

THE INA ROAD LANDFILL AS A SOURCE  
OF GROUND-WATER POLLUTION

by

Michael Minas Mooradian

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APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

L. G. Wilson  
Dr. L. G. Wilson  
Hydrologist

11/18/83  
Date

## PREFACE

This thesis is based on research funded by the Pima Association of Governments (PAG), 208 Project with support from the City of Tucson and the Pima County Wastewater Management Department. The study was started in the Spring of 1979 to determine if the Ina Road landfill is a source of ground-water contamination. The study included the design and installation of monitoring wells and the monthly collection of surface and ground-water samples for chemical analyses. The results of the study were published by PAG in a technical report entitled "Landfill Leachate and Groundwater Quality Analysis: Ina Road Landfill" (Mooradian, 1980a). Although some of the analytical techniques performed by the laboratory provided questionable results, the data allowed qualitative conclusions to be developed about the landfill as a source of ground-water contamination. In addition, this investigation provided the impetus for subsequent studies about the sources of ground-water contamination in the Cortaro Basin.

In 1980, the Arizona Department of Health Services (ADHS) continued the monitoring program established by this study. The program included analyzing for a larger number of chemical constituents including organics. The program was later incorporated into a regional monitoring network under the joint supervision of ADHS, PAG, and Pima County Wastewater Management. During this program, new monitoring wells

were installed by Pima County Wastewater Management to replace wells destroyed during operations at the landfill. The results of the monitoring program were in general agreement with the results of the technical report prepared for PAG.

In 1981, an investigation to identify sources of ground-water contamination in the Cortaro Basin was conducted by the Water Resources Research Center, University of Arizona for PAG (Wilson, Keith, and Fitch, 1983). The development of this study was based directly on recommendations presented in the technical report prepared for PAG on the Ina Road landfill.

The results of all these studies and investigations have resulted in an awareness of the seriousness of ground-water contamination from landfills and other sources in the Tucson and Cortary basins. In 1982, the people of Pima County approved a \$9,000,000 bond to secure both abandoned and active landfills in the county from contaminating ground water in the basin. The Pima County Wastewater Management Department is currently conducting a project to define the source and extent of contamination at the El Camino del Cerro and Ina Road landfills. The final stages of the project will be to design and implement remedial measures to mitigate ground-water contamination from these landfills.

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## ABSTRACT

A monitoring program was established at the Ina Road landfill in Tucson, Arizona to evaluate the potential for ground-water pollution. Seven observation wells were installed as part of this study. Ground-water samples were collected monthly from July 1979 to February 1980.

Mean concentrations of bicarbonate, chloride, and sulfate, and values of specific conductance were the most reliable indicators of contaminated ground water. Chemical maps of these constituents indicated a plume of contamination originating in that portion of the landfill adjacent to the Santa Cruz River and extending northward. The source of water for leachate generation was hypothesized as being major runoff events in the Santa Cruz River. The northerly direction of the plumes, instead of northwesterly along the regional gradient of ground-water flow, was attributed to flood waters of good quality percolating through the bottom of the abandoned sand and gravel pit west of the landfill.

## CHAPTER 1

### INTRODUCTION

#### Statement of Problem

Ground water is the sole source of water for the Tucson metropolitan area, Arizona. As a result, the abatement and prevention of ground-water pollution has a high priority in this region. The sanitary landfill is recognized as one potential source of ground-water contamination in the Tucson area. When solid waste comes into contact with an aqueous solution such as water, a highly polluted substance known as leachate is produced. Ground water becomes contaminated when leachate infiltrates through the bottom of the landfill and percolates to the water table. Heavy rainfall, a shallow depth to ground water, and proximity to surface water are conditions generally recognized as increasing the potential for leachate production in landfills. A low rate of precipitation combined with a high rate of evapotranspiration is generally considered to preclude rainfall as a source of water for the production of leachate in the Tucson area.

Traditionally, landfills have been located in abandoned gravel pits along ephemeral stream channels in the Tucson area. These sites were most likely selected because minimal excavation is required for the landfills to become operational. Ground-water contamination from these landfills was of great concern because of the proximity to surface water and the high permeability associated with the sand and gravel deposits

found in these areas. It is highly possible that flood waters will inundate these landfills and interact with the solid waste to produce leachate. The relatively high permeability of the surrounding geologic deposits increases the potential for the leachate to migrate from the landfill to the water table. Stream channels in the Tucson area also serve as recharge areas during runoff events. Previous investigations have shown that streamflow percolating into the subsurface may travel for considerable distances laterally in the vadose zone before moving downward to the water table (Wilson and DeCook, 1968). The subsurface movement of flood waters through the vadose zone and into the landfill may also result in the production of leachate and the subsequent migration of contaminants to the water table.

The Ina Road landfill was selected as a case study for this investigation to evaluate the potential for ground-water pollution from landfills adjacent to ephemeral streams. The Ina Road landfill is adjacent to the Santa Cruz River in the northwest portion of the Tucson Basin known as the Cortaro Basin (see Figures 1 and 2). Historically, storm-water runoff in the Santa Cruz River has resulted in the periodic flooding of cell 1 of the landfill (see Figure 3). In October 1978, high flood waters eroded the north bank of the river exposing layers of solid waste. It is believed that the flood waters provided the mechanism for leachate production in the landfill and the subsequent local contamination of ground water.

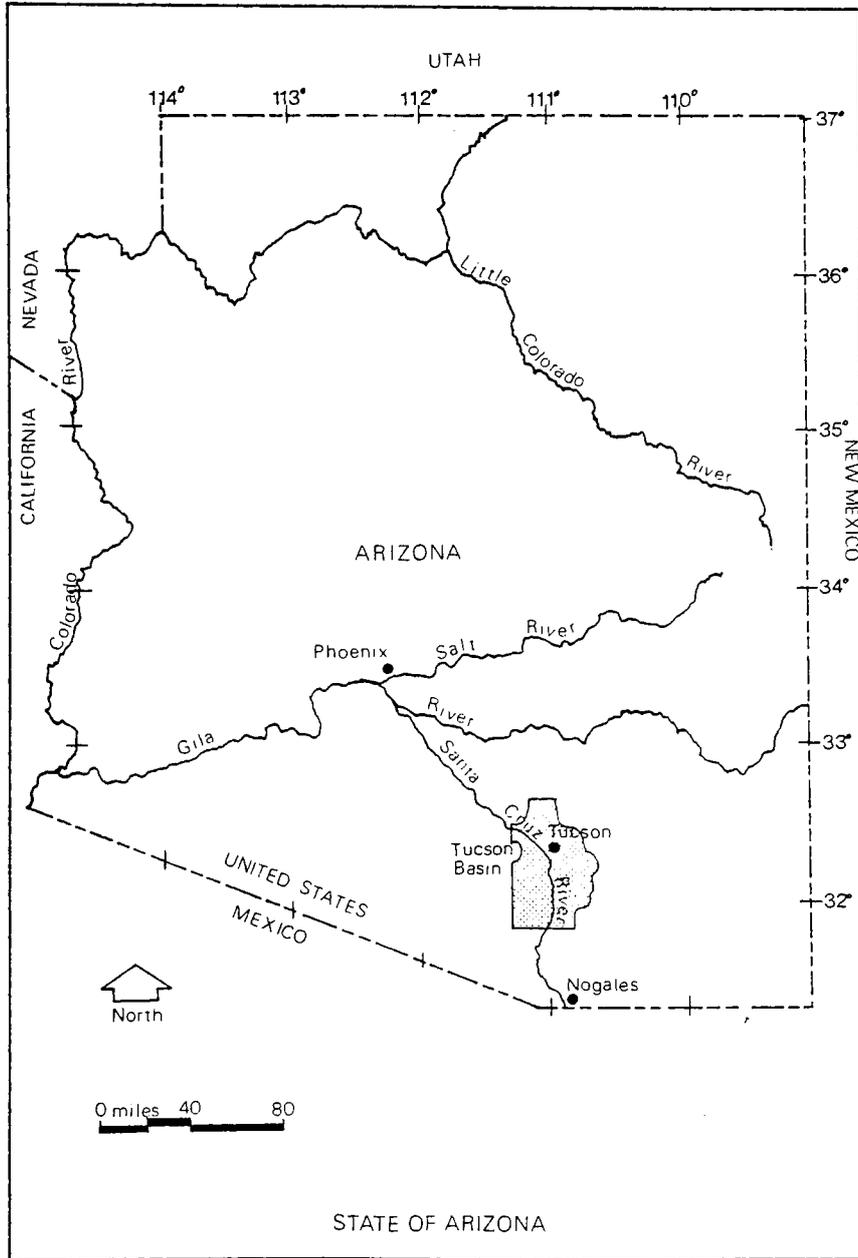


Figure 1. Map of Arizona showing the Tucson Basin.

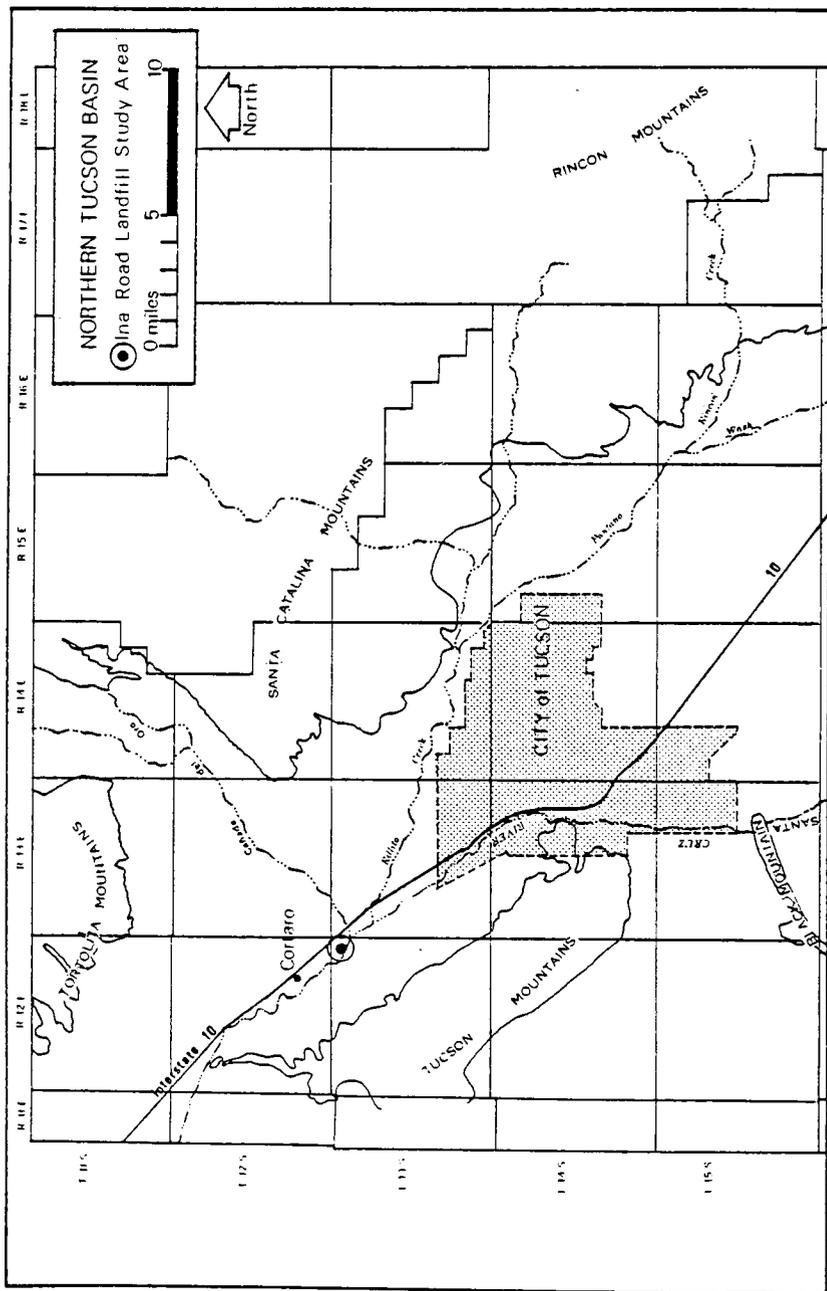


Figure 2. Map of the northern Tucson Basin showing the study area.

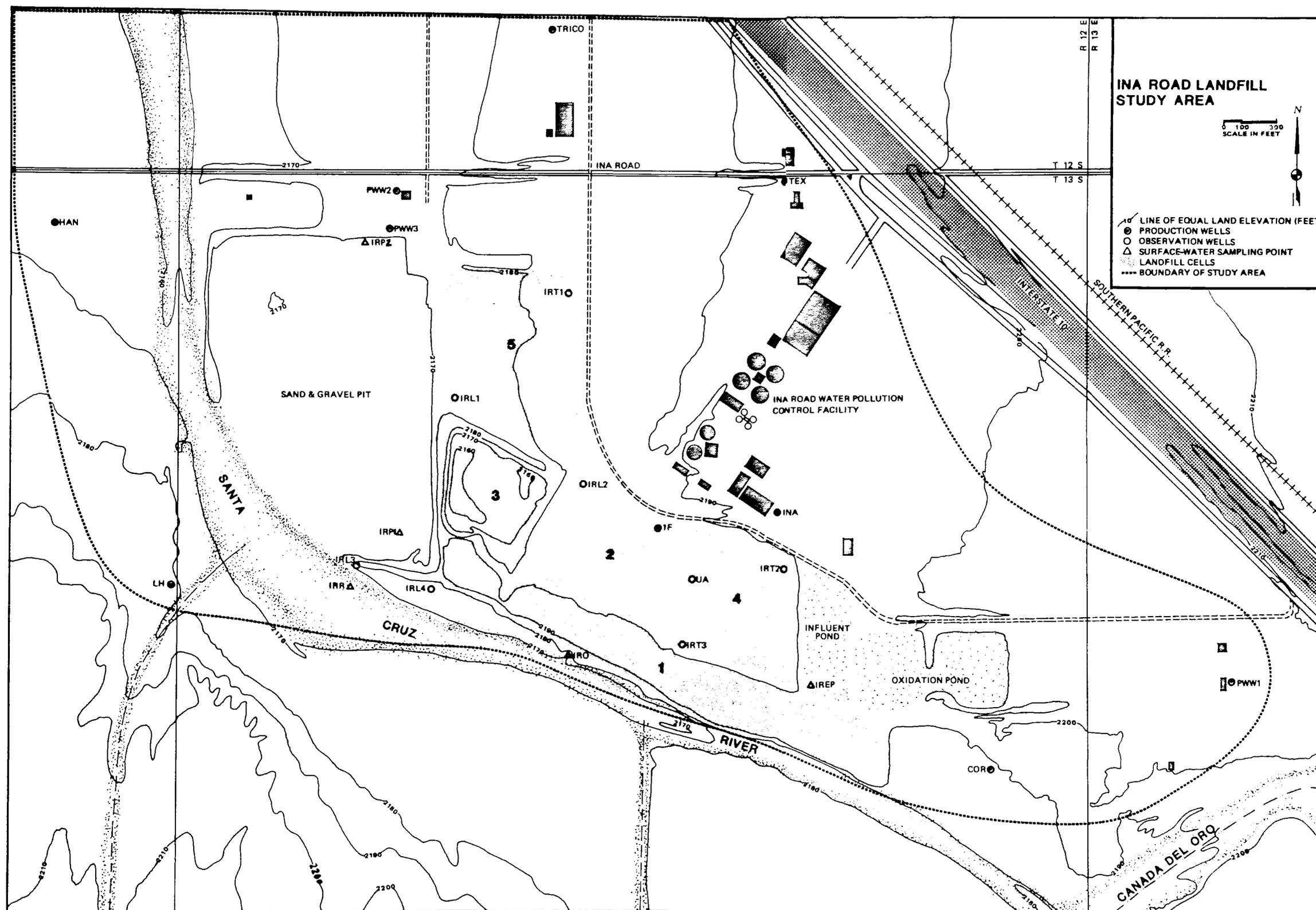


Figure 3. Map showing the Ina Road landfill study area.

### Purpose and Scope

The purpose of this study is to evaluate the potential for ground-water pollution from landfills adjacent to the ephemeral streams. The Ina Road landfill was selected as a case study for this evaluation because of its proximity to the Santa Cruz River and the occurrence of a major flood event in the fall of 1978.

The scope of the investigation included reviewing existing information on the geology and hydrology of the region as well as previous investigations of landfills as sources of ground-water pollution, and designing and installing a ground-water monitoring network. Water samples were collected monthly from wells, ponds, and the Santa Cruz River and analyzed for 26 chemical constituents and parameters. Analytical results were used to identify the presence and source of ground-water contamination. In addition, the areal distribution of bicarbonate, chloride, and sulfate concentrations, as well as values of specific conductance, were mapped from the results of the chemical analyses.

### Previous Investigations

#### Area Specific Investigations

The Ina Road landfill was first suspected of being a potential source of ground-water contamination in 1971 during a study by Small (1973). The purpose of the study was to detect and monitor the migration of contaminants below an oxidation pond that had recently been installed near the landfill. The oxidation pond was excavated immediately north of cell 1 of the Ina Road landfill approximately 500 feet from the Santa

Cruz River. Two wells were constructed in the oxidation pond to depths of 40 feet and 60 feet below land surface to monitor water in the vadose zone. A third well was completed at 100 feet below land surface to permit ground-water sampling.

In August 1971, a major flood, with a peak flow of 2,190 cubic feet per second (cfs), occurred in the Santa Cruz River (U.S. Geological Survey, 1972). During this flood, the landfill became inundated by the Santa Cruz River. Within ten days, a wave of contaminated ground water was detected in the well completed at 60 feet. The wave of contaminants was most clearly shown by the trend in the concentration of chloride which increased from 88 milligrams per liter (mg/l) to 570 mg/l before decreasing to background levels (see Figure 4). The trend for other constituents was found to be similar to that of chloride. The chemical trends observed in the well completed at 60 feet were not exhibited by the other two wells, indicating that the contaminant migration from the landfill occurred mainly in the vadose zone above a perching layer about 60 feet below land surface. The absence of contaminants in the 40 foot well indicated that a high degree of uncertainty exists when locating monitoring wells in the vadose zone. In addition, the absence of contaminants in the 100 foot well showed that, if samples had not been collected from the vadose zone, the migration of leachate from the landfill may not have been detected.

