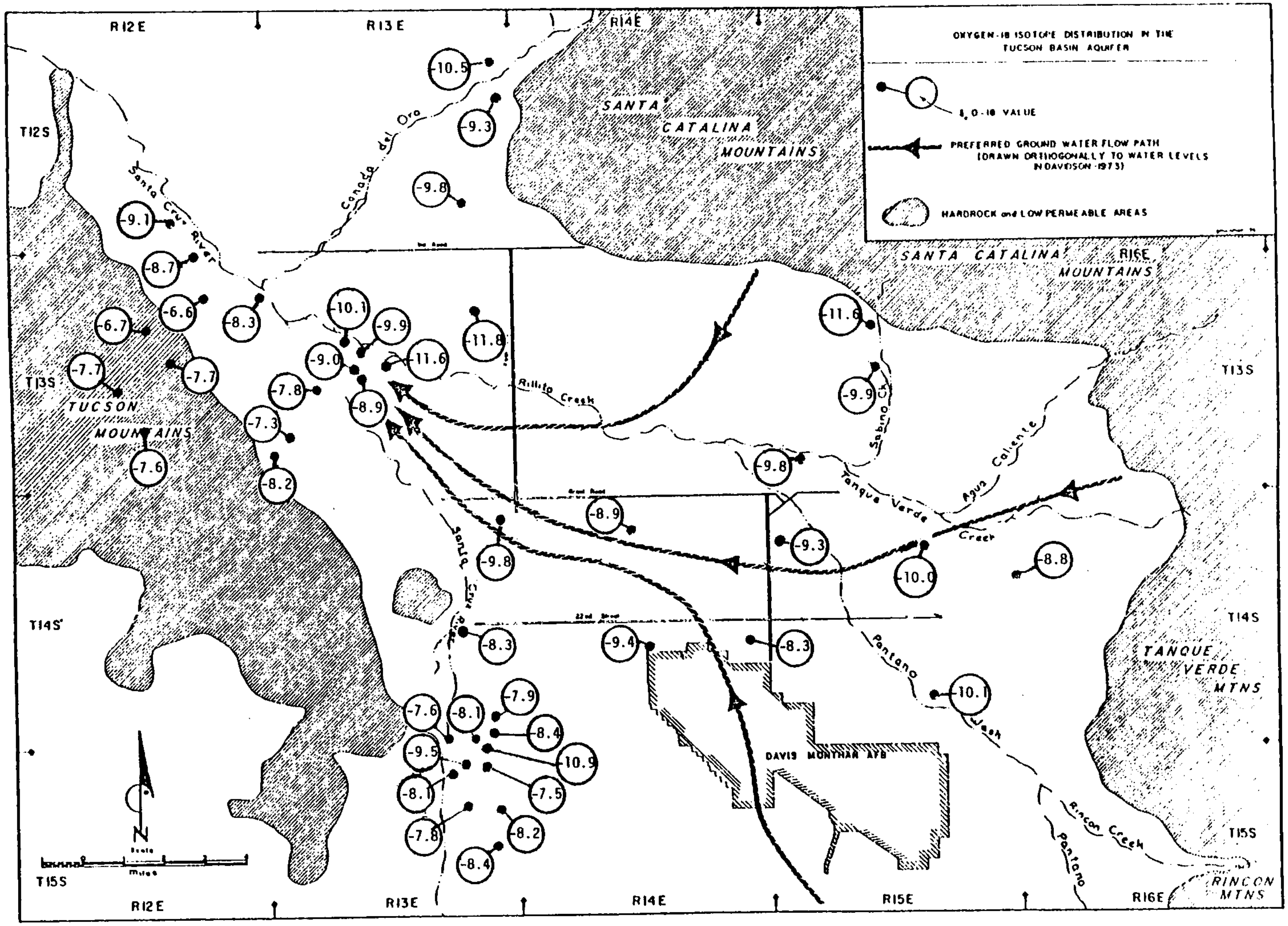

Figure 23. Comparison of the Oxygen-18 Content of Ground Water from the Study Area and Throughout the Tucson Basin (data from this study and Gallaher, 1979).

samples from the bottom-land area. The average oxygen-18 value of all seven bottom-land samples is -8.6. The average of the three piedmont samples is -7.2 and of the three mountain samples is -7.3. Figure 23 shows the oxygen-18 distribution of the Tucson basin as presented by Gallaher (1979) with the samples taken for this study added.