The Ina Road landfill was investigated as a source of ground-water contamination for a second time by Wilson and Small (1973). Seismic refraction and electrical resistivity surveys of the area, and the monitoring of water-level fluctuations in a single observation well,

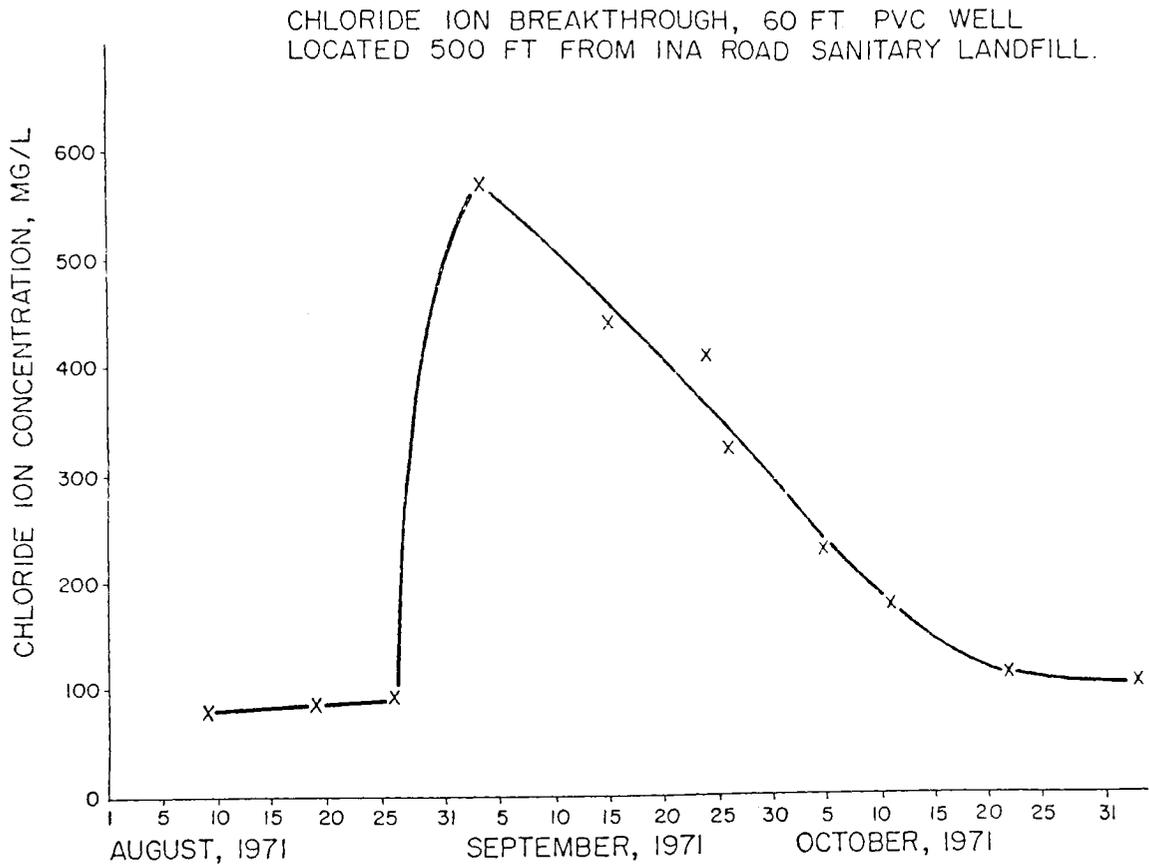


Figure 4. Chemical hydrograph of chloride in the vadose zone following a major runoff event in the Santa Cruz River (Wilson and Schmidt, 1978).

identified a perched water table. The interaction of perched water with the landfill deposits occurred only during major runoff events in the Santa Cruz River.

Chemical analyses of leachate obtained from the landfill revealed concentrations of soluble salts, biochemical oxygen demand (BOD), and nitrate similar to those found in water collected from the river. Although concentrations of metals in the leachate slightly exceeded recommended limits, sorption of these elements was believed to occur on sediments in the vadose zone. From chemical analyses of water samples and monitoring water levels in wells, Wilson and Small (1973) concluded that flood waters were the cause of leachate production at the Ina Road landfill. The investigators also concluded that the landfill did not represent a hazard to the quality of ground water, but that further investigations were needed.

Wilson, Herbert, Ramsey, and Randall (1974) characterized the hydrogeology in the area of the Ina Road landfill from the results of aquifer tests and data obtained from previous investigations. The surficial deposits and Fort Lowell Formation were found to have an average thickness of 80 feet and 100 feet, respectively. The transmissivity was estimated to be 4,700 feet squared per day ( $\text{ft}^2/\text{day}$ ) for the Fort Lowell Formation and Tinaja Beds, and 20,000  $\text{ft}^2/\text{day}$  to 40,000  $\text{ft}^2/\text{day}$  for the overlying surficial deposits.

Chemical analyses of water samples collected from wells in the study area indicated a decrease in salinity with increasing distance from sewage lagoons also present in the study area. In addition, the chemical

data indicated the quality of recharge water improved as it percolated through the surficial deposits (Wilson et al., 1974).

Wilson, Herbert, and Ramsey (1975) conducted a study along the Santa Cruz River in the vicinity of the El Camino del Cerro landfill approximately 3 miles upstream from the Ina Road landfill. The purpose of the study was to determine the effects of sewage effluent on leachate generation. During this study, the City of Tucson Treatment Plant discharged sewage effluent into the Santa Cruz River approximately 0.5 miles upstream from the El Camino del Cerro landfill. The study included chemical analysis of effluent samples obtained from the Santa Cruz River, and of water samples collected from a shallow well completed at the base of the landfill in a zone of perched water and a deeper well on the west side of the river that tapped the surface of the main water table. Samples were also collected from a well upstream from the treatment plant and a well downstream from the landfill. These wells were both screened at the surface of the main water table. Water-level measurements made in the landfill well showed a hydraulic connection between the Santa Cruz River and the perched water zone. Chemical analyses of water samples collected from all the monitoring wells showed no evidence of leachate generation in the landfill.

The El Camino del Cerro landfill was investigated as a source of ground-water contamination by Mooradian (1980b). A monitoring program was established which included the chemical analysis of samples collected from neighboring production wells, the Santa Cruz River, a

large sewage effluent pond south of the landfill, and an observation well on the west side of the river used in the study by Wilson et al. (1975). The observation well was completed at 100 feet below land surface and screened approximately 20 feet below the main water table. In addition, samples were collected from two monitoring wells installed in the vadose zone as part of this study. One well, designated RR1, was completed between the landfill and the river at a depth of 40 feet below land surface. The presence of water in this well indicated a zone of perched water near the base of the landfill. The second well, designated RR2, was completed to a depth of 29 feet. The well was approximately 700 feet north of RR1 and remained dry throughout the entire study.

In August 1979, a local thunderstorm resulted in a minor runoff in the Santa Cruz River. Water levels in RR1 rose approximately 5 feet within 24 hours of the storm. Ground-water levels remained static in the observation well west of the river during the same period. The rise in the water level in RR1 was attributed to recharged storm water moving laterally from the river through the vadose zone. The static water level in the deep observation well provided additional evidence that the recharged water flowed for considerable distances laterally in the vadose zone before percolating to the water table.

The results of the chemical analyses indicated that ground water in the study area is generally of poor quality. However, leachate was not detected in the samples collected from the wells completed in the vadose zone and there was no indication of ground-water contamination from the landfill.

## Leachate Investigations

Previous investigations of the production and migration of leachate were reviewed during this study to help understand the mechanisms of leachate production, migration, and attenuation. These investigations also provided information useful in the design and implementation of the monitoring system at the Ina Road landfill.

Pollutant reactions in the subsurface are important in determining the presence of leachate and assessing soil capabilities in preventing pollutant mobility. Langmuir (1972) discussed the controls on the release and movement of pollutants in ground water and the capacity of the soil and rock matrix of the subsurface to purify them. The discussion included the probable effects of various physical, geochemical, and biochemical processes on the mobility of landfill leachate in subsurface waters. The processes examined included dilution, dispersion, adsorption, and decay.

Fuller (1977) presented information on the movement of arsenic, asbestos, beryllium, cadmium, chromium, copper, cyanide, iron, lead, mercury, selenium, and zinc, in various soils. Based largely on the review of literature, Fuller found several physical, biological, and chemical factors involved in the attenuation of contaminants on soils. The most significant of these included soil texture, particle size distribution, the content and distribution of iron oxides, the nature of the soil colloid fraction, the presence of lime, and pH. Based solely on pollutant properties, laboratory experiments showed cyanide and selenium as mobile in soils; iron, lead, copper, and beryllium as moderately

mobile; and arsenic, cadmium, mercury, and asbestos as slightly mobile. The results of Fullers's (1977) investigation are presented in Figures 5 and 6.

Fuller (1978) continued laboratory investigations on pollutant mobility in soils. The results of this study verified many of his earlier findings. The migration of trace elements was found to be dependent on the properties of soils, leachate, and the element under investigation. Fuller found attenuation to be a function of permeability, and of the amount of clay, hydrous iron oxides, and lime present in the soil matrix. In addition, the pH, types of ions present, the presence of organic matter, and the carbon dioxide tension of the leachate; and the concentration of the specific metal under investigation were found to affect the mobility of the trace element. The production of leachate in landfills was investigated by Cameron (1978). Cameron discovered that the action of water as a solvent was dependent upon the age of the landfill. Acid produced from microbial activity in a new landfill was observed to lower the pH and increase the solvent capabilities of water. As the landfill aged, a decrease in microbial activity, an increase in pH, and a reduction in the solvent properties of water were detected. Cameron concluded that the concentration of leachate peaks early in the life of a landfill and then decreases exponentially with time. After studying a number of waste disposal sites, Cameron found that each landfill behaved differently in the production of leachate. Although the age of the landfill, ambient temperature, landfill depth, and precipitation played an important role in the type and

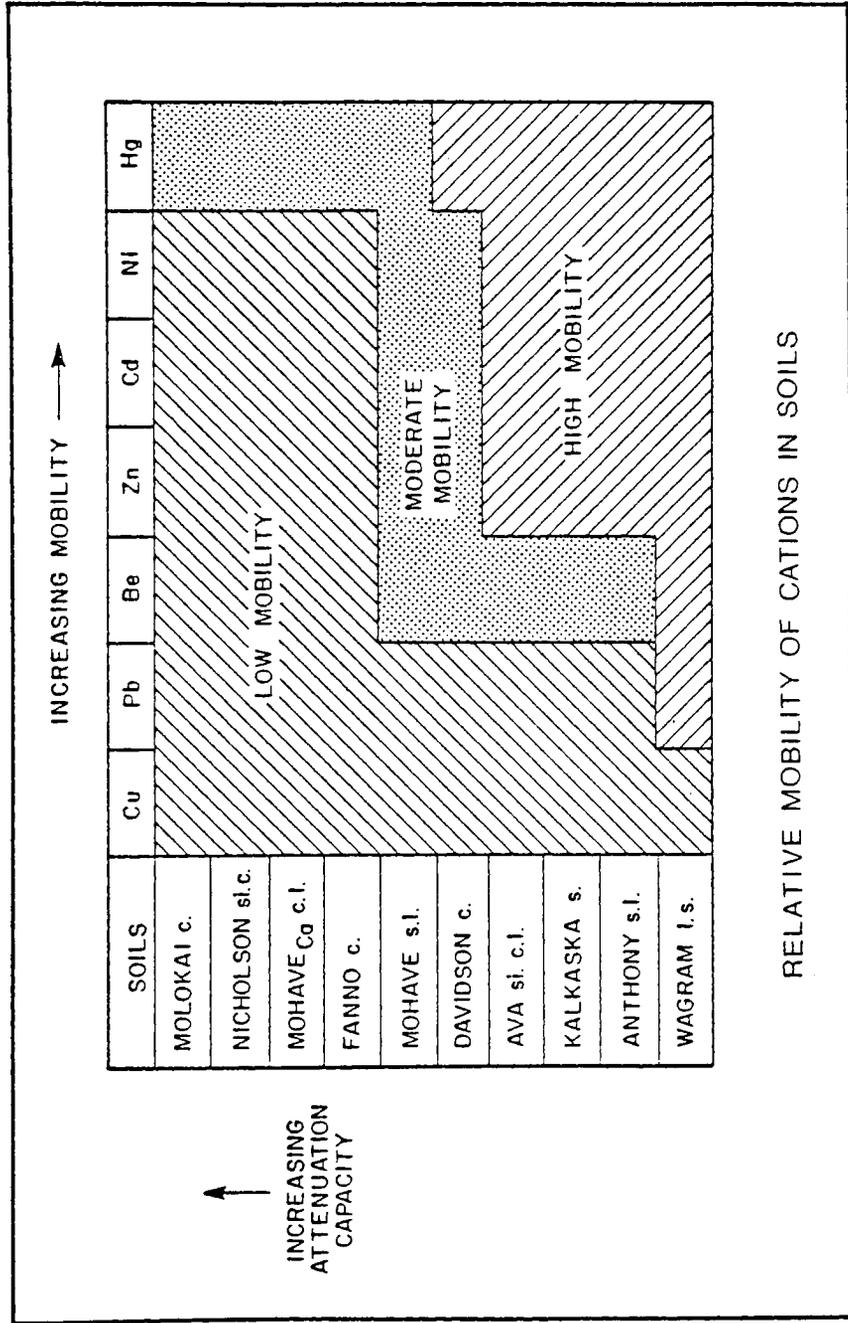


Figure 5. Relative mobility of cations in soils (Fuller, 1977).

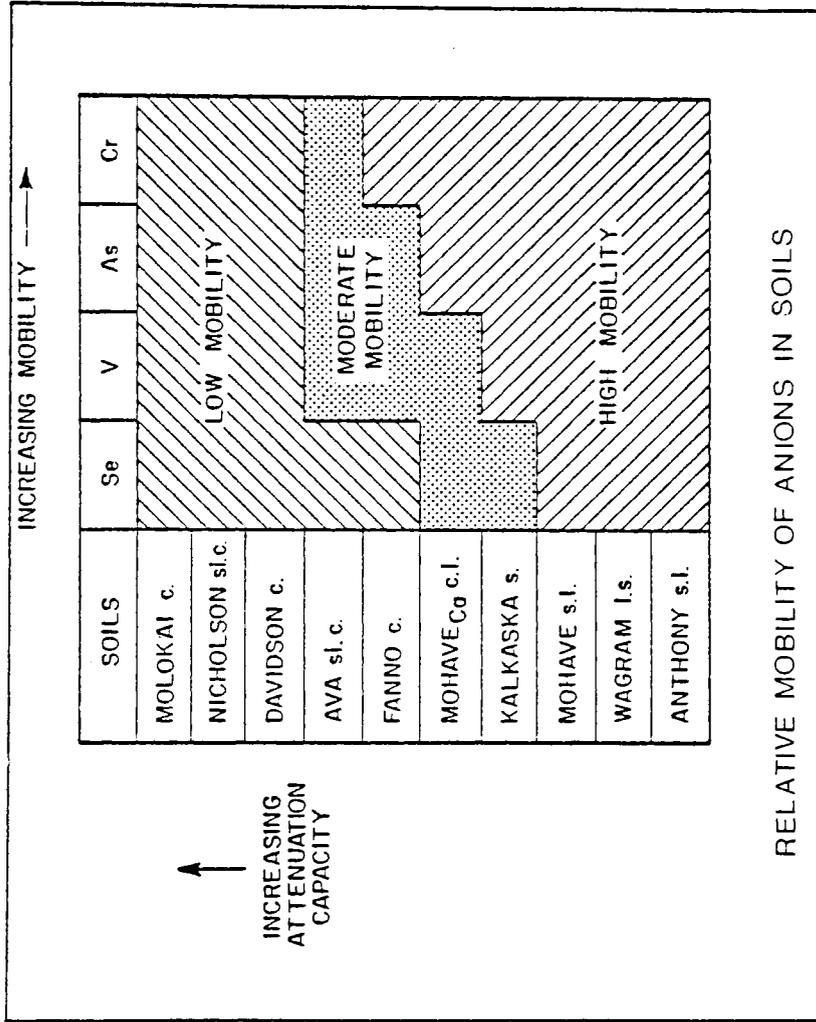


Figure 6. Relative mobility of anions in soils (Fuller, 1977).

concentration of the leachate produced, important factors in the migration of pollutants were found to include depth to ground water, the composition and permeability of the underlying soils, and the rate of ground-water flow.

The results of Cameron's investigation also indicated that, in addition to grain size, pH is an important factor which affects the attenuation capabilities of soils. Under conditions of high pH, cationic metals tend to precipitate and become filtered in the soil. However, the overall attenuation capability was found to decrease under these circumstances because of clogged soil pores which resulted from the abundance of precipitate present. Neutral pH values provided the best environment for soil attenuation.

Baedecker and Back (1979) investigated the chemical effects of leachate production on ground water in the Army Creek landfill near Wilmington, Delaware. The landfill consisted of industrial solid and liquid wastes as well as municipal refuse. The landfill was established in an abandoned sand and gravel quarry from which approximately 30 feet of sand and gravel were removed. The quarry was full of water as a result of the shallow water table. The landfill was operated by depositing the solid waste into the ponded quarry.

In the late 1960s, a well field was developed about 3,500 feet southeast of the Army Creek landfill. The wells were completed depths ranging from 150 to 200 feet below land surface. In 1973, the discovery of leachate in some of these wells led to the implementation of a recovery well field. The wells were designed to remove the leachate from

the subsurface and create a barrier to prevent the further migration of contaminants in the ground water. A number of observation wells were installed as part of this program to monitor the effectiveness of the recovery system.

Baedecker and Back (1979) collected water samples for chemical analysis from the observation, recovery, and production wells in the area of the landfill. Measurements of dissolved oxygen indicated the presence of aerobic, anaerobic, and transitional zones in the study area. A nitrogen index, the ratio of organic and ammonia-nitrogen to nitrite and nitrate-nitrogen, was developed to identify reducing fronts caused by the migration of leachate.

Baedecker and Back concluded that the pumping of recovery wells caused leachate to mix with ground water and become oxygenated. The oxygenation of leachate was believed to be one of the controls on the chemical character of the contaminated ground water. The natural ground water was found to have a lower pH than ground water contaminated with leachate. The high pH of the contaminated water was believed to be the result of the production of carbon dioxide, ammonia, and methane gas in the subsurface. The major sources of cations in the natural ground water were identified as rainfall and the alteration of silicate minerals. Suspected sources of cations in the leachate were solid waste, the alteration of silicate minerals in the landfill, and clays by exchange with the large amount of ammonium generated. High concentrations of manganese and iron in the leachate were believed to have been derived from the waste.

## CHAPTER 2

### BACKGROUND

#### Geography

The Tucson Basin occupies approximately 1,000 square miles in the upper Santa Cruz River drainage basin. The City of Tucson is in the northern portion of the basin at an average elevation of 2,300 feet above mean sea level. The basin is drained by the north-flowing Santa Cruz River and its three principal tributaries, known as the Pantano Wash, Canada del Oro Wash, and the Rillito River.

The Ina Road landfill is in the northwest portion of the Tucson Basin in an area known as the Cortaro Basin (see Figure 2). The Cortaro Basin ranges in elevation from 2,050 feet to 2,300 feet above mean sea level and is bordered by the Santa Catalina Mountains on the east, the Tortolita Mountains on the north, and the Tucson Mountains on the west. The mountains on the north and east range from 6,000 feet to 8,000 feet in elevation. The Tucson Mountains, on the west, range in elevation from 3,000 feet to 6,000 feet above mean sea level.

The Ina Road landfill study area is in Section 1, Township 13 South, Range 12 East. The study area ranges in elevation from 2,160 feet to 2,210 feet above mean sea level. In addition to the landfill, an abandoned sand and gravel pit, farmland, and the Ina Road Water Pollution Control Facility are also present in the study area. The landfill occupies approximately 65 acres in the floodplain of the Santa Cruz River

and consists of five cells (see Figure 3). During the field program for this study, landfilling operations were underway in cell 3. Cells 1 and 2 were completed prior to this study and cells 4 and 5 were scheduled for future use. The depth of the cells varied from 20 feet to 50 feet below land surface. In addition to solid waste, sludge from the Ina Road Water Pollution Control Facility was also disposed of in the landfill.

### Climate

The Tucson metropolitan area has a semiarid climate which is characterized by a mean annual temperature of 67.3° F. Temperatures range from a high monthly mean of 86.1° F in July to a low monthly mean of 50.0° F in January. The potential pan evaporation at the University of Arizona, Tucson is more than 80 inches per year (Laney, 1972).

Precipitation in the Tucson area is variable, dependent mainly on altitude. The mean annual precipitation is approximately 11 inches in the basin and as much as 30 inches in the nearby mountains. The Tucson Basin is typified by summer and winter storms. Approximately 50 percent of the rainfall occurs from July through August. Summer precipitation occurs as the result of convective storms which precipitate moisture blown in from the Gulf of California. Winter storms, cyclonic in type, occur from December through March. These storms originate in the northwest and move eastward across the nation. Winter storms are widespread, longer and less intense than those occurring in the summer.

### Geology

#### Regional Geology

The Cortaro Basin is in the northwest portion of the Tucson

Basin, Arizona. The basins are part of the Basin and Range Physiographic Province. The geology of the Tucson and Cortaro basins was described in a comprehensive report by Davidson (1973). The structure of the Tucson Basin consists of down-dropped blocks caused mainly by normal faulting. Igneous, metamorphic, and highly cemented sedimentary rocks make up the basement complex and the mountains surrounding the basin.

A geophysical study conducted by Goodoff (1975) indicated that the Cortaro Basin is a faulted block basin distinct from the Tucson Basin. The center of the basin, which is northeast of the Ina Road landfill in Sections 29 and 30, Township 12 South, Range 13 East, has a depth of approximately 5,000 feet (Goodoff, 1975). The entrance to the basin lies between the Rillito and Santa Cruz rivers in an area of shallow bedrock approximately 1,700 feet in elevation. The basin exit is in the northwest, in an area known as the Rillito Narrows. Bedrock in this area is also shallow, approximately 1,600 feet in elevation.

The Santa Catalina and Tortolita mountains consist of metamorphic and intrusive igneous rocks. These formations are mainly granodioritic gneiss and granite which range in age from Precambrian to late Tertiary. The ability of these rocks to store and transmit water is dependent upon the presence of fractures (Davidson, 1973).

The Tucson Mountains form the western boundary of the Tucson Basin and are largely composed of andesitic and rhyolitic flows, tuff, and agglomerate. The older formations of Mesozoic and Tertiary age have low to moderate porosities and permeabilities. The younger volcanics of late Tertiary age are present along the eastern face of the Tucson

Mountains. These rocks have larger vesicular openings and a greater percentage of fractures than the older volcanics (Davidson, 1973).

The sedimentary units making up the Tucson and Cortaro basins are generally unconsolidated sediments derived from the surrounding mountains. These deposits range in age from Tertiary to Quaternary and are up to 2,000 feet thick in some locations. The Pantano Formation, Tinaja Beds, and Fort Lowell Formation are the principal deposits of the main aquifer in the Tucson and Cortaro basins. The Pantano Formation, of Oligocene age, ranges from several hundred to 1,000 feet thick in the center of the basin. The unit consists mainly of conglomerate, sandstone, gravel, and mudstone. The porosity of the Pantano Formation was estimated from borehole-formation-density logs to range from 20 to 26 percent (Davidson, 1973). The permeability of this unit was estimated from aquifer tests to range from 0.67 to 13.4 feet per day (ft/day) (Davidson, 1973).

The Tinaja Beds unconformably overlie the Pantano Formation throughout most of the Tucson Basin. Davidson (1973) estimated from aquifer tests that the permeability of this unit ranges from about 1.3 to 13.4 ft/day. The Tinaja Beds are several hundred feet thick in much of the Tucson Basin.

The Fort Lowell Formation, the most productive unit of the Tucson aquifer, unconformably overlies the Tinaja Beds and other older deposits. The unit ranges from 300 to 400 feet thick throughout most of the basin but thins toward the mountains (Laney, 1972). The Fort Lowell Formation, of Pleistocene age, consists of uncemented dark-to-light reddish-brown gravel, sand, and silt (Davidson, 1973). The porosity of the unit, as

determined from borehole logs, ranges from 26 to 34 percent (Davidson, 1973). The permeability of the Fort Lowell Formation ranges from 20 to more than 94 ft/day (Davidson, 1973).

The surficial deposits of fluvial origin overly the aquifer formations in most locations. These deposits range in thickness from a few inches to approximately 100 feet. The surficial deposits are typically unsaturated but yield large amounts of ground water along stream channels where they are readily recharged by streamflow. The reader is referred to Laney (1972) and Davidson (1973) for a more detailed description of the geology of the Tucson and Cortaro basins.

Keith described the sedimentary units in the Cortaro Basin as part of the "Cortaro Area Pollution Source Assessment" (Wilson, Keith, and Fitch, 1983). The study identified three geologic units based on data from well cuttings analyzed by the Department of Soils, Water, and Engineering, University of Arizona, the U.S. Geological Survey, and the City of Tucson Water Department. The oldest unit identified was a reddish claystone-mudstone. Although the thickness is unknown, wells in the basin have penetrated up to 800 feet into this clay unit. The unit was found at about 200 feet below land surface (about 1,900 feet in elevation) in several wells along the Tucson Mountains. East of Interstate 10, the unit is approximately 200 feet deeper at an elevation of about 1,650 feet. The unit was believed to be faulted, with the block to the east downdropped as much as 300 feet.

A coarser-grained unit consisting of volcanic clast overlies the red clay unit in much of the basin. The unit was found to range in thickness from 90 to 350 feet. The surface of the unit is approximately

1,800 feet or more in elevation in the northwest, and up to 2,100 feet in elevation in the southeast. Keith believed that the surface elevation of the volcanic unit indicated that it had been deposited after the period of deformation that resulted in the displacement of the clay unit.

The upper geologic unit in the Cortaro Basin was identified as consisting of stream channel, floodplain, terrace, and alluvial fan deposits. The predominantly granitic-metamorphic unit overlies, or is interfingered with, the volcanic clast unit and extends to the land surface. A high degree of horizontal and vertical variability was identified in the lithology, texture, sorting, and grain-size distribution in this unit. The high variability in the source rock was believed to largely depend on the proximity to the source rock. Most wells in the Cortaro Basin are completed in this unit (Wilson et al., 1983).

#### Site Geology

The geology of the study area is based on information from lithologic logs prepared by drillers and geologists for wells in the region. These logs were obtained from the U.S. Geological Survey, the Arizona Department of Water Resources, and the Soils, Water, and Engineering Department, University of Arizona. These logs indicate that the upper 100 feet of sediments are heterogeneous, consisting mainly of sandy gravel and gravelly sand with some silt and clay. Comparing the logs of wells in the study area did not indicate either thick or continuous sequences of clay. Seismic refraction and electrical resistivity surveys were conducted at the Ina Road landfill by Peterson and Staley (1973). Their investigation suggested a clay lens existed in the area of cells 1

and 2 of the landfill. The lens ranged in depth from 10 to 30 feet below land surface.

The limited number of wells, and the lack of precision and detail in logs prepared by well drillers, preclude accurate construction of geologic cross sections for the study area. However, a detailed lithologic log was available for the production well (INA) supplying the Ina Road Water Pollution Control Facility. Cuttings collected during the drilling of this well were analyzed by the Soils, Water, and Engineering Department, University of Arizona (Posedly, 1979). A detailed description of the lithology of the study area is based largely on this log. The description appears consistent with the lithology identified in logs of other wells in the study area. The surficial floodplain deposits (Davidson, 1973), or the granitic-metamorphic unit (Wilson et al., 1983), are up to 100 feet thick in the study area. These deposits consisted mainly of boulders, gravel and sand. Sediments in the upper 10 to 30 feet were generally fine- to medium-grained micaceous sand mixed with quartzite pebbles and granitic granules. A thin clay lens was also detected in this zone.

The gravel fraction of the surficial deposits was found to be approximately 80 percent granitic and 20 percent volcanic in composition. The granitic material consisted principally of quartzite, with less than 10 percent Catalina Gneiss. These sediments are believed to result from stream deposition of detritus materials from the Tortolita and Santa Catalina mountains. The volcanic rocks consisted mainly of welded tuff and are believed to be derived from the Tucson Mountains.

Analyses of drill cuttings indicated rounded to subrounded sands and subrounded to subangular gravels. These configurations indicate stream deposition of sediments. Less than 20 percent of the gravels retrieved were angular, most likely fragments that were fractured during drilling.

Yellow stains of iron oxides on the granitic materials were used to differentiate the surficial floodplain deposits from the underlying sedimentary units (Davidson, 1973). The base of the surficial floodplain deposits was also marked with the presence of conglomerate at an average depth of 85 feet below land surface.

From 100 to 200 feet below land surface, a gradual color change from yellow to grayish-brown was apparent in the drill cuttings. This zone was characterized by loosely packed, uncemented to weakly cemented sediments. The matrix was found to be a sandy gravel, less than 50 percent granitic and more than 50 percent volcanic materials. The volcanics were mainly purplish-gray porphyry with some yellowish-white and light gray banded welded tuff. The granitic material was mainly quartzite with some gneiss. The granitic-metamorphic unit was thought to be interbedded with the volcanic clast unit in this zone, as described by Keith (Wilson et al., 1983). Analyses of sediments collected from this zone indicated a subrounded to subangular configuration. In addition, approximately 30 to 50 percent of the gravels found were angular. The configuration and composition of the sediments seem to indicate talus from the Tucson Mountains is a major source of these deposits.

The lithology between 100 and 200 feet cannot easily be associated with the sedimentary units described by Davidson (1973). Sediment properties gradually changed with depth, indicating a possible transition zone to older surficial deposits or the Fort Lowell Formation (Davidson, 1973).

A strongly cemented conglomerate was detected below an average depth of 200 feet. The Tinaja Beds, described as a distinct sedimentary unit by Davidson (1973), have a similar lithology to the deposits found below 200 feet in the study area. The sediments in this zone were gray, moderately cemented, and consisted mainly of pyroclastic and volcanic rocks. Less than 5 percent of the samples collected were granite. Calcareous materials were also found in this zone. This description also coincides with the volcanic clast unit described by Keith (Wilson et al., 1983). The correlation between this unit and the units described by Davidson (1973) are not clear.

The configuration of the sediments was greater than 50 percent angular, again indicating talus deposition from the Tucson Mountains. The lack of granitic rocks in the drill cuttings may indicate deposition occurred before major uplift of the Santa Catalina and Tortolita mountains.

#### Soils

The soil description for the study area is based on the U.S. Soil Conservation Service Soil Survey of the Tucson-Avra Valley Area, Arizona (Gelderman, 1972). Additional information was obtained from analyses of soils obtained from borings drilled in landfill cells 4 and 5. Soils of

the Anthony-Vinton, Arizo, Brazitio, Comoro, Gila, Grabe, and Pima series are present in the study area. These soils were all formed in material laid down by rapidly flowing water on floodplains. A complete description of soils in the study area is presented in Gelderman (1972).

The soil horizon was removed during the excavation of the cells at the Ina Road landfill (Nowak, 1979). With the exception of cell 1, a silty clay liner was applied to the bottom of the cells to prevent pollutant migration from the landfill. As a result, the capability of natural soils to attenuate pollutants is of limited importance in the present investigation.

#### Hydrology

Both surface and ground water are present in the Ina Road study area. The physical and chemical characteristics of these resources were investigated to establish a baseline of information.

#### Surface Water

The Santa Cruz River and the Canada del Oro are the major stream channels in the vicinity of the study area. Canada del Oro is immediately south of the eastern portion of the study area. The stream is ephemeral, with a mean annual flow of 5.5 cfs (U.S. Geological Survey, 1978). Fogg (1978) found recharge from the Canada del Oro to represent only a small portion of the total recharge to the Cortaro Basin. Flow in the wash is from precipitation in the Santa Catalina Mountains and urban runoff. Canada del Oro is dry most of the year.

The confluence of Canada del Oro and the Santa Cruz River is east of the landfill. The Santa Cruz River forms the southern boundary

of the Ina Road landfill. The channel ranges from 125 to 500 feet wide and consists of alluvium to an average depth of 15 feet (Burkham, 1970). The river is ephemeral except for sewage effluent discharged from two treatment plants operated by Pima County. Streamflow in the Santa Cruz River is directly affected by the type of storm occurring as well as the rate of sewage effluent discharge into the channel. The mean annual discharge in the Santa Cruz River was calculated at 36.2 cfs at the gaging station at Cortaro approximately 2.5 miles downstream from the study area (U.S. Geological Survey, 1978). The hydrograph of the Santa Cruz River shows extreme variability in annual flows for the years 1949 to 1980 (see Figure 7). Since 1969, the U.S. Geological Survey has included sewage effluent flows in its measurements.

The infiltration and recharge capabilities of the Santa Cruz River have been subjects of a number of investigations. Matlock (1966) estimated the infiltration rate for a 6 mile segment of the river to be  $2.6 \times 10^5$  cubic feet per day per mile (cfd/mile). The area of investigation included the stream segment adjacent to the Ina Road landfill. Cluff, DeCook, and Matlock (1972) measured the rate of infiltration along a 17 mile segment of the Santa Cruz River which also included the reach adjacent to the present study area. Study results indicated that the rate of infiltration increased in areas where the stream slope decreased and the width of the stream channel increased. The average infiltration rate was reported as  $2.16 \times 10^5$  cfd/mile (Cluff et al., 1972). Sebenik, Cluff, and DeCook (1972) found the infiltration rate of the Santa Cruz River channel increased after runoff flows from storms. The rapid flows

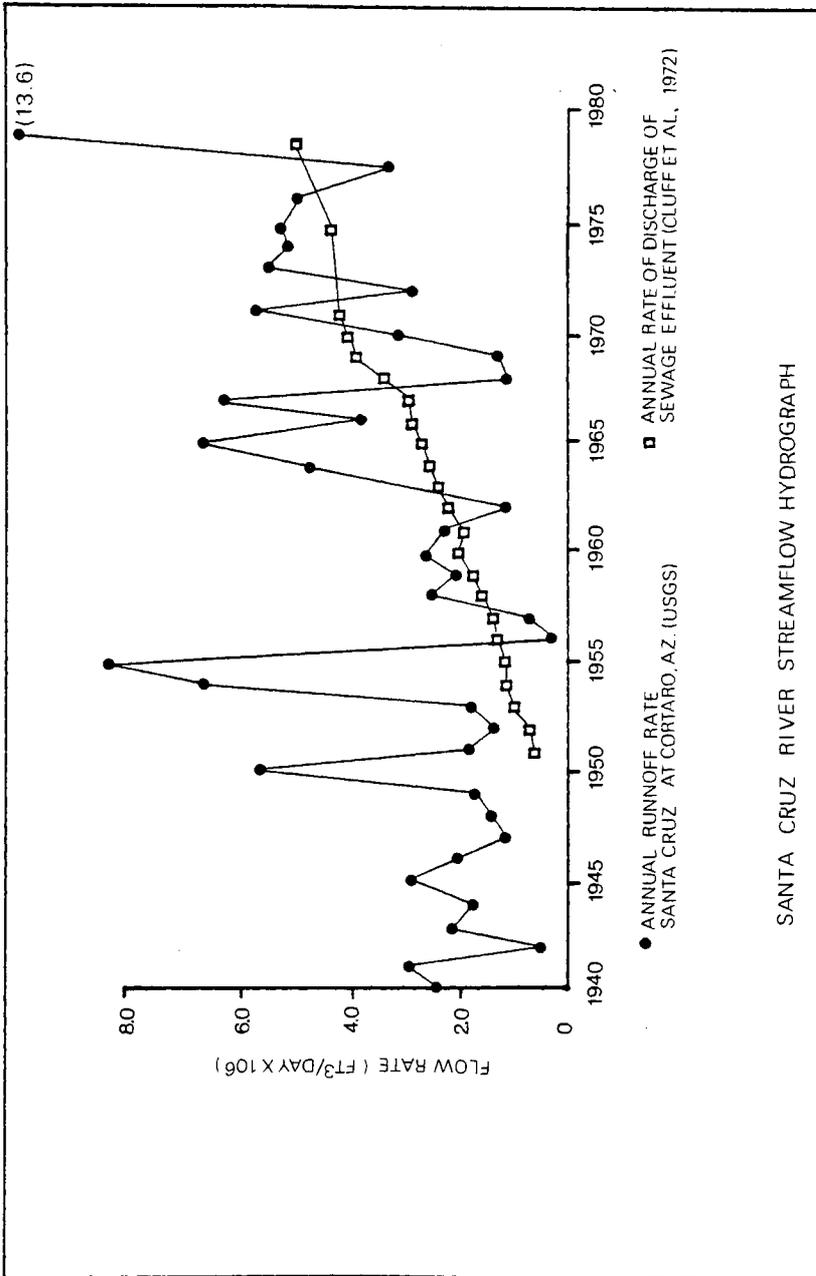


Figure 7. Streamflow hydrograph of the Santa Cruz River at Cortaro, Arizona (updated from Fogg, 1978).

were believed to scour the stream channel, removing much of the organic and inorganic material deposited by the effluent (Sebenik et al., 1972).