Isotopically lighter water is found near the Santa Catalina Mountains. A large part of the recharge from these mountains falls at high elevations. Therefore, the precipitation has less time to evaporate as it falls. The Tucson Mountains, on the other hand, are much lower and precipitation is only slightly lighter than that which falls on the basin floor. The average oxygen-18 of precipitation samples collected throughout the basin by Turner (1979) was -6.3. Ground water in the bottom-land area is probably a mixture of recharge coming from the Santa Catalina Mountains and heavier water which infiltrates along the Santa Cruz River. Some ground water flows from the Tucson Mountains into the bottom-land area. But this is a minor volume compared to recharge along the Santa Cruz channel. Oxygen-18 cannot be used readily to trace recharge from the Tucson Mountains because of this much larger source of isotopically similar water.

An Estimate of Recharge

Bromide/chloride and calcium/sulfate ratios of ground water from the mountain area indicate that evaporites are probably not the source of high TDS. Other mechanisms for building up high TDS imply that little water flows through the aquifer in the mountain area. On the other hand, the low TDS found in piedmont ground water shows that the piedmont is a likely recharge area. Most of the precipitation falling in the mountain area probably evaporates, or runs off and infiltrates in the piedmont area.

The volume of precipitation recharging the piedmont area is equal to the volume received by the piedmont and that part of the mountain area tributary to the piedmont, minus what is lost through evapotranspiration and surface runoff. Precipitation contains about 1 ppm chloride, whereas the median concentration in piedmont samples was 46 ppm. Weathering of rocks contributes little chloride to the water. Therefore, chloride balance shows that 98% of the precipitation evaporates. Assuming that average annual precipitation is 0.92 feet, as it is at Cortaro, about 28,260 acre-feet of precipitation is received each year by the 48 square-mile area. Ninety eight percent is lost to evaportranspiration, leaving 565 acre-feet which runs off or recharges the ground water. The amount of runoff is not known, but is expected to be small because of the coarse sediments in the piedmont area.

Mountain-front recharge along the Tucson Mountains is probably greater than the 100 acre-feet per year estimated by Oskerkamp (1973). However, it is minor compared with other sources listed in Table 2. Burkham (1970) used measurements taken at gauging stations to estimate that about 479 acre-feet per year infiltrates each mile of the Santa Cruz River channel. The study area includes 21 miles of river bed which infiltrates approximately 10,000 acre-feet per year.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The quality of water from wells in the study area is related to the topographic setting of the wells. Ground water in higher mountainous areas and in the bottom-land area, near the Santa Cruz River, contained fairly high concentrations of dissolved solids. On the other hand, wells from the piedmont area yielded water with low concentrations of dissolved solids.

The distribution of several chemical constituents, and the stable isotopes deuterium and oxygen-18 were examined in order to determine the source of dissolved solids and the pattern of flow through the study area. Hydrochemical facies show that ground water in the piedmont was recently recharged. These samples had a high proportion of carbonate. Samples from the mountainous area had a higher proportion of sulfate and chloride anions. Therefore, ground water from this area does not flow into the piedmont aquifer in appreciable amounts.

An examiniation of well logs showed that mountain wells commonly tap sedimentary rocks that underlie the most recent volcanics. These sediments may be isolated from fresh recharge by impermeable rocks, such as tuff, that have been deposited over them. Examination of nitrate concentrations shows that few of the samples in the mountain and piedmont area may have been contaminated by human activity. However, most are not affected and contamination does not explain the high TDS found in most mountain wells. Bromide/chloride and calcium/sulfate ratios found in the mountain ground water indicate that evaporites are probably not the source of dissolved solids. Other possible sources include (1) salts present in rainfall and concentrated by evapotranspiration, (2) connate water in the sedimentary rocks, or (3) mineral crystals or interstitial ions deposited with the sedimentary rocks and subsequently redissolved. These sources imply the ground-water flow is sluggish in the mountain area and little water flows into either the piedmont or bottom-land areas. Dissolved solids in the bottom-land area probably do not originate in mountain ground water.