Wilson and Small (1973) used a current meter at two locations 1,420 feet apart to measure stream losses adjacent to the Ina Road landfill. Recharge in this segment of the river was estimated to be  $1.6 \times 10^6$  cfd/mile, approximately six times that reported by Matlock (1966).

#### Surface-Water Quality

Water quality in the Santa Cruz River is generally excellent, except for high concentrations of suspended sediment (Laney, 1972). Calcium, bicarbonate, and sulfate are the major chemical constituents found in runoff, while nitrate and chloride are prominent in effluent discharges. The difference in quality between runoff and effluent was studied by Wilson and Small (1973). Samples collected during runoff events had significantly lower concentrations of all tested constituents than samples collected during low effluent flows. For example, the concentration of chloride was reported as 8 mg/l in runoff and 84 mg/l in effluent (Wilson and Small, 1973).

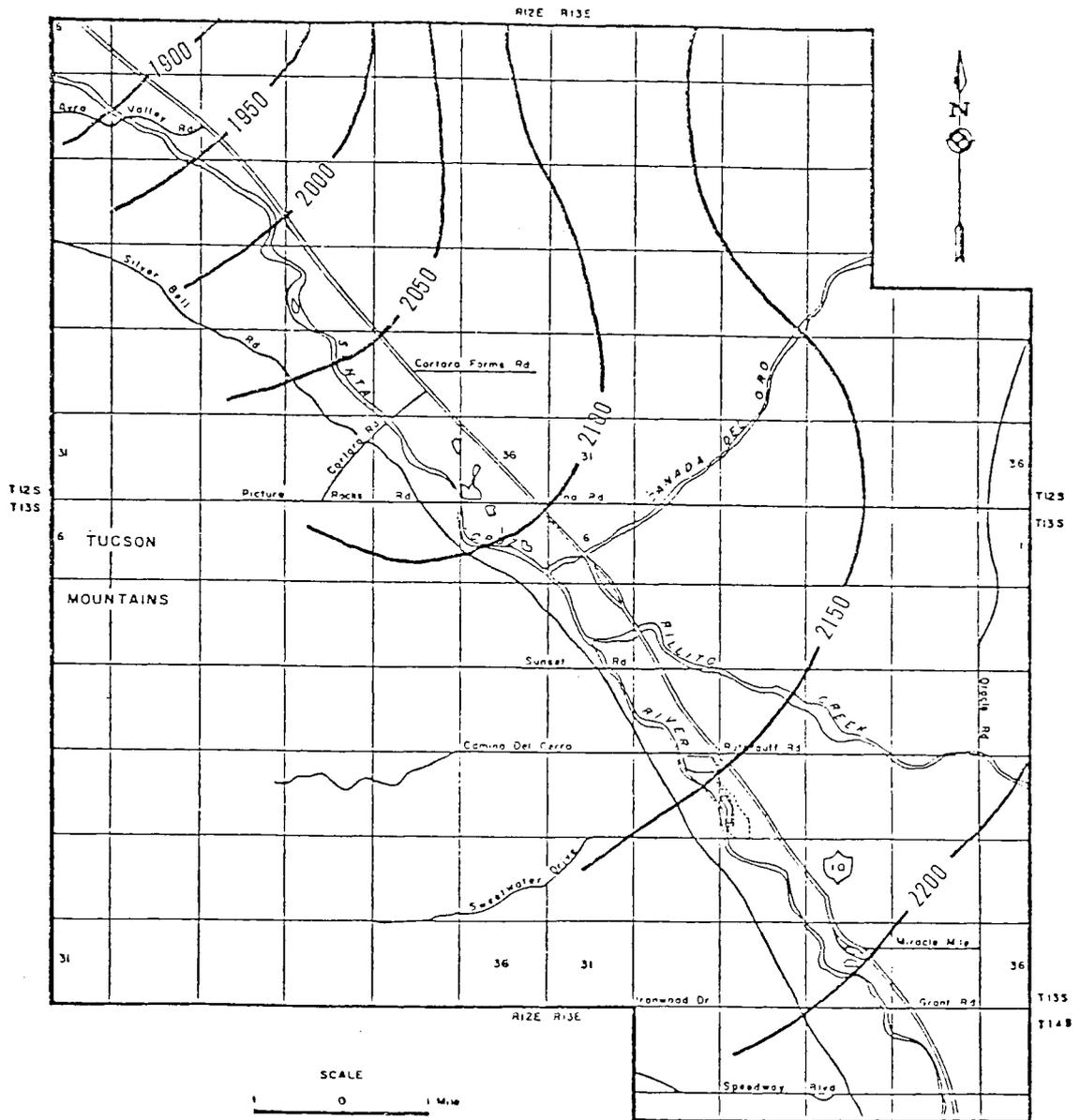
Since 1975 the protective bank separating the Santa Cruz River from a gravel pit west of the landfill has been breached several times by flood waters. The 33-acre pit remained full following the recession of each flood. In each instance, sewage effluent discharged into the river channel entered the pit prior to the installation of a new dike (Wilson, Martin, and Lonergan, 1977). The pit was largely filled with sediment after flooding in 1980.

Two lagoons operated by the Ina Road Water Pollution Control Facility are present in the study area. The influent pond is used to temporarily detain sewage inflow during maintenance periods at the sewage treatment plant. However, a constant water level is always maintained in the pond to minimize odors (Geiser, 1980). The oxidation lagoon, adjacent to the influent pond, remained dry throughout this study.

#### Ground Water

The aquifer in the Tucson Basin extends through the Cortaro Basin. The aquifer is generally unconfined and consists of the Pantano Formation, Tinaja Beds, Fort Lowell Formation, and surficial deposits. The Fort Lowell Formation is the most productive zone in the Cortaro Basin (Davidson, 1973). Martin (1980) indicated that ground-water elevations ranged from about 2,200 feet in the southeast to about 1,900 feet in the northwest in 1974 (see Figure 8). Similar elevations were reported by Wilson et al. (1983) for 1981, indicating very little change had occurred in the regional direction and rate of ground-water flow. Flow is generally from the south and east to the northwest. Ground water flows out of the basin in an area known as the Rillito Narrows. The subsurface structure at the Rillito Narrows limits outflow to the upper 500 feet of the basin (Goodoff, 1975). As a result, the basin has the potential to become a closed hydrologic system.

The aquifer in the Cortaro Basin is replenished by recharge from surface water, and ground-water inflow from the Tucson Basin. Recharge in the Cortaro Basin occurs principally along the main stream channels, namely the Santa Cruz River, the Rillito River, and Canada del Oro. In



—2200— LINE OF EQUAL GROUND-WATER LEVEL, 1974—  
 Shows altitude of ground-water level in feet above mean sea level. Interval 50 feet. Water-level data from the Department of Soil, Water, and Engineering, University of Arizona.

Figure 8. Map showing the elevation of ground water, 1974 (Martin, 1980).

addition to irrigation return flow and occasional runoff events, a significant amount of recharge is from sewage effluent discharged in the Santa Cruz River.

In addition to the Santa Cruz River, irrigated farmland and the flooded gravel pit west of the landfill represent major sources of recharge in the study area. The recharge water may have a major effect on the local quality of ground water because sewage effluent is a major portion of all surface water in the study area.

Estimates of transmissivity for the Tucson and Cortaro basins were determined from aquifer tests conducted by the U.S. Bureau of Reclamation and the University of Arizona (Anderson, 1972). The results were mapped by Davidson (1973) and indicate a transmissivity of about 20,000 ft<sup>2</sup>/day for the study area. Fogg (1978) verified this estimate using a numerical model developed for the Cortaro Basin. Randall analyzed lithologic logs and conducted a 78-day aquifer test at a well operated by the Cortaro Water Users Association (designated 1F) in the present study area (Wilson et al., 1974). Randall concluded that the saturated thickness averaged 80 feet for the surficial deposits and 100 feet for the Fort Lowell Formation. The transmissivity was estimated from the results of the aquifer test to range from 10,000 ft<sup>2</sup>/day to 40,000 ft<sup>2</sup>/day for the surficial deposits. The hydraulic conductivity was estimated from these data to range from 250 ft/day to 500 ft/day. The transmissivity of the Fort Lowell Formation and upper portion of the Tinaja Beds was estimated to be about 4,700 ft<sup>2</sup>/day. The corresponding hydraulic conductivity, using an average saturated thickness of 200 feet, was estimated to be about 25 ft/day (Wilson et al., 1974).

Davidson (1973) estimated the specific yield of the upper portion of the aquifer ranges from 10 to 25 percent. However, 20 percent is believed to be closer to the actual value because of the effects of long-term drainage (Davidson, 1973).

#### Vadose Zone

The area from land surface to the water table, known as the vadose zone, also has an important role in pollutant mobility. Chemical processes such as cation exchange, adsorption, precipitation, and microbial activity are most prominent in the vadose zone and are the primary mechanisms in attenuating contaminants. The types of chemical processes that will occur are largely dependent upon the mineralogy and chemical composition of the vadose zone. Chemical processes such as cation exchange and adsorption occur primarily on clay minerals and hydrous coatings, whereas the presence of calcareous deposits may increase the alkalinity in the subsurface thereby reducing the solubilities of cationic heavy metals and inducing their precipitation. The effectiveness of the vadose zone largely depends on its thickness. The thicker the zone, the greater the capacity and the more time available for contaminants to be attenuated before reaching the water table. The vadose zone in the study area ranges from 60 to 80 feet thick based on water levels in the area. Depths to ground water were found to increase with lateral distance from the Santa Cruz River.

Wilson and DeCook (1968) found that the vadose zone in the Cortaro Basin is capable of storing a vast quantity of water. Their study indicated that one third of all flood waters in the Santa Cruz

River immediately recharged the aquifer, while the remainder took up to six months to replenish the saturated zone. In addition, significant lateral flow occurred in the vadose zone during infiltration indicating that the concept of vertical percolation is too simplistic. Flow velocities in the vadose zone were also found to be much higher in the vadose zone than in the saturated zone (Wilson, 1971).

In the Tucson and Cortaro basins, percolating waters often form perched water tables in the vadose zone (Wilson et al., 1977). The perched zones form where a change in sediment texture occurs in the vadose zone. Wilson and DeCook (1968) utilized moisture logging techniques to observe the mounding and dissipation of percolating waters in areas where coarse sediments overly finer-grained deposits. Wilson et al. (1975) and Mooradian (1980a) identified a perched water table at the El Camino del Cerro landfill following runoff events in the Santa Cruz River. Water in the river was believed to infiltrate through the stream channel and flow laterally above finer-grained deposits in the vadose zone. Lateral movement of water from the Santa Cruz River through the vadose zone was observed in the present study area by Wilson and DeCook (1968) and Wilson and Schmidt (1979). Peterson and Staley (1973), using geophysical techniques, found a clay lens underlying cell 1 of the Ina Road landfill at a depth ranging from 10 to 30 feet below land surface. Perched water above this lens may serve as a vehicle for contaminants to migrate to the main water table.

## Ground-Water Quality

The chemical quality of ground water in the Cortaro Basin has been studied extensively by Laney (1972), Schmidt (1973), Wilson et al. (1977), Martin (1980), and Wilson et al. (1983). Previous investigations by Wilson and Small (1973), Wilson et al. (1974), and Wilson and Schmidt (1978) provided further information on the quality of ground water in the study area.

Laney (1972) described the ground water quality in the study area as a calcium sodium sulfate type to a sodium sulfate type with a dissolved solid concentration in excess of 500 mg/l. The ratio of calcium to sodium ranged from 0.5 to 2.0. Although a significant concentration of bicarbonate was also identified in the study area, the concentration of sulfate was substantially greater. Laney suggested that the elevated concentration of many constituents was due to the dissolution of relict salts that were precipitated during evaporation of water in the surficial deposits. These salts are believed to dissolve as recharge waters percolate to the ground water.

Martin (1980) identified the present study area as a region of ground-water mixing. Ground-water flow occurs northward along the Santa Cruz River as well as from the southeast along the Rillito. Additional sources of ground water in the study area include the infiltration of streamflow from the Santa Cruz River, infiltration of sewage effluent, and irrigation return flow. Each of these sources has a distinct chemical characteristic. Ground water along the Santa Cruz River, sewage effluent, and streamflow in the Santa Cruz River are all calcium sodium

bicarbonate sulfate type. In contrast, underflow from the southeast, along the Rillito, and northeast, from the Canada del Oro Valley, is generally a calcium sodium bicarbonate type. Streamflow in the Santa Cruz River is distinguished from ground water and sewage effluent by its lower proportions of sodium and lower concentration of TDS (Martin, 1980). The coincidence of the landfill and the Ina Road Water Pollution Control Facility being in a mixing area of regional ground waters substantially increases the complexity of identifying sources of ground-water contamination.

In addition to being discharged into the Santa Cruz River, sewage effluent has been used extensively for irrigation in the Cortaro Basin. The percolation of sewage effluent is believed to be a major source of nitrate in the ground water of the basin. Schmidt (1973) attributed distribution of nitrate in the Cortaro Basin to sewage effluent, regional ground-water movement, and poor well construction. Martin (1980) believed sewage effluent was the primary source of nitrate because the distribution of chloride coincided with the distribution of nitrate (see Figures 9 and 10). Other sources of nitrate include organic decomposition and the widespread use of fertilizers in the basin (Laney, 1972).

The water quality in the Cortaro Basin was also described by Keith as part of the "Cortaro Area Pollution Source Assessment" (Wilson et al., 1983). Keith delineated a low-quality zone along the Santa Cruz River floodplain and a high-quality zone to the east and northeast. An area of mixing was denoted between the two zones. The mixing zone was based on chemical concentrations of ground water intermediate between

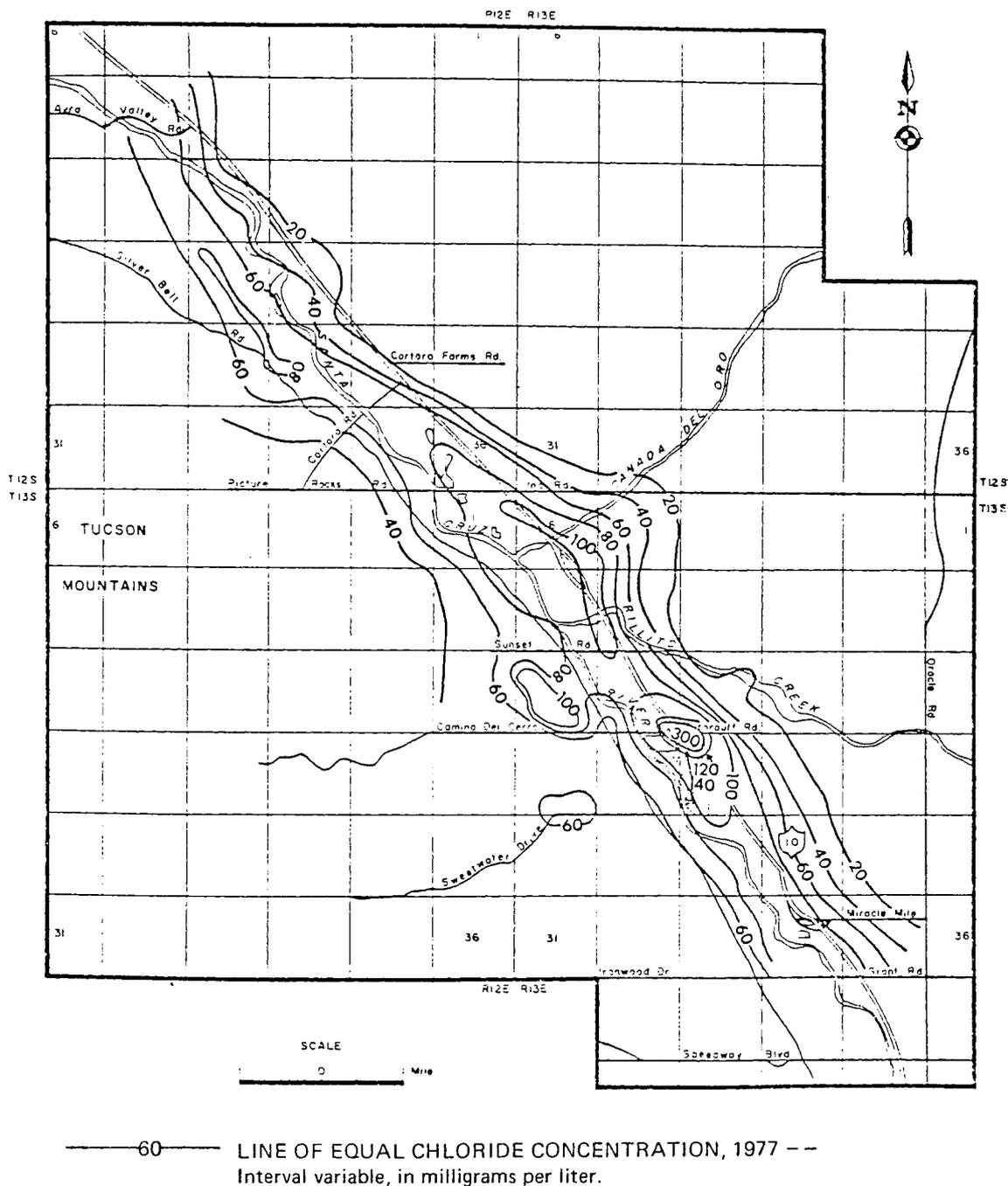
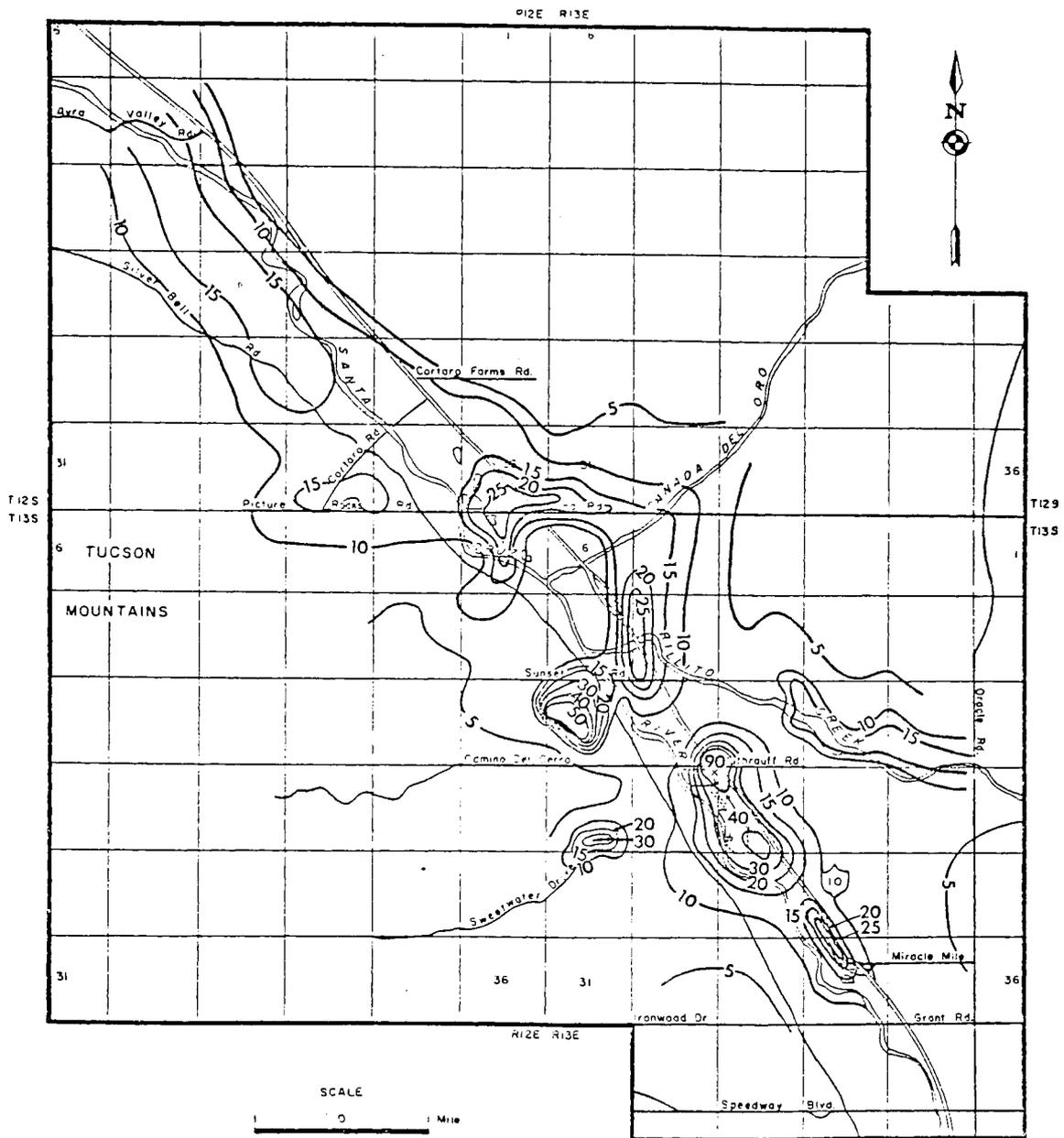