Any of the three sources listed above could have resulted in the observed composition of mountain ground water. Stable isotopes, deuterium and oxygen-18, were analyzed in a few samples from each area because a greater amount of evapotranspiration could have resulted in relatively heavy water in the mountain aquifer. In fact, isotopic compositions of mountain and piedmont samples were about the same. Salts may have been concentrated in the mountain area without appreciable isotopic fractionation. Therefore, the stable isotope evidence neither supports, nor disproves, evapotranspiration as the source of high TDS in the mountain area. Samples from mountain and piedmont wells were significantly heavier than ground water from both the bottom-land and the rest of the Tucson basin. Much of the ground water in the bottom-land area originated as precipitation on higher mountain slopes.

This water is lighter because it fell less distance and experienced less evaporation than rainfall in the Tucson Mountains.

Little recharge occurs in the mountain area. However precipitation could runoff and infiltrate the coarse sediments in the piedmont area. Chloride balance was used to estimate the precentage of precipitation which had evaporated before recharging the piedmont aquifer. The rate of recharge was then found by multiplying this precentage by the average annual precipitation falling on both the mountain and piedmont areas. About 500 acre-feet per year was estimated to recharge the piedmont aquifer. A much greater volume, about 10,000 acre-feet per year, infiltrates from the Santa Cruz River as it flows through the bottom-land area.

APPENDIX A

CHEMICAL DATA USED IN THIS STUDY

Reference Number	Location	Classification	pH	Specific Conductance (umohs/cm at 25° C)	NO_3^- (ppm)	SiO_2 (ppm)	F^- (ppm)	Calcium (ppm)	Magnesium (ppm)	Sodium (ppm)	Potassium (ppm)	Sulfate (ppm)	Bicarbonate (ppm)	Chloride (ppm)	Bromide (ppm)	Br/Cl
1	D 13 13 31bba	Piedmont	7.6	540	2.5	-	.35	40	16	45	-	14	246	32	-	-
2	D 13 12 34aaa	Mountain	7.2	1990	24.4	34	.73	160	78	180	6.5	375	372	201	1.80	.009
3	D 14 13 6aab	Piedmont	7.3	643	14.6	65	.60	80	16	37	2.9	18	342	23	.19	.008
4	D 13 13 27bbb	Mountain	7.1	1810	2.2	42	1.25	232	51	140	3.4	312	439	104	1.01	.010
5	D 13 13 30adc	Piedmont	7.1	1025	6.2	44	.56	105	30	57	5.2	105	182	170	.77	.005
6	D 13 13 30bcd	Piedmont	7.1	538	13.3	63	1.06	57	15	32	2.8	18	238	30	.18	.006
7	D 13 13 30bbc	Piedmont	7.1	653	11.5	49	1.03	71	20	41	2.9	37	231	59	.45	.008
8	D 13 12 14dcc	Piedmont	6.9	770	8.0	63	.52	96	15	33	2.7	74	259	72	.55	.010
9	D 13 12 15dbb	Piedmont	7.6	710	22.1	18	1.22	13	3	125	2.4	27	239	68	.68	.010
10	D 13 12 a5bca	Mountain	6.8	1750	2.2	49	.60	191	27	145	7.8	200	449	221	2.06	.009
11	D 13 12 21abd	Mountain	7.5	1400	12.8	29	1.48	86	51	144	5.9	165	314	210	2.15	.010
12	D 13 12 21abd	Mountain	7.6	1950	5.3	39	2.71	242	50	334	3.0	544	370	384	3.75	.010
13	D 13 12 10ddd	Piedmont	7.4	538	13.3	44	1.75	21	0	102	3.0	34	194	40	.47	.012
14	D 13 12 11baa	Piedmont	7.4	535	13.7	46	1.17	48	15	45	3.1	22	222	39	.30	.008
15	D 13 12 4aaa	Piedmont	6.9	1003	12.0	17	1.23	112	16	46	3.3	22	223	124	.31	.003
16	D 13 12 3bdc	Piedmont	7.2	485	6.6	36	1.22	33	7	66	2.8	25	214	18	.22	.012
17	D 12 12 34caa	Piedmont	7.9	442	8.0	18	1.45	4	1	87	1.6	17	211	15	.17	.011
18	D 12 12 27cbb	Bottom-Land	7.0	903	11.9	33	1.16	85	8	87	5.0	120	282	70	.45	.006
19	D 12 12 33ada	Piedmont	6.9	553	7.5	49	1.50	53	9	47	5.4	43	238	28	.23	.008
20	D 12 12 34aba	Bottom-Land	7.0	860	22.1	28	1.32	75	11	85	5.7	130	266	49	.36	.007
21	D 13 12 9ada	Mountain	7.1	3580	31.4	60	.83	47	13	645	5.4	180	312	817	7.1	.009
22	D 14 13 17bbd	Mountain	6.9	528	6.2	53	.92	44	14	52	2.0	19	272	20	.18	.009
23	D 14 13 20bab	Mountain	7.1	527	9.7	50	.89	44	14	50	2.0	18	275	20	.18	.009
24	D 13 12 10ccc	Mountain	7.4	1270	2.7	55	1.00	161	38	82	5.0	150	439	123	1.10	.009
25	D 13 13 29dda	Bottom-Land	6.6	1180	3.5	41	1.98	108	16	107	4.6	240	253	39	.34	.009
26	D 12 12 20caa	Piedmont	6.7	980	7.5	42	1.52	83	15	80	4.7	164	190	61	.43	.007
27	D 12 12 29cda	Piedmont	7.1	640	4.8	54	.72	32	3	73	2.0	92	203	45	.34	.008
28	D 12 12 29bdd	Piedmont	7.0	920	1.8	45	1.32	81	20	92	4.7	186	246	42	.32	.008
29	D 13 12 15dac	Piedmont	7.4	735	19.9	20	1.17	18	4	106	1.7	28	232	76	.85	.009
30	D 13 13 18ccb	Piedmont	7.3	1140	3.1	36	2.00	109	17	114	4.6	285	212	49	.43	.009
31	D 12 12 21dcd	Bottom-Land	7.3	1200	29.0	24	.4	126	19	125	3.5	190	327	96	-	-
32	D 12 12 22dcd	Bottom-Land	7.4	900	11	30	.6	70	36	71	2.1	170	229	48	-	-
33	D 12 12 35add	Bottom-Land	7.5	1200	18	22	.6	100	20	152	3.3	250	325	84	-	-
34	D 12 12 34dbb	Piedmont	9.2	300	.6	11	1.3	4	0	66	.8	38	63	60	-	-
35	D 12 12 34dcc	Piedmont	8.0	500	7	35	.5	59	9	55	2.6	26	278	40	-	-
36	D 13 13 7cdd	Piedmont	7.5	1100	9	30	1.2	76	17	166	3.5	158	356	104	-	-
37	D 13 13 6cdd	Bottom-Land	7.8	1300	34	19	.8	154	20	120	2.6	262	322	92	-	-
38	D 13 13 8ccc	Bottom-Land	7.1	800	14	17	1.4	76	7	83	2.6	140	142	76	-	-
39	D 13 13 18aca	Bottom-Land	7.5	900	14	34	1.2	66	10	154	3.6	112	342	100	-	-
40	D 12 12 34dbb	Piedmont	7.7	500	7	45	.7	48	13	51	3.3	32	258	56	-	-