Figure 9. Map showing the distribution of the concentration of chloride in the Cortaro area, 1977 (Martin, 1980).



— 5 — LINE OF EQUAL NITRATE CONCENTRATION, 1977--  
Interval variable, in milligrams per liter.

Figure 10. Map showing the distribution of the concentration of nitrate in the Cortaro area, 1977 (Martin, 1980).

those found in the high- and low-quality zones. Keith suggested that the low-quality zone may be due to the mudstone and volcanic clast geologic units in the Cortaro Basin. The geologic units generally coincide in areal distribution with the zone of low-quality ground water. In addition, a major cause of temporal changes in the quality of ground water in the northwest portion of the basin is attributed to sewage effluent used for irrigation (Wilson et al., 1983).

According to Keith, the Ina Road landfill is within the zone of low-quality ground water. The concentration of major ions in this zone were found to range from 70 mg/l to over 100 mg/l for calcium and sodium; 20 mg/l to 400 mg/l for chloride; 100 mg/l to over 500 mg/l for sulfate; and 10 mg/l to 95 mg/l for nitrate. The concentration of total dissolved solids was found to be greater than 600 mg/l in the low-quality zone.

Wilson and Small (1973) conducted a leachate investigation at the Ina Road landfill. The results of their study indicated that sewage effluent was the cause of poor quality ground water in the shallow deposits of the area. Although leachate was detected within cell 1 of the landfill, no migration of contaminants to the water table was detected.

A continuation of the study by Wilson and Small (1973) on the potential for leachate in cell 1 to migrate to the ground water was conducted by Wilson et al. (1974). The investigation was based largely on samples collected from two observation wells designated IRA 11 and IRA 21. These wells were constructed identically, each consisting of a 2-inch inside diameter (ID) steel casing. Well IRA 11, designated UA in this study, was in an oxidation lagoon north of cell 1. The pond was

being excavated to establish cell 4 of the landfill during the field program for this investigation. Well IRA 21, destroyed prior to this study, was in the northwest corner of cell 3. The results of the study indicated poor quality ground water beneath the oxidation lagoon.

Sodium, calcium, magnesium, and bicarbonate concentrations were markedly higher in IRA 11 than IRA 21 (Wilson et al, 1974). In contrast, total nitrogen and sulfate concentrations were higher in IRA 21. The investigators suggested the quality of ground water in the study area was caused by the seepage of effluent from the lagoon, coupled with the dissolution of relict salts. Chemical analyses of samples collected from pumping wells indicated that the quality of ground water improved with depth.

## CHAPTER 3

### METHODOLOGY

During this study, a monitoring network was established to monitor ground-water quality in the vicinity of the Ina Road landfill. The monitoring program was designed to detect ground-water contamination originating in the Ina Road landfill. Active and passive programs were considered in the design of the monitoring network. An active program requires continuous pumping of ground water from wells to intercept potential contaminants. In contrast, a passive program relies on periodic sampling of wells in the suspected path of pollution to detect changes in the concentration of chemical constituents. Hart and Associates (1979) discussed the advantages and disadvantages of both programs. A passive program of monitoring ground water was used in the study area because continuously pumping wells may induce the migration of pollutants.

Wherever feasible, existing observation, domestic, industrial, agricultural, and municipal wells were incorporated in the monitoring network. In addition, seven observation wells were installed as part of this study. An inventory of the wells used in the monitoring program is presented in Table 1.

The locations of the observation wells installed as part of this study were based on accessibility and the direction of ground-water flow as anticipated from the available hydrogeologic maps and reports (see Figure 8). Wells were not installed upgradient from the landfill because

Table 1. Inventory of Wells in the Ina Road Study Area

Well Designation	Drill Method	Diameter (Inches)	Depth (Feet)	Casing Material	Perforation Type (Inches)	Perforation Interval (Feet)	Well Use	Pump Equipped
IRL1	Rotary	2-1/2	100	PVC	1/4 drill	70 - 100	observation	no
IRL2	Rotary	3	100	PVC	1/4 drill	70 - 100	observation	no
IRL3	Rotary	3	100	PVC	1/4 drill	70 - 100	observation	no
IRL4	Rotary	3	100	PVC	1/4 drill	70 - 100	observation	no
IRT1	Rotary	3	95	PVC	1/4 drill	70 - 100	observation	no
IRT2	Rotary	2-1/2	85	PVC	1/4 drill	65 - 95	observation	no
IRT3	Rotary	2-1/2	85	PVC	1/4 drill	65 - 95	observation	no
UA	Driven	2	100	Steel Wellpoint	screen	99 - 100	observation	no
TEX	NA (1)	6	200	Welded Steel	3/16 x 5 slot	140 - 195	industrial	yes
PWW1	NA	8	NA	Steel	NA	NA	industrial	yes
PWW2	NA	6	NA	Steel	NA	NA	industrial	yes
PWW3	NA	6	NA	Steel	NA	NA	domestic abandoned	no
TRICO	NA	8	NA	Steel	NA	NA	industrial	yes
LH	NA	8	300	Steel	4/16 x 6 slot	80 - 245	municipal	yes
INA	Cable Tool	12	400	Steel	3/8 slot	150 - 185	industrial	yes
				Welded		215 - 285		
				10 gage		300 - 390		
(2) COR	NA	24	200	Steel Stovepipe	3/4 x 3 slot	24 - 201	agriculture abandoned	yes
HAN	NA	16	300	Steel Stovepipe	1/2 x 4 slot	69 - 215	agriculture	yes
(3) IF	Cable Tool	20	280	Steel Stovepipe	1/2 x 4 slot	80 - 278	agriculture	yes

(1) Information not available

(2) Used for water level measurements only

(3) Used to obtain lithological information only

access was not available to these areas. However, information on the background quality of ground water was obtained from existing production wells along the margins of the study area. Observation wells were installed immediately downgradient of each of the landfill cells to identify the source of potential contaminants in the ground water. These wells were not drilled directly into the landfill to avoid promoting the vertical flow of leachate to the water table. During this study, cells 4 and 5 were designated for future landfilling operations. Wells were drilled in these cells to identify the areal distribution of potential contaminants in the ground water. Observation well design was based on the depth to ground water, lithology, and budget (see Figure 11). A 2.5-inch ID casing was used in the construction of wells IRL1, IRT1, IRT2, and IRT3. A 3.0-inch ID casing was used for wells IRL2, IRL3, and IRL4. Polyvinyl chloride pipe was selected as a casing material to minimize chemical interactions with the ground water. Although this type of casing may increase the concentration of specific organic constituents in the ground water, chemical analyses for these constituents were not included in this study.

The observation wells installed as part of this monitoring program were drilled using a rotary rig equipped with a 6.75-inch bit. Direct rotary methods often require thicker drilling fluids to remove the cuttings than other drilling techniques. A drilling fluid consisting of bentonite clay and water was used to install the observation wells in the study area. A high fluid viscosity was used to maintain the integrity of the borehole during drilling. The high viscosity was required because of the absence of clay in the surrounding formation.

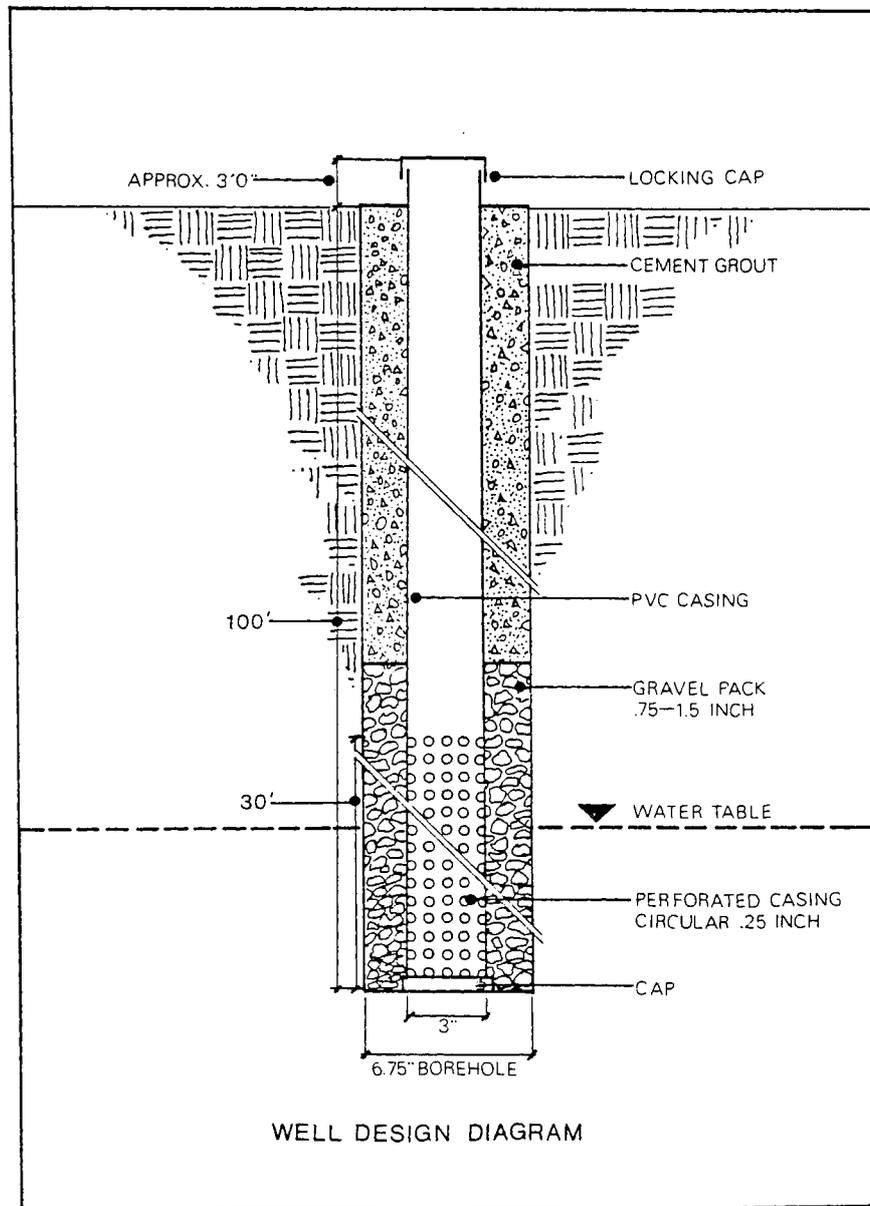


Figure 11. Design of observation wells.

The observation wells were generally constructed to a depth of about 100 feet, with the bottom 30 feet of the casing perforated. Information obtained from cuttings collected during drilling indicated a lithology consisting predominantly of coarse gravels with some intermixed sand and clay. Based on this information, and budgetary constraints, 0.25-inch circular perforations, approximately two inches apart, were made using an electric drill. A graded washed gravel from 0.5 to 1.0 inches in diameter was used as an annulus pack in each of the newly installed wells.

The wells were developed after construction using an airlift technique. The wells were surged for approximately 0.5 hours and then airlifted to loosen and remove the drilling fluid and fine-grained sediments from the walls of the borehole. Immediately following airlifting, fresh water was circulated in the casings and the wells were again airlifted. This procedure was repeated at least twice before the well was allowed to recover. The wells were airlifted immediately after recovery and again one week later to ensure the removal of all fluids introduced during drilling and development.

Surface-water samples were also collected regularly as part of the monitoring program to help identify potential sources of ground-water contamination. Samples were collected from the outflow of the Ina Road Water Pollution Control Facility (IRO), the sewage influent pond (IREP), water ponded in the sand and gravel pit west of the landfill (IRP) and the Santa Cruz River (IRR) downgradient from the effluent discharge.

A six-month sampling program was started in July, 1979. Upon arrival at each monitoring well, the depth to ground water was measured using a steel tape and recorded in a log book. Measurements were not made in most of the production wells because access into the casing was not available.

Wells not equipped with pumps were purged using a hand bailer prior to sampling, and samples were collected using the hand bailer. The hand bailer consisted of a PVC pipe, 1.5-inch ID by 36 inches, with a check valve at one end. The production wells were purged by pumping prior to sampling. A "Yellow Springs Instrument", Model 33, Salinity, Conductivity, and Temperature meter; a "Digisense" field pH unit; and a hand thermometer were used to monitor the specific conductance, pH, and temperature, respectively, of the discharge water while purging the well. Ground-water samples were collected for chemical analyses following stabilization of each of the above parameters, which was typically after the removal of one casing volume of water. With the exception of wells HAN and PWW3, all the production wells sampled were in operation daily.

Water samples were collected in bottles provided by the laboratory performing the chemical analyses. The hand bailer was used to collect samples from the wells not equipped with pumps. Water samples were collected from the production wells during pumping from the discharge outlet nearest the well head. The sampling procedure included collecting and preserving each sample prior to shipment to the laboratory. Each sample bottle was labeled with the identification symbol for each sampling location, the date, and the preservative used. The time,

date, number and type of sample bottle used, and the receiving laboratory were all recorded in the log book. Field determinations of pH, specific conductance, and temperature were also recorded. The log book was also used to record observations of sample color and odor, as well as weather conditions and changes in landfill activities near the sampling locations.

At least one quart and two pint bottles made of plastic were used to collect each sample for a minimum volume of 0.5 gallons. Each aliquot was preserved by cooling to 4° C prior to shipment to the laboratory. In addition, the two pint aliquots required acidification. One pint aliquot, specified for metal analyses, was acidified with nitric acid ( $\text{HNO}_3$ ) to a pH of less than 2 as indicated by the U.S. Environmental Protection Agency (1974). The remaining pint aliquot, designated for nitrogen analyses (nitrate and ammonia), was acidified with sulfuric acid ( $\text{H}_2\text{SO}_4$ ), also to a pH of less than 2 as indicated by the U.S. Environmental Protection Agency (1974). During some sampling periods, the acids were added to the appropriate bottles by the laboratory prior to sample collection. During other periods, the acids were added in the field immediately after sample collection. All sample bottles and preservatives were supplied by the laboratory conducting the chemical analyses.

The Pima County Laboratory at the Ina Road Water Pollution Control Facility (IRWPCF) was selected as the primary laboratory for this study. Chemical analyses were made for a large number of constituents because of the variable quality of ground water and the presence of other potential sources of contamination in the study area. In addition, the chemical composition of leachate depends upon the nature of the disposed

wastes. However, the nature of the wastes in the Ina Road landfill were unknown. By analyzing for a large number of constituents, the ability to detect contaminants originating from the landfill was increased. The suite of constituents analyzed by the IRWPCF is presented in Figure 12. All laboratory techniques followed procedures outlined by the U.S. Environmental Protection Agency (1974) and the American Public Health Association (1975). An atomic absorption spectrophotometer was used for most analyses. Chloride concentrations were determined by the titrimetric procedure using mercuric nitrate. Analyses for fluoride were made using the SPADNS method. The turbidimetric method was used to determine sulfate concentrations. The single reagent method, utilizing ascorbic acid with presulfate digestion, was used to analyze for phosphate. The Brucine and distillation methods were used for the analyses of nitrate and ammonia, respectively. Duplicate analyses were conducted on every tenth sample as a quality control check by the laboratory (Meissner, 1979).

As an external check on the analytical quality of the laboratory, replicate samples were collected at all monitoring locations during the third sampling period (November) and sent to the field laboratory of the Water Resources Research Center, University of Arizona and the Arizona Department of Health Services. Four replicate samples were collected from well IRL4, of which two were sent to the IRWPCF laboratory and one each to the alternate laboratories. One of the samples sent to the IRWPCF laboratory was labeled with a false identification symbol to provide an additional check of the precision of the laboratory. Six replicate samples were collected from well LH, of which duplicates were

## Sample Analysis Data Sheet

DATE \_\_\_\_\_

SAMPLE POINT \_\_\_\_\_

Sample Number			
Lab Sample Number		SiO <sub>2</sub>	
Temperature °C		pH	
Turbidity JCU		Fe	
Suspended Solids mg/l		Cu	
Volatile Susp Solids mg/l		Mn	
Elect. Conductvty $\mu$ mho		Pb	
Total Dissolved Solids mg/l		Sr	
COD mg/l		Cr	
Ca <sup>++</sup> mg/l		Cd	
Mg <sup>+</sup> mg/l		Co	
Total Hardness $\frac{\text{mg/l as CaCO}_3}{\text{CaCO}_3}$		Zn	
Na <sup>+</sup> mg/l		Ni	
CO <sub>3</sub> <sup>=</sup> mg/l		Phenols	
HCO <sub>3</sub> <sup>=</sup> mg/l		Total Organic Carbon	
Cl <sup>-</sup> mg/l		Amonnia- Nitrogen	
SO <sub>4</sub> <sup>=</sup> mg/l		Oil and Grease	
NO <sub>3</sub> <sup>=</sup> mg/l		K <sup>+</sup>	
F <sup>-</sup> mg/l			
PO <sub>4</sub> <sup>=</sup> mg/l			

Figure 12. Data sheet used to record the results of laboratory analyses.

sent to each of the three laboratories. One sample from each set of duplicates was labeled with a false identification symbol to ensure an unbiased analyses and, therefore, provide an additional check of the precision of each laboratory.

## CHAPTER 4

### RESULTS

#### Physical Results

A depth to ground water map for Fall 1979 was prepared to help determine the thickness of the vadose zone in the study area (see Figure 13, in pocket). The map was prepared from measurements made in the observation wells and those production wells where access was available. The measurements were converted to elevation and used in conjunction with Figure 8 to prepare a flow-net diagram (see Figure 14, in pocket). Figure 14 indicates that ground-water elevations range from 2,125 feet in the southeast to 2,100 feet in the northwest. The average hydraulic gradient is approximately  $4.2 \times 10^{-3}$  feet per foot (ft/ft), with the direction of ground-water flow from southeast to northwest.

The configuration of the elevation contours are considered to be general because of the limited distribution of observation wells and the limited accessibility to production wells. In addition, wells where access was available were operating regularly, making static measurements difficult. The flow-net diagram is also considered to be a general representation of ground-water flow because quantitative information on the homogeneity and isotropy of the upper portion of the aquifer was not available. As a result, the flow net was constructed under the assumption that the aquifer is homogeneous and isotropic. Under these conditions, the direction of flow is perpendicular to the contours of equal

ground-water elevation. If the aquifer is heterogeneous or anisotropic, which is most likely the case, ground water will still flow from higher to lower elevation but will follow the path of highest permeability. As a result, the direction of flow may not be perpendicular to the lines of ground-water elevation. If information on the anisotropy and heterogeneity of the study area were available, it could be incorporated to construct a more accurate flow-net diagram.

The velocity of ground water in the surficial deposits was estimated using information from the flow-net diagram and Darcy's equation:

$$K \times I = q$$

where:

$K$  = hydraulic conductivity (ft/day)

$I$  = hydraulic gradient (ft/ft)

$q$  = specific discharge or Darcy velocity (ft/day)

Hydraulic conductivity values of 250 ft/day and 500 ft/day were used to represent maximum and minimum conditions in the surficial deposits in the study area (Wilson et al., 1974). Using the average hydraulic gradient as estimated from Figure 14 ( $4.2 \times 10^{-3}$  ft/ft), the Darcian velocity of ground water in the surficial deposits was calculated to range from 1.1 ft/day to 2.1 ft/day.

The velocity of a particle in the ground water was estimated by dividing the Darcy velocity by the porosity of the formation. The resulting value provided an estimate of the time required for a contaminant to travel a specific distance in the saturated zone. The effects of dispersion, diffusion, and other chemical processes, however,

are not included in the calculation. Using a porosity of 25 percent (Davidson, 1973), the velocity of a particle in the saturated zone of the surficial deposits was calculated to range from 4.2 ft/day to 8.4 ft/day.

### Chemical Results

The results of the laboratory analyses are reported in Table 2. The accuracy of the chemical data for each sample was checked by calculating the cation-anion balance. The sum of the cations, in milliequivalents per liter, should equal the sum of the anions expressed in the same units. The difference between the two sums should be within 1 or 2 percent of the total of the cations and anions (Hem, 1970). The percentage difference between the sum of the cations and the sum of the anions for the samples collected as part of this study are presented in Table 3. Cation-anion balances were not performed on samples collected during the January or February sampling periods because of incomplete laboratory analyses.

The percentage difference between total cations and anions may be attributed to a combination of factors, including incomplete well development, insufficient purging of the well prior to sampling, inaccuracies in sample collection and preservation procedures, and laboratory errors. Airlifting prior to the first sampling period may have resulted in the speciation of some constituents that were not detected during laboratory analyses. If sufficient concentrations of these constituents were present, a high percentage difference in the calculated cation-anion balance would result. In addition to speciation, airlifting may have released carbon dioxide, thus reducing the concentration of bicarbonate in solution.

Table 2. Results of Chemical Analyses in mg/l

Sampling Location	Date	HCO <sub>3</sub> <sup>1</sup>	CO <sub>3</sub>	Cl	SO <sub>4</sub>	F	PO <sub>4</sub>	NO <sub>3</sub>	NH <sub>3</sub>	Ca	Na	Mg	K	Fe	Mn	Cu	Zn	Ni	Cr	Cd	Pb	TOC	COD	SS <sup>2</sup>	TDS	SC µmhos/cm @25°C	Field Temp pH	Temp °C	LAB <sup>3</sup>
IRL1	7/28/79	140	0	160	130	.6	0.6	24	NA <sup>4</sup>	103	92	12	NA	6	.2	.12	.23	.04	.02	.01	.09	23	69	140	690	940	7.3	21	1
IRL1	8/21/79	290	0	110	120	.6	0.5	2.7	4.9	140	160	9.6	2.1	4.8	.46	.04	.09	.04	.008	.004	.06	19	61	64	730	990	7.6	21	1
IRL1	11/13/79	350	0	74	96	.9	1.7	5.8	0	50	180	11	3.0	0.62	1.8	.05	.07	.02	.01	.003	.07	NA	34	110	710	1,100	7.7	19	1
IRL1	11/13/79	360	0	77	85	.8	NA	4.0	NA	65	170	12	8.0	2.6	2.4	.09	.09	NA	<.01	NA	.01	NA	NA	NA	720	1,100	7.7	19	2
IRL1	11/13/79	410	0	80	120	NA	NA	1.7	.6	64	150	11	5.2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,100	7.7	19	3
IRL1	12/10/79	370	0	65	110	.9	.6	33	.2	NA	180	14	5.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	24	300	700	1,000	7.9	20	1
IRL1	2/13/80	360	0	53	100	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,000	7.9	20	1
IRL2	7/28/79	190	0	170	150	.4	0.1	19	0	110	200	15	NA	11	.90	.12	.30	.06	.02	.01	.16	41	69	160	810	1,100	7.0	23	1
IRL2	8/21/79	610	0	120	160	.3	1.2	1.8	3.5	200	280	24	8.0	33	2.7	.11	.36	.12	.04	.007	.19	1200	75	450	1,200	1,600	6.8	22	1
IRL2	11/13/79	710	0	110	130	.4	4.3	2.3	0	150	280	22	4.2	2.4	3.2	.066	.13	.07	.05	.007	.21	0	55	650	1,300	1,700	6.9	22	1
IRL2	11/13/79	680	0	120	180	.4	NA	0.3	NA	140	240	24	10	5.2	3.2	.12	.16	NA	<.01	NA	.18	NA	NA	NA	1,200	1,700	6.9	22	2
IRL2	11/13/79	780	0	120	220	NA	NA	1.9	.8	140	230	23	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,700	6.9	22	3
IRL2	12/10/79	660	0	98	150	.4	1.3	36	.3	NA	240	23	7.4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	200	1,200	1,600	7.4	20	1
IRL2	2/13/80	660	0	88	140	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,500	6.4	22	1
IRL3	7/28/79	150	0	170	200	NA	0.7	29	NA	170	180	58	NA	180	7.0	.65	1.6	.20	.10	.03	1.7	110	230	12000	1,800	1,200	8.0	27	1
IRL3	8/21/79	180	32	96	110	.4	3.7	0	2.2	48	200	3.4	2.4	5.4	2.5	.09	.24	.12	.16	.005	.11	19	61	76	580	800	8.3	26	1
IRL3	11/13/79	380	0	80	83	.4	2.8	.9	9.6	66	150	12	95	2.1	3.8	.063	.08	.03	0	.003	.13	NA	37	340	780	1,300	7.0	25	1
IRL3	11/13/79	372	0	80	80	.3	NA	0.9	NA	68	140	14	20	4.0	3.8	.11	.17	NA	.01	NA	.19	NA	NA	NA	700	1,300	7.0	25	2
IRL3	11/13/79	430	0	89	100	NA	NA	1.6	12	68	130	14	11	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	190	740	1,300	7.0	25	3
IRL3	12/10/79	430	0	77	81	.3	1.2	4.2	6.7	NA	170	15	13	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,300	7.0	25	1
IRL3	2/13/80	450	0	73	67	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,200	6.7	25	1

Table 2. Results of Chemical Analyses in mg/l (continued)

Sampling Location	Date	HCO <sub>3</sub> <sup>1</sup>	CO <sub>3</sub>	Cl	SO <sub>4</sub>	F	PO <sub>4</sub>	NO <sub>3</sub>	NH <sub>3</sub>	Ca	Na	Mg	K	Fe	Mn	Cu	Zn	Ni	Cr	Cd	Pb	TOC	COD	SS <sup>2</sup>	TDS	SC µmhos/cm @25°C	Field Temp pH	Temp °C	LAB <sup>3</sup>
IRL4	7/28/79	170	0	160	87	1.1	6.3	19	2.8	82	150	18	NA	32	1.0	.20	.32	.04	.02	.01	.40	48	110	910	670	960	7.4	19	1
IRL4	8/21/79	240	56	120	150	.6	2.6	6.6	2.2	27	240	48	2.2	5.2	.14	.07	.14	.04	.014	.004	.11	18	53	230	900	1,400	8.6	20	1
IRL4	11/13/79	340	0.8	110	130	.6	6.8	1.7	1.2	42	270	5.7	3.0	1.6	.47	.033	.07	.03	.02	.003	.16	NA	36	520	950	1,300	6.2	24	1
IRL4	11/13/79	340	1.4	110	130	.6	6.8	1.7	1.9	40	270	5.6	3.4	1.5	.45	.027	.07	.03	.02	.003	.16	11	45	460	860	1,300	6.2	24	1
IRL4	11/13/79	350	0	110	150	.6	NA	.5	NA	37	240	8	10	3.2	.55	.1	.13	NA	<.01	NA	.02	NA	NA	NA	910	1,300	8.2	24	2
IRL4	11/13/79	380	0	120	220	NA	NA	0.6	1.9	38	200	6.6	8.4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,300	8.2	24	3
IRL4	12/10/79	340	2.6	110	140	.6	1.5	3.2	1.8	NA	260	7.6	6.3	NA	NA	NA	NA	NA	NA	NA	NA	NA	48	320	900	1,300	8.1	22	1
IRL4	2/13/80	460	0	91	150	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,250	7.3	22	1
IRT1	7/28/79	40	0	170	200	.6	2.2	40	0	110	220	68	NA	300	3.2	.59	1.3	.22	.16	.02	.74	19	15	7,600	830	1,200	7.7	21	1
IRT1	8/21/79	320	0	120	130	.7	3.1	35	1.1	140	240	14	5.3	31	.34	.12	.20	.09	.05	.006	.11	11	31	490	870	1,100	7.8	20	1
IRT1	11/13/79	460	0	110	150	.6	6.9	76	0	100	280	20	3.0	1.4	1.6	.07	.08	.03	.007	.005	.08	NA	17	10,000	1,000	1,400	7.8	21	1
IRT1	11/13/79	490	0	120	200	NA	NA	76	NA	76	210	14	4.4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,400	7.8	21	3
IRT1	12/10/79	480	0	110	190	.4	2.0	97	.3	NA	290	15	5.3	NA	NA	NA	NA	NA	NA	NA	NA	NA	40	5,000	1,500	1,500	7.7	18	1
IRT1	2/13/80	470	0	94	150	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,400	7.6	18	1
IRT2	8/21/79	270	0	32	160	.3	3.8	4.4	6.2	160	130	12	9.3	16	1.2	.15	.5	.23	.20	.01	.33	46	120	380	620	800	7.3	46	1
IRT2	12/10/79	930	0	42	84	.3	2.0	6.7	15	NA	210	24	12	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	400	1,300	1,700	7.0	20	
IRT3	8/21/79	590	0	100	110	.7	0	3.1	7.8	210	260	18	10	32	4.6	.15	.44	.15	.06	.007	.17	64	190	450	1,000	1,400	6.6	21	1
IRT3	11/13/79	950	0	89	44	.4	5.5	3.0	5.1	130	280	22	5.6	4.5	13	.027	.10	.04	.003	.005	.08	NA	160	280	1,300	1,900	6.5	42	1
IRT3	11/13/79	530	0	100	7	.4	NA	.4	NA	140	270	24	15	6.5	11	.17	.14	NA	<.01	NA	.09	NA	NA	NA	1,200	1,900	6.9	42	2
IRT3	11/13/79	1,100	0	100	16	NA	NA	.6	9.0	150	220	24	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,900	6.9	42	3

Table 2. Results of Chemical Analyses in mg/l (continued)

Sampling Location	Date	HCO <sub>3</sub> <sup>1</sup>	CO <sub>3</sub>	Cl	SO <sub>4</sub>	F	PO <sub>4</sub>	NO <sub>3</sub>	NH <sub>3</sub>	Ca	Na	Mg	K	Fe	Mn	Cu	Zn	Ni	Cr	Cd	Pb	TOC	COD	SS <sup>2</sup>	TDS	SC µmhos/cm @25°C	Field Temp pH	°C	LAB <sup>3</sup>
UA	7/28/79	63	20	140	34	.2	0.3	9.7	0	18	84	20	NA	70	.60	.39	.82	.09	.04	.02	.09	17	38	150	360	560	9.0	22	1
UA	8/21/79	180	61	92	<5	.2	0	1.8	4.5	45	100	19	2.2	64	.71	.43	.86	.06	.04	.01	.17	23	55	330	430	620	8.5	22	1
UA	12/10/79	230	2.4	89	24	NA	.1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,700	8.4	22	1	
UA	2/13/80	320	0	89	24	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	750	7.6	22	1	
IND	8/21/79	220	0	103	98	.5	12	8.4	21	130	100	3	7.9	.67	.04	.04	.10	.04	.01	.002	.03	27	83	38	510	840	7.0	29	1
IRR	8/21/79	250	0	75	93	.4	21	.8	NA	98	270	7.0	7.1	NA	.08	.05	.18	.16	.14	.004	.03	NA	75	76	460	900	7.3	34	1
IRR	11/13/79	270	0	74	74	.6	56	7.7	24	42	110	46	7.5	.17	.07	.03	.04	.02	.01	.003	.04	NA	93	49	520	1,000	7.1	27	1
IRR	11/13/79	270	0	76	70	.6	NA	3	NA	33	100	6	NA	.55	.10	<.05	.07	NA	.01	NA	<.02	NA	NA	NA	520	1,000	7.1	27	2
IRR	11/13/79	310	0	83	65	NA	NA	2.3	23	44	94	7.2	7.6	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,000	7.1	27	3
IRR	12/10/79	280	0	76	73	.5	31	3.7	23	NA	110	6.0	7.2	NA	NA	NA	NA	NA	NA	NA	NA	NA	55	34	540	1,000	7.3	25	1
IRR	2/13/80	280	0	86	66	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,000	7.1	25	1
IREP	8/21/79	240	0	120	87	.1	9.1	1.3	11	96	140	3.6	NA	.20	.02	.07	.09	.04	.01	.002	.02	108	10	130	630	820	8.4	26	1
IREP	12/10/79	250	2.0	100	65	.5	28	6.8	22	NA	120	6.8	13	NA	NA	NA	NA	NA	NA	NA	NA	NA	85	28	570	800	8.2	26	1
IRP1	7/18/79	160	NA	32	100	.8	NA	31	0	32	46	12	NA	8.0	.90	.10	.20	.03	.02	.008	.03	61	0	160	470	390	9.0	37	1
IRP2	12/10/79	140	2.2	24	73	.7	2.9	2.4	0.1	NA	65	13	7.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	55	110	430	400	8.5	10	1
TEX	7/28/79	120	0	130	110	.3	0.5	42	0	85	120	6.0	NA	.13	.04	.08	.28	.03	<.01	.01	.02	3	15	18	620	840	7.3	25	1
TEX	11/13/79	240	0	84	110	.2	.8	30	0	72	120	5.6	1.2	.50	.02	.16	.31	.02	.02	.003	.05	NA	7	13	610	900	7.4	19	1
TEX	11/13/79	240	0	83	120	.2	NA	14	NA	86	120	7.0	4.0	.40	<.05	.11	.32	NA	<.01	NA	<.02	NA	NA	NA	640	900	7.4	19	2
TEX	11/13/79	280	0	89	140	NA	NA	3.5	0.4	88	110	7.4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	900	7.4	19	3
TEX	12/10/79	250	0	80	130	.2	.1	22	0.1	NA	130	7.0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	16	630	800	7.5	17	1
INA	12/10/79	310	0	77	94	.4	.2	20	0.6	96	130	15	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	8	14	700	980	7.2	18	1
INA	2/13/80	370	0	79	100	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,000	7.0	18	1
HAN	12/10/79	230	0	83	79	.9	0	22	0.1	72	110	15	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	16	18	610	950	7.2	23	1

Table 2. Results of Chemical Analyses in mg/l (continued)

Sampling Location	Date	HCO <sub>3</sub> <sup>1</sup>	CO <sub>3</sub>	Cl	SO <sub>4</sub>	F	PO <sub>4</sub>	NO <sub>3</sub>	NH <sub>3</sub>	Ca	Na	Mg	K	Fe	Mn	Cu	Zn	Ni	Cr	Cd	Pb	TOC	COD	SS <sup>2</sup>	TDS	SC µhos/cm @25°C	Field Temp pH	°C	LAB <sup>3</sup>
PWW1	7/28/79	130	0	170	130	.4	0.9	6.6	NA	110	99	16	NA	.25	.02	.02	1.3	.03	<.01	.01	.03	15	8	2	630	900	7.1	21	1
PWW1	11/13/79	250	0	99	99	.3	.8	9.8	1.4	110	110	85	1.3	.17	.03	.15	.07	.23	.04	.003	.05	NA	12	20	680	1,000	7.3	23	1
PWW1	11/13/79	250	0	110	120	.3	NA	7.0	NA	110	100	10	4	.14	<.05	<.01	<.05	NA	NA	NA	NA	NA	NA	NA	280	1,000	7.3	23	2
PWW1	11/13/79	300	0	110	130	NA	NA	3.7	1.1	110	94	11	2.0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,000	7.3	23	3
PWW1	12/10/79	260	0	98	130	.3	.2	11	.9	NA	110	11	2.2	NA	NA	NA	NA	NA	NA	NA	NA	NA	31	10	680	950	7.4	22	1
PWW2	7/28/79	190	0	82	120	.8	0	29	3.3	100	100	10	NA	.04	.06	.06	.02	.02	<.01	.01	.02	24	8	8	670	940	7.1	25	1
PWW2	11/13/79	320	0	40	110	.8	.7	28	0	100	100	14	1.6	.65	.02	.04	3.4	.02	.02	.007	.07	NA	12	13	670	1,000	6.8	24	1
PWW2	11/13/79	320	0	43	110	.8	NA	24	NA	110	100	15	5.0	.73	<.05	.07	4.0	NA	<.01	NA	.03	NA	NA	NA	680	1,000	6.8	24	2
PWW2	11/13/79	280	0	48	140	NA	NA	5.8	.7	100	90	17	2.4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,000	6.8	24	3
PWW2	11/13/79	290	0	41	130	.8	1.1	30	.1	NA	100	16	2.6	NA	NA	NA	NA	NA	NA	NA	NA	NA	12	6	650	820	7.4	14	1
PWW3	12/10/79	240	0	43	98	.8	.6	23	.2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	27	130	520	700	7.7	18	1
TRICO	7/28/79	110	0	160	340	.5	0	26	0	140	150	19	NA	.10	.02	.04	.20	.02	<.01	.02	.03	6	8	18	990	1,200	7.4	21	1
TRICO	12/10/79	230	0	104	390	.3	.3	55	0	NA	160	22	3.4	NA	NA	NA	NA	NA	NA	NA	NA	NA	8	18	1,000	1,400	7.8	19	1
LE	7/28/79	130	0	96	200	.7	0	8.9	0	95	110	19	NA	.10	.01	.05	.04	.03	<.01	.01	.02	13	0	8	740	1,000	7.2	33	1
LE	11/13/79	270	0	62	180	.7	0.6	29	0	110	130	19	1.8	.21	.02	.04	.16	.08	.15	.003	.05	8	13	13	770	1,000	7.6	17	1
LE	11/13/79	270	0	64	190	.7	9.2	22	0	88	130	20	NA	.44	.01	.03	.15	.02	.03	.003	.06	NA	240	74	800	1,000	7.6	17	1
LE	11/13/79	270	0	65	140	.7	NA	16	NA	100	130	20	5.0	.16	<.05	<.05	.08	NA	NA	NA	NA	NA	NA	NA	780	1,000	7.6	17	2
LE	11/13/79	270	0	63	240	.7	NA	21	NA	100	120	20	5.0	.11	<.05	<.05	.15	NA	<.01	NA	<.02	NA	NA	NA	780	1,000	7.6	17	2
LE	11/13/79	170	0	73	280	NA	NA	3.7	.5	74	110	20	2.0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,000	7.6	17	3
LE	11/13/79	300	0	70	280	NA	NA	4.2	.6	110	110	20	3.2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,000	7.6	17	3
LE	12/10/79	280	0	59	180	.7	1.7	29	0	NA	130	22	3.2	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	18	790	1,100	7.6	21	1

1 Constituents from HCO<sub>3</sub> to TDS in mg/l

2 Concentration of suspended solids

3 Laboratory identification numbers: 1 = IRMPCF; 2 = Arizona Department of Health Services; 3 = Water Resources Research Center, University of Arizona

4 Chemical analyses not performed

Table 3. Percent Difference Between Total Cations and Total Anions. (1)

Sampling Location	Sampling Period			
	July 28	August 21	November 13	December 10
IRL1	1.5	17.0	5.7	-9.6 <sup>(2)</sup>
IRL2	17.0	21.0	10.0	NA <sup>(3)</sup>
IRL3	40.0	12.0	4.0	NA
IRL4	16.0	13.0	12.0;11.0	NA
IRT1	51.0	25.0	12.0	NA
IRT2	NA	28.0	NA	NA
IRT3	NA	25.0	4.0	NA
UA	15.0	18.0	NA	NA
IRO	NA	14.0	NA	NA
IRR	NA	36.0	14.0	NA
IREP	NA	10.0	NA	NA
IRP	NA	NA	NA	NA
TEX	7.0	NA	2.2	NA
INA	NA	NA	NA	10.0
HAN	NA	NA	NA	7.0
PWW1	7.3	NA	31.0	NA
PWW2	11.0	NA	7.5	NA
PWW3	NA	NA	NA	NA
TRICO	3.4	NA	NA	1.6
LH	10.0	NA	4.9;9.5	NA

(1) Analyses performed by the IRWPCF laboratory

(2) Negative sign indicates the percentage of total anions is greater than the percentage of total cations. Where no sign is present, the percentage of total cations is greater than the percentage of total anions.

(3) Insufficient data available to calculate cation-anion balance.

Another explanation may be associated with the high concentration of suspended sediments in the samples collected from the observation wells. The suspended sediments may be residual drilling fluid or fine-grained sediments found naturally in the formation that were not removed during well development. Aliquots of each sample were acidified for preservation in the field, prior to filtration in the laboratory. This may have caused the dissolution of certain suspended minerals resulting in an increase in the concentration of TDS. Dissolution of some organic constituents also may have occurred releasing additional trace metals that were adsorbed onto these molecules. Laboratory procedures indicate that the acidified aliquot of the sample was used in the analyses for cations. In contrast, the nonacidified aliquots were used in the analyses for anions. As a result, a significant percentage difference occurred when the sum of the cations in the acidified portion of the sample was compared to the sum of the anions in the nonacidified aliquot. The problem associated with the suspended solids may have been minimized by filtering all samples upon collection and prior to acidification. This procedure was not performed because a portable filtering apparatus was not available.

During the November sampling interval, replicate samples for each location were sent to the Arizona Department of Health Services and the field laboratory of the Water Resources Research Center, University of Arizona for chemical analyses. A comparison of the cation-anion balance computed from each laboratory's results is presented in Table 4. The results in the table indicate that samples analyzed by the Water Resources Research Center had the closest agreement between total cations

Table 4. Percent Difference Between Total Cations and Total Anions for the November 11, 1979 Sampling Period.

Sampling Location	Laboratory		
	IRWPCF <sup>(1)</sup>	ADHS <sup>(2)</sup>	WRRC <sup>(3)</sup>
IRL1	5.7	-3.8 <sup>(4)</sup>	9.8
IRL2	10.0	5.6	-6.9
IRL3	4.0	6.3	-4.9
IRL4	12.0;11.0	6.0 <sup>(5)</sup>	-11.0
IRT1	12.0	NA	-6.4
IRT2	NA	NA	NA
IRT3	4.0	29.0	-6.0
UA	NA	NA	NA
IRO	NA	NA	NA
IRR	14.0	-11.0	11.0
IREP	NA	NA	NA
IRP	NA	NA	NA
TEX	2.2	5.3	-1.6
INA	NA	NA	NA
HAN	NA	NA	NA
PWW1	31.0	4.3	-1.2
PWW2	7.5	10.0	0.19
PWW3	NA	NA	NA
TRICO	NA	NA	NA
LH	4.9	2.8	-1.6
LH <sup>(6)</sup>	9.5	14.0	-2.1

(1) Ina Road Pollution Control Facility

(2) Arizona Department of Health Services

(3) University of Arizona, Water Resources Research Center

(4) Negative sign indicates the percentage of total anions is greater than the percentage of total cations. Where no sign is present, the percentage of total cations is greater than the percentage of total anions.

(5) Insufficient data available to calculate cation-anion balance.

(6) Duplicate samples from well LH were sent to each laboratory for analysis

and anions. In addition, the results derived by this laboratory compared closely with at least one of the other laboratories. The chemical analyses performed by the IRWPCF laboratory generally showed the greatest difference between total cations and anions.

Six replicate samples were collected from well LH during the November sampling period. Two of these samples were sent to each of the three laboratories for analysis to obtain an indication of the precision of each laboratory. The cation-anion balance of these aliquots indicated that the field laboratory of the Water Resources Research Center exhibited the greatest precision; about 30 percent. The variabilities in precision for the IRWPCF and Arizona Department of Health Services laboratories were about 100 percent and 400 percent, respectively. Four replicate samples were also collected from well IRL4 during the November sampling period. Two were submitted to the IRWPCF laboratory and one was submitted to each of the alternate laboratories. The analytical results indicated a close agreement in the percent difference between the total cations and total anions of each sample.

The results of the comparison of the percent difference in cations and anions for replicates of each sample are believed to indicate that laboratory error in analytical procedures played a significant role in the results of the study. The error attributed to laboratory procedure is most evident from comparing the percentage difference between total cations and anions for the aliquots of the sample collected from well LH.

The analysis for total dissolved solids (TDS) was performed using the evaporation method. A filtered, nonacidified aliquot of

each sample was used for this analysis. With the exception of a possible reduction in the concentration of bicarbonate due to the release of carbon dioxide during evaporation, the analytical results are believed to be accurate. Two exceptions are noted however, for the samples collected from wells IRL3 in July 1979, and IRT1 in November 1979. Laboratory results for the sample collected from well IRL3 indicate a TDS concentration greater than the measurement of specific conductance made in the field. The analytical results of the sample collected from IRT1 indicate that the concentration of TDS is only slightly lower than the measurement of specific conductance. The TDS concentration, in mg/l, should be about 0.65 times the specific conductance, in micromhos per centimeter (umhos/cm), for waters in the study area (Martin, 1980). The discrepancy between the laboratory results of TDS and the field measurements of specific conductance for these two samples is attributed to laboratory error.

A review of the chemical data in Table 2, with the exception of chloride, did not reveal trends in the quality of ground water with time. Chemical hydrographs for chloride, prepared for wells IRL1 and LH, showed an initial decrease in the concentration of chloride with time (see Figure 15). The most dramatic decrease occurred between the first (July 28) and second (August 21) sampling intervals. Similar trends were identified in all the wells sampled as part of this study. Some variation in the trend would be expected between wells along the path of ground-water flow, as well as between the deeper production wells and the shallow observation wells. As a result, the time trend associated with the concentration of chloride is attributed to laboratory error.

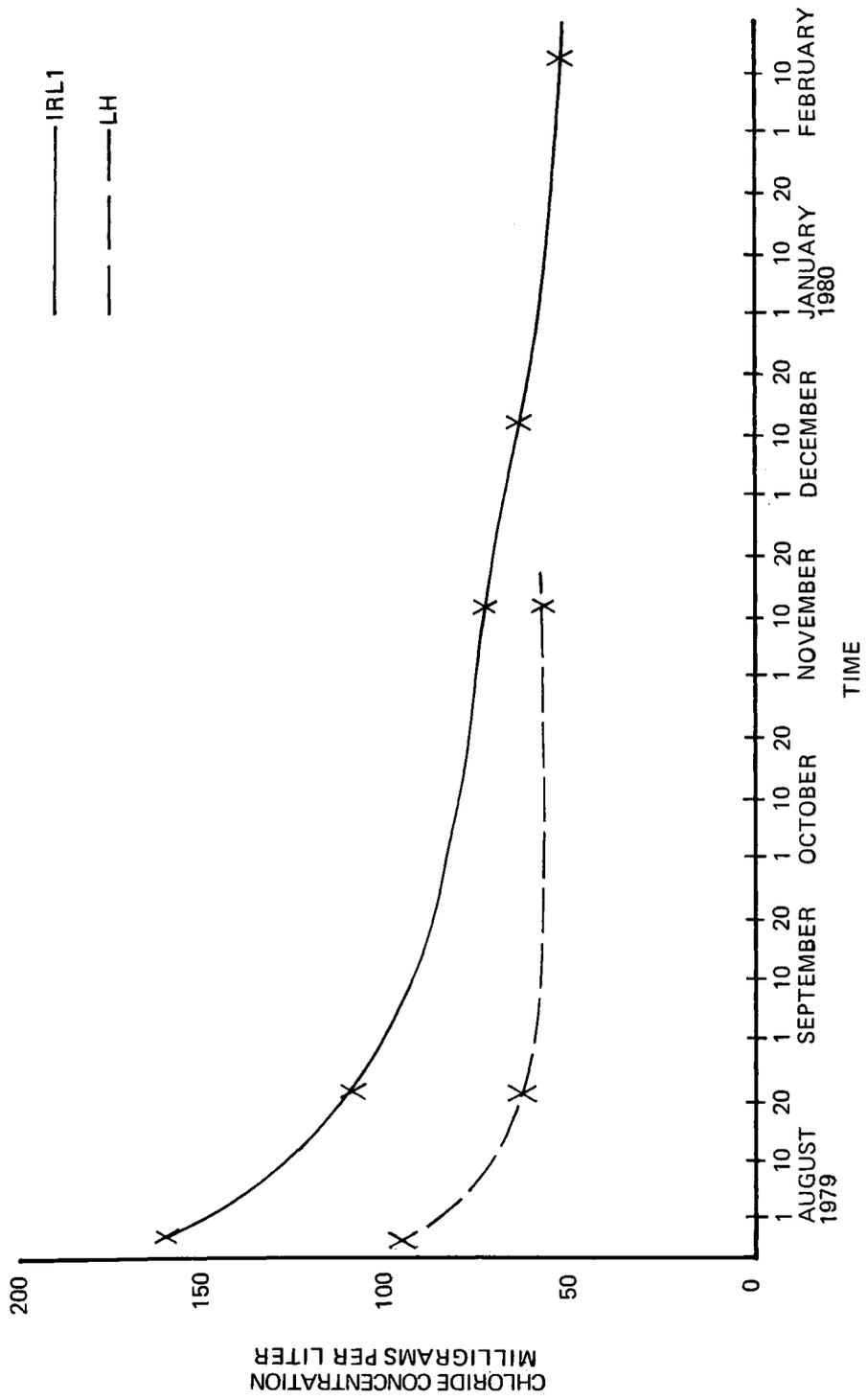


Figure 15. Chemical hydrograph of chloride in wells IRL1 and LH.

A trilinear diagram was prepared to identify spatial trends in the quality of ground water (see Figure 16). The relative proportions of cations (calcium, magnesium, sodium, and potassium) and anions (chloride, sulfate, bicarbonate, and carbonate) can be determined from the position of the points plotted on the diagram. Although the chemical results from the Water Resources Research laboratory showed the greatest precision, a complete analysis for all sampling locations was not performed. As a result, the chemical data from the IRWPCF laboratory for the November sampling period were used in the construction of the trilinear diagram. If the data were incomplete for a particular location, then data from an alternate sampling period were used. The results show a similarity in the quality of streamflow and ground water in the shallow observation wells. These waters were generally a sodium calcium bicarbonate to a calcium sodium bicarbonate type. In contrast, ground water from the deeper production wells was a calcium sodium bicarbonate sulfate to a calcium sodium sulfate type.

Water quality maps for bicarbonate, chloride, sulfate, and specific conductance were prepared to identify spatial trends in the quality of ground water as well as the extent and sources of potential pollution (see Figures 17, 18, 19 and 20; in pockets). Chloride, bicarbonate, and sulfate were selected because of greater confidence in the analyses for these constituents. Specific conductance was also selected because these results were determined in the field immediately following sample collection, thereby eliminating laboratory errors. The maps were prepared by drawing contours of equal concentration or conductance from the mean value of the chemical data for each of the observation wells.

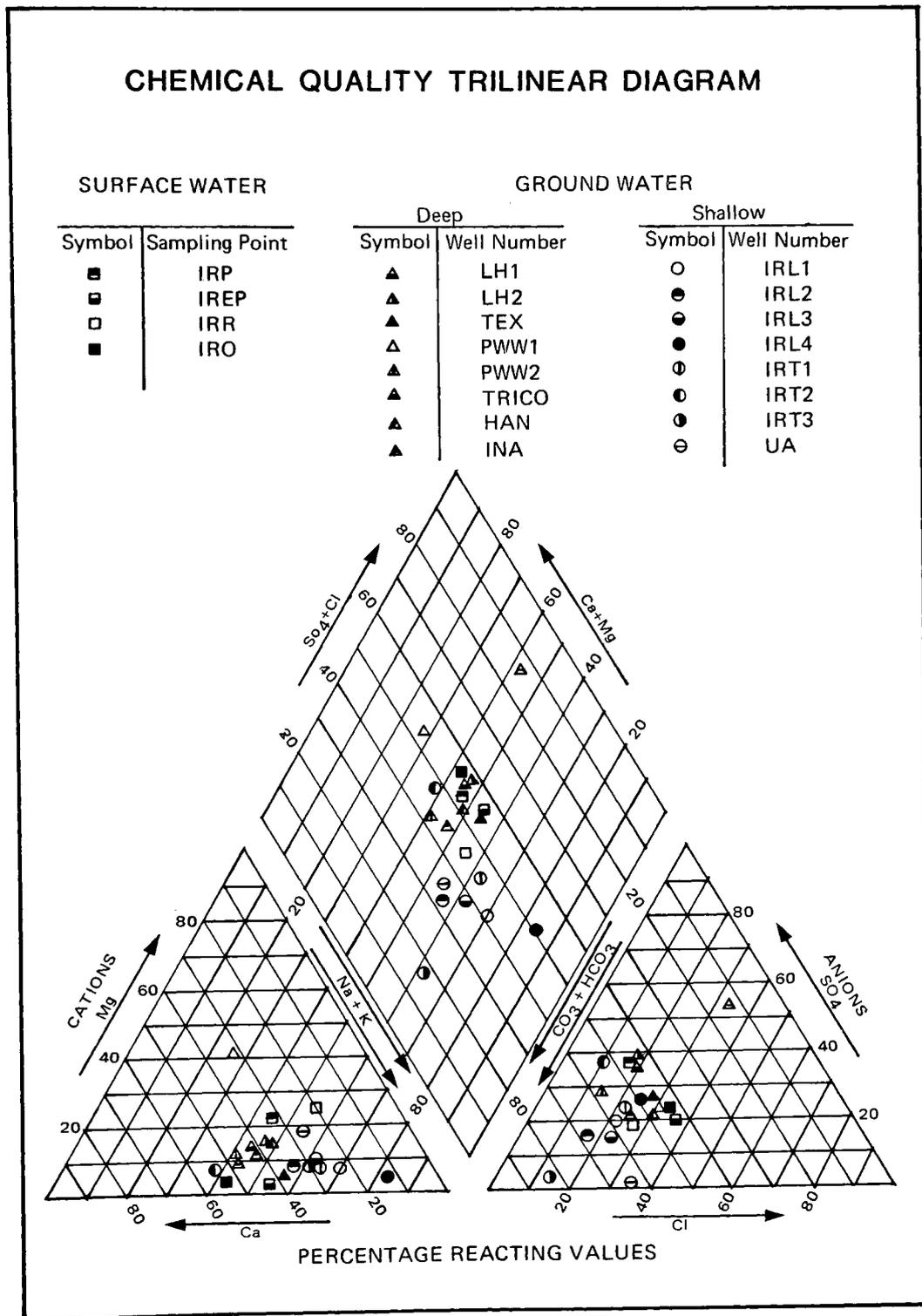


Figure 16. Trilinear diagram of water samples collected in November, 1979.

Data collected during the July sampling period were not included in the mean because of the high variance from data collected during subsequent sampling periods. Contours based on chemical data from the deeper wells were drawn as dashed lines to reflect limited confidence because of the variations in the quality of ground-water with depth.

## CHAPTER 5

### DISCUSSION

The quantitative interpretation of the results was impossible because of the variability of the chemical data. The variability of the data was attributed mainly to incomplete well development and poor analytical techniques. A review of the analytical procedures indicated that the concentrations of individual anions and all field measurements were generally reliable. The data from the first (July) sampling period were not used in the interpretation of areal trends in the quality of ground water to eliminate some of the variability. In addition, chemical data from the remaining sampling periods were averaged for each sampling point. These values are believed to be representative of conditions in the ground water because of the relatively short duration of the monitoring program.

Bicarbonate, chloride, sulfate, and specific conductance were selected as the primary indicators of contaminated ground water in the study area. The numerous sources of nitrate and ammonia in the study area precluded the use of these constituents as indicators of contamination originating from the landfill. The chemical data showed that concentrations of nitrate were generally high throughout the study area. Higher concentrations of ammonia were found in the observation (shallow) wells. This relationship provides some evidence of a stratification in the quality of ground water with depth. The sources of ammonia are most likely derived locally, whereas nitrate has been mapped regionally in

the Cortaro Basin and attributed to agriculture (Martin, 1980). Fertilizers and sewage effluent for irrigation are the major contributors to the high concentrations of nitrate in the Cortaro Basin.

The potential contamination of ground water from the Ina Road landfill is believed to be limited to the upper portion of the aquifer. The trilinear diagram shows a stratification in the quality of ground water in the aquifer (see Figure 16). Ground water from the production (deep) wells is mainly a sodium calcium sulfate to a calcium sodium sulfate type. The higher proportions of sulfate found in the deeper portions of the aquifer are believed to be indicative of the regional flow of ground water along the Santa Cruz River (Martin, 1980). In contrast, ground water in the observation (shallow) wells was mainly a calcium sodium bicarbonate to a sodium calcium bicarbonate type. The higher proportions of bicarbonate in the shallow wells are believed to be the result of localized conditions. Some vertical mixing is also evident from the diagram, however it is believed to be limited to production wells screened at multiple intervals in the aquifer (Schmidt, 1973). Based on this interpretation, the delineation of potential contaminants in the ground water focused on the chemical data collected from the observation wells.

In contrast, the data collected from the production wells were used to represent the background quality of ground water in the study area. Background data are used as a baseline to help identify a change in the chemical quality of ground water. Background data are generally collected from historic information or from wells installed upgradient

from the potential source of contamination specifically for this purpose. The absence of historical information on the quality of ground water and upgradient observation wells required the reliance on the data collected from the deeper production wells in the study area. These data are believed to reliably represent background conditions in the study area. The trilinear diagram indicates a similarity in the quality of ground water in spite of the wide areal distribution of these wells. In addition, the data from these wells are also similar to regional data for the Cortaro Basin reported by Martin (1980).

The distribution of the concentration of bicarbonate in the study area is shown in Figure 17. Concentrations of bicarbonate in ground water range from 200 to 800 mg/l in the study area. The bicarbonate map shows a high concentration originating in cell 1, and possibly in cell 2, and extending northward. Concentrations in the plume range from 300 to 800 mg/l. Background concentrations in the area are believed to range from about 200 mg/l to 400 mg/l (Wilson et al., 1977). The high concentration of bicarbonate in cells 1, 2 and 4 may be related to microbial decomposition of organic matter as suggested by the relatively high concentration of total organic carbon (TOC) and chemical oxygen demand (COD) collected from wells IRL2, IRT3, and IRL3. However, the high concentration of suspended solids found in well IRL3 during the July sampling period makes the associated analytical results for this well suspect. Sources of organic matter for microbial decomposition include sewage sludge and other wastes deposited in the landfill as well as sewage effluent discharged into the Santa Cruz River from the IRWPCF. In

addition, residual organic matter may be present in the vadose zone beneath cell 4 as a result of the historic use of this cell as an oxidation lagoon for the sewage treatment plant.

The oxidation of organic matter by bacteria results in the production of carbon dioxide and heat. The carbon dioxide reacts with water to form carbonic acid which lowers the pH of the environment. The carbonic acid then reacts with the calcareous deposits in the subsurface resulting in an increase in calcium and bicarbonate ions in solution. Field measurements indicate that the pH was as low as 6.4 in samples collected from wells IRL2 and IRT3 (see Table 2). The reduced pH increased the mobility of trace metals (Fuller, 1977), as is evident from the relatively high concentrations of manganese, iron, lead, and cadmium in wells IRL2 and IRT3. The low pH values and higher temperatures in ground water collected from these wells provide some evidence of these reactions. The Santa Cruz River is believed to provide the water necessary for the production of carbonic acid and transport of pollutants to the ground water. The high concentration of chromium was also found at well IRT3.

Landfill leachate and residual sewage effluent are believed to be two potential sources of ground-water contamination beneath cell 4. Flood waters in the Santa Cruz River moving laterally through the vadose zone are believed to be the method of transport of leachate contaminants to the water table. The decrease in the concentration of the bicarbonate and the cationic metals between wells IRT3 to IRT2 provides some evidence that the cell 1 is a major source of contamination.

A less severe source of contamination may be residual organic matter and metals attenuated in the vadose zone as sewage effluent leaked through the bottom of cell 4 when this cell served as an oxidation lagoon for the neighboring sewage treatment plant. During its initial operating period, sewage effluent most likely percolated through the bottom of the lagoon. However, only minimal leakage is believed to have occurred because of the self sealing potential from the organic matter deposited on the bottom of the lagoon. As the effluent percolated through the vadose zone, much of the organic matter and metals were probably either filtered or sorbed. Microbial decomposition of the organic matter and residual moisture in the vadose zone may be partially responsible for the high concentration of bicarbonate in the ground water. In addition, microbial activity would be partially responsible for the decrease in pH which most likely resulted in the increased concentration of cationic metals in the ground water (Fuller, 1977). Flood waters moving through the vadose zone are most likely the method of transport of these residual contaminants to the water table. The oxidation lagoon was dry throughout this study. The minor amount of leakage that most likely occurred and its operational status during this study are believed to be indications that the historic oxidation lagoon does not represent the major source of contamination in the study area.

High concentrations of bicarbonate were also found in samples from well IRL3. The biological oxidation of organic matter is again a possible mechanism for the high concentrations of bicarbonate. Relatively high concentrations of TOC, COD, and heavy metals, as well as

elevated temperatures, were detected in ground water collected from this well. Organic matter deposited by the Santa Cruz River may be the source for this reaction.

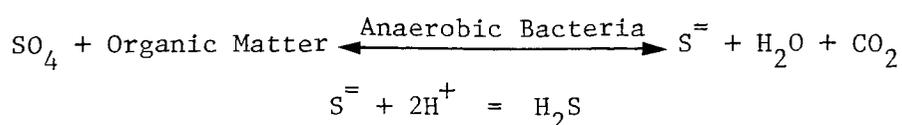
Concentrations of chloride in ground water ranged from about 40 mg/l to 110 mg/l in the study area (see Figure 18). These concentrations compare closely with regional values for the Cortaro Basin reported by Martin (1980). The major sources of chloride in the region are the dissolution of relict salts and the historic use of sewage effluent for irrigation. High concentrations of chloride along the Santa Cruz River are the result of sewage effluent discharged into the river. Chloride concentrations of the Santa Cruz River at sampling point IRR averaged 80 mg/l, while samples collected from the outflow of the Ina Road Water Pollution Control Facility averaged 100 mg/l.

Although large concentration gradients are not present in the study area, the configuration of the chloride map does provide some indication of contamination originating in the landfill area. The nearly closed contour of 100 mg/l originates in cell 1 and extends northward in approximately the same location as the bicarbonate plume. Chloride is generally a good indicator of contaminated ground water because of its high mobility and presence in most wastes. The high background concentration of chloride, however, is believed to largely limit the use of this constituent as a sole indicator of ground-water contamination originating in the landfill. The low concentration of chloride surrounding the sand and gravel pit to the west of the landfill area is attributed to

the recharge of flood waters of generally good quality. Water samples collected from the pit at IRP1 and IRP2 revealed concentrations of 32 mg/l and 24 mg/l, respectively. Concentrations in wells immediately north of the pond are approximately 40 mg/l.

High concentrations of sulfate are common in the Cortaro Basin with background levels generally ranging from about 150 mg/l to 300 mg/l (Wilson et al., 1977). The major source of sulfate is dissolution of relict salts in the subsurface (Laney, 1972). Figure 19 shows the concentrations of sulfate range from less than 50 mg/l to greater than 350 mg/l in the study area. Background concentrations, based on samples collected from the production wells in the study area ranged from 80 mg/l to 340 mg/l. A number of factors are believed to cause the wide range in concentration of sulfate.

The low concentrations of sulfate in ground water beneath cells 1 and 4, with respect to background levels, are believed to be good indications of contamination originating in the landfill. The low concentrations are believed to be derived from the biological oxidation of organic matter in the landfill. The utilization of oxygen in the respiratory process of the bacteria results in the transition to an anaerobic environment. In the presence of certain anaerobic bacteria, sulfate is also converted to a reduced form as stated in the following biochemical reaction:



The major sources of energy for these bacteria are methane and carbon dioxide. In well IRT3, where the pH was measured at less than 7, hydrogen sulfide ( $H_2S$ ) was produced. The presence of hydrogen sulfide was verified by the "rotten egg" odor detected during sampling at this well. The dissociated form of hydrogen sulfide ( $HS^-$ ) is most likely present at wells IRT2 and UA because pH values were measured at greater than 7. The decrease in pH and the presence of reducing conditions resulting from these reactions are believed to be responsible for the high concentration of various metals in the samples collected from wells IRT3, IRT2, and UA. These conditions tend to cause the solution of various precipitates and an increase in the mobility of cationic metals found in landfill leachate (Fuller, 1977).

The concentration of sulfate increases northwesterly from cell 4 and in the eastern portion of cell 1 to cell 4. At this location the concentration increases northward similar in configuration to concentration of bicarbonate and chloride. The concentration gradient is believed to be due to the mixing of low sulfate water beneath cells 1 and 4 with ground water naturally high in sulfate. In addition, a transition from a reducing to an oxidizing environment is expected to occur with distance from cells 1 and 4. Although this transition is expected to occur naturally with the movement of ground water, oxygenation is enhanced with the pumping of wells 1F and INA as described by Baedecker and Back (1979). The presence of certain aerobic bacteria could convert the reduced forms of sulfur back to sulfate.

The high concentrations of sulfate in the extreme northern portion of the study area are most likely due to the dissolution of relict salts and historic agricultural activities. The average concentration of sulfate in ground water from the well supplying the Trico Electric Cooperative was reported at 390 mg/l, 140 mg/l higher than recommended drinking water standards (Angell, 1979).

Low concentrations of sulfate (less than 150 mg/l) were also found in ground water from wells IRL3, IRL1, PWW2, and PWW3, and are believed to be the result of dilution. Surface water in the abandoned sand and gravel pit west of the landfill area was found to have an average sulfate concentration of about 90 mg/l. In addition, the average concentration of samples collected from the Santa Cruz River at IRR was approximately 70 mg/l. Percolation of this relatively good quality water will result in lower sulfate concentrations in ground water beneath the pit.

The specific conductance of ground water in the study area was also mapped to provide an indication of the distribution of TDS in the study area (see Figure 20). Specific conductance, measured in umhos/cm, multiplied by 0.65 approximates the concentration of TDS, in mg/l, in the region (Martin, 1980). The specific conductance in ground water ranged from 850 umhos/cm to greater than 1,600 umhos/cm in the study area. The highest values of specific conductance were measured at wells IRL2 and IRT3 which also indicate a plume of ground water consisting of high concentrations of TDS originating in cell 1. The contours of specific conductance coincide closely with the plumes of bicarbonate and chloride.

A comparison of the four water quality maps shows that the high concentration of ions in ground water appear to originate in cell 1 of the landfill. Samples collected from well IRT3 are believed to be the most representative of ground water flowing beneath cell 1 of the landfill. The high concentration of bicarbonate, TDS, and heavy metals such as iron, manganese, chromium, cadmium, and lead are believed to be good indications of the production of leachate in cell 1 and its subsequent migration to the water table. Major flood events in the Santa Cruz River are the most likely sources of water required for the generation of leachate. High flows in the Santa Cruz River have periodically washed out the southern bank to the river (Nowak, 1979). The major flood of October 1978 exposed solid waste along the northern bank of the Santa Cruz River. This flood is believed to have saturated major portions of cell 1 thereby supplying both a source of water for leachate generation and a conveyance for the contaminants to migrate to the water table. The flood was the last major runoff event in the Santa Cruz River before the completion of the field program associated with this study. Wilson and DeCook (1968) found that water percolating from the Santa Cruz River flowed for considerable distances laterally in the vadose zone before recharging the water table. The lateral flow of percolating water has historically been suspected of producing leachate in cell 1 (Wilson and Small, 1973). Peterson and Staley (1973) found a lens of clay from 10 to 30 feet below land surface in the vicinity of cell 1. Surface water percolating into the vadose zone along the landfill could travel along the top of the lens into the base of cell 1 thereby supplying a source of

water for leachate generation. The presence of this lens, however, could not be verified or refuted from the lithologic logs of the few existing wells in the study area. Wilson and Schmidt (1979) described contaminant migration from cell 1 of the landfill after a major runoff event in the Santa Cruz River. Approximately 10 days after the event, a wave of contaminated ground water was detected in a monitoring well completed in the vadose zone. However, contaminated ground water was not detected in a nearby monitoring well completed in the saturated zone. The results of the study indicate that the lateral flow of water in the vadose zone is much more rapid than vertical percolation in the study area. As a result, contaminants may be transported for considerable distances in the vadose zone before percolating to the water table.

Ground-water levels in Fall 1979 ranged from 60 to 70 feet below land surface in the study area. In contrast, Wilson et al. (1983) reported that depths to ground water in 1982 ranged from 95 to 135 feet in the Ina Road landfill study area. The high levels reported in 1979 may be representative of a declining water table as a result of the dissipation of flood waters in the vadose zone from the October 1978 runoff event.

Daily flows in the Santa Cruz River are not believed to be a source of water for leachate generation in the landfill. The proximity of the active channel and its relative elevation to the bottom of the landfill are believed to preclude any significant quantities of water from entering the landfill. Wilson and Small (1973) found cell 1 of the

landfill to remain dry except following flood events in the Santa Cruz River.

The relationship between estimated ground-water velocity and the configuration of the pollutant plume provides additional evidence that the October 1978 flood was the source of water for leachate generation in the landfill and the subsequent migration of contaminants to the water table. The maximum extent of contamination appears to be best represented by the plume of bicarbonate. The longitudinal length of this plume is approximately 1,800 feet. Using ground-water velocities of 4.2 ft/day and 8.4 ft/day, it would require from about 6 to 13 months for contaminants to travel this distance in the saturated zone. The distance of contaminant migration using the average ground-water velocity is about 10 months. These estimations are based on the assumption that leachate is generated rapidly and that the hydraulic properties are valid. These time periods compare closely with the 10 month-interval from the October 1978 flood to the beginning of the monitoring program. During this period, no other events occurred that could supply the necessary moisture for leachate generation and migration to the water table.

The plume of contamination is shown by the chemical maps to extend north from cell 1. The regional direction of ground-water flow from the flow-net diagram (see Figure 14) is northwesterly. The lateral expansion of the chemical plumes can be explained by hydrodynamic dispersion, however this process cannot account for their northerly extension. One possible explanation for the northerly migration of the chemical plumes is the recharge of flood water from the abandoned sand and gravel pit west of the landfill area. This pit has been inundated

with water from the Santa Cruz River on several occasions as a result of major storm events. The last flood to break the banks of the river prior to this study was in October 1978, approximately 10 months before the study began. Dilution from generally high quality flood water reduces the chemical concentration in the ground water northward around the pit. As a result, the recharge water acts as a boundary by altering the regional flow of ground water northward around the pit. The boundary is not shown in the flow-net diagram because of the absence of wells adjacent to the pit. However, leakage from the abandoned pit was also suggested by Wilson et al. (1977) and Wilson et al. (1983).

Anisotropy and heterogeneity also are believed to be important factors in the northerly direction of the chemical plumes. Movement of water in the vadose zone during recharge events is preferentially perpendicular to the river because of the manner in which the sediments were deposited (Wilson and DeCook, 1968). In the present study area this direction would be northward from the Santa Cruz River (Wilson and Schmidt, 1979). A zone of highly permeable sediments extending northward from the Santa Cruz River could serve as a conduit for ground-water flow