Reference Number	Location	Classification	pH	Specific Conductance (umohs/cm at 25° C)	NO_3^- (ppm)	SiO_2 (ppm)	F^- (ppm)	Calcium (ppm)	Magnesium (ppm)	Sodium (ppm)	Potassium (ppm)	Sulfate (ppm)	Bicarbonate (ppm)	Chloride (ppm)	Bromide (ppm)	Br/Cl
41	D 12 12 2add	Bottom-Land	7.6	1200	2	28	.7	105	20	138	3.6	266	352	72	-	-
42	D 13 12 1bba	Bottom-Land	7.5	700	23	26	1.0	58	7	98	2.8	100	234	40	-	-
43	D 12 12 36cdc	Bottom-Land	7.4	1300	22	18	.8	145	17	158	3.7	300	317	112	-	-
44	D 13 12 1baa	Bottom-Land	7.5	1000	14	29	1.2	101	15	104	3.3	140	317	72	-	-
45	D 13 12 1aba	Bottom-Land	7.5	1300	34	26	.6	146	12	142	3.6	260	327	100	-	-
46	D 12 12 1bda	Bottom-Land	7.4	1100	25	23	1.0	113	17	133	3.2	190	332	84	-	-
47	D 13 13 7caa	Bottom-Land	7.6	900	4	25	.8	80	14	104	3.2	100	307	80	-	-
48	D 13 13 18abb	Bottom-Land	7.5	1000	10	45	1.0	64	13	173	3.0	108	361	104	-	-
49	D 13 13 17bad	Bottom-Land	7.8	1100	13	25	.4	162	12	25	3.7	262	181	70	-	-
50	D 13 13 17caa	Bottom-Land	7.8	1000	7	12	.4	104	12	105	3.3	200	220	84	-	-
51	D 13 13 17cad	Bottom-Land	7.6	1600	44	30	.4	199	21	173	4.4	340	371	140	-	-
52	D 12 12 21dcc	Bottom-Land	7.3	1100	-	-	.5	115	17	121	-	220	303	80	-	-
53	D 13 12 1bdd	Bottom-Land	7.3	1200	-	-	.8	128	16	145	-	276	317	92	-	-
54	D 13 13 19cdd	Piedmont	7.5	804	-	19	.4	70	24	69	-	176	214	46	-	-

APPENDIX B

ISOTOPIC DATA USED IN THIS STUDY

Reference number	δ Oxygen-18 ($^{o}/oo$)	δ Deuterium ($^{o}/oo$)
6	-7.3	-59
4	-7.6	-59
12	-7.7	-60
14	-6.6	-55
20	-9.1	-69
24	-6.7	-54
29	-7.7	-64

APPENDIX C

METHODS OF CHEMICAL AND ISOTOPIC ANALYSIS

Water samples with reference numbers from 1 to 30 were collected and analyzed by the author. Results of analyses for the other samples were obtained from the City of Tucson and the U. S. Geological Survey. These samples were collected since 1965, but the exact analytical procedures are not known. This appendix is intended to give information of the methods and equipment used in analyzing samples collected by the author.

Sampling Procedure

Samples were taken directly from the well after several minutes pumping, whenever possible. However, samples sometimes had to be taken from a storage tank because no outlet was available at the well. Care was taken to insure that the water had not passed through a water-softener or other treatment system. About 1.5 liters of water were collected and stored in polyethylene bottles for later chemical analyses. Where samples for isotopic analyses were taken, water was obtained directly from the well and stored in air-tight glass bottles that were completely filled.

pH Measurements

Measurements of pH were made in the field at the time of sampling. A Leeds and Northrop portable pH meter was used for this purpose. The pH of ground water is likely to change when exposed to the atmosphere because of the loss or gain of carbon dioxide.

Specific Conductance

The specific electrical conductance of each sample was measured in the laboratory. A Markson "Electro-Mark" meter was standardized by using a potassium chloride reference solution before each measurement.

Titrimetric Measurements

Chloride, bicarbonate, calcium and magnesium concentrations were determined by titration. The reagents and equipment were determined by titration. The reagents and equipment used in these tests were part of a Hach Chemical Company "DR-EL/4" portable laboratory. A "digital titrator" which delivers titrant from a cartridge of standardized solution to the sample was employed. Endpoints were determined by a change in the color of an indicator.

Colorometric Measurements

The Hach portable laboratory also provided a spectrophotometer and reagents that were used to analyze for nitrate, sulfate and silica. Samples were treated with chemicals designed to form a milky precipitate in the case of sulfate. The proper wavelength for measuring the amount of color or turbidity was then set by rotating a diffraction grating inside the instrument.

Analyses Using Flame Photometry

Sodium and potassium were determined by using a Perkin Elmer atomic adsorption/flame photometer. Small amounts of each sample were burned in an air and acetylene flame under controlled conditions. The amount of light at a certain wavelength that is absorbed by the flame corresponds to the concentration of sodium or potassium in the sample. The adsorptions of several standards were measured and used to construct a calibration curve. Unknown concentrations were then found by comparing measured adsorption to the curve.

Specific Ion Electrode Measurements

Concentrations of fluoride and bromide were found by using specific ion electordes designed to measure these constituents. These electrodes have a membrane which is permeable only to the ion being measured. When the membrane is in contact with a solution of the ion, an electrode potential develops across the membrane. The potential is measured against a reference electrode with a milivolt meter.

Stable Isotope Measurements

Deuterium and oxygen-18 were measured by the stable isotope geochemistry lab at the University of Arizona. The oxygen-18 results are accurate to within $\pm$ 0.2^{o}/oo and the deuterium results are accurate to within $\pm$ 2^{o}/oo.

APPENDIX D

DESCRIPTION OF THE SAMPLE POINTS

Reference Number	Date Sampled	Location	Description of Sampling Point	Reported Well Depth (feet)	Approximate Depth to Water (feet)	Comments
1	1/31/79	D 13 13 31bba	Well with wind mill pump.	300	250	Pump was broken. Copy of previous chemical analysis obtained from owner.
2	10/30/80	D 13 12 34aaa	Well with submersible pump.	400	90	
3	11/6/80	D 14 13 6aab	Well with submersible pump.	330	218	Owner says water bearing strata was encountered at 330 feet.
4	11/6/80	D 13 12 27bbb	Well with submersible pump.	90	50	Low yield.
5	11/11/80	D 13 13 30adc	Well with submersible pump.	450	222	Sample taken from pressure tank.
6	11/11/80	D 13 13 30bcd	Well with submersible pump.	-	-	Sample taken from house after going through large storage tank.
7	11/11/80	D 13 13 30bbc	Well with submersible pump.	-	-	
8	11/11/80	D 13 12 14dcc	Well with submersible pump.	450	295	Maximum yield 50 gallons/min.
9	11/11/80	D 13 12 15dbb	Well with submersible pump.	450	-	
10	11/11/80	D 13 12 15bca	Well with submersible pump.	340	76	Maximum yield 20 gallons/min.
11	11/20/80	D 13 12 21abd	Well with wind mill pump.	230	140	
12	11/20/80	D 13 12 21abd	Well with submersible pump.	150	-	
13	11/20/80	D 13 12 10ddd	Well with submersible pump.	> 250	-	
14	11/20/80	D 13 12 11baa	Well with submersible pump.	-	-	
15	11/20/80	D 13 12 4daa	Well with submersible pump.	560	100	

Reference Number	Date Sampled	Location	Description of Sampling Point	Reported Well Depth (feet)	Approximate Depth to Water (feet)	Comments
16	1/6/81	D 13 12 3bdc	Well with turbine pump.	-	-	
17	1/6/81	D 12 12 34caa	Well with motorized pitcher pump.	150	-	Low yield, well no longer used.
18	1/6/81	D 12 12 27cbb	Well with submersible pump.	200	135	
19	1/6/81	D 12 12 33ada	Well with submersible pump.	-	-	Sample taken from pressure tank.
20	1/6/81	D 12 12 34aba	Well with turbine pump.	470	370	Large capacity well used by water company.
21	1/6/81	D 13 12 9ada	Well with motorized pitcher pump.	153	50	Sample taken from house.
22	1/6/81	D 14 13 17bbd	Stone storage tank near well.	171	-	Low yield from volcanic rocks.
23	1/6/81	D 14 13 20bab	Well with submersible pump.	265	-	Sample taken from house.
24	2/6/81	D 13 12 10ccc	Shallow game well with wind mill pump.	-	3	Small spring about 10 feet away.
25	6/11/81	D 13 13 29dda	Well with submersible pump.	320	200	Sample from pressure tank. Two older wells also on property.
26	6/11/81	D 12 12 20caa	Well with submersible pump.	-	-	Sample taken from house.
27	6/11/81	D 12 12 29cda	Well with submersible pump.	315	310	Sample from pressure tank.
28	6/11/81	D 12 12 29bdd	Well with turbine pump.	-	-	
29	6/11/81	D 13 12 15dac	Well with submersible pump.	-	-	
30	6/11/81	D 13 13 18ccb	Well with submersible pump.	-	-	

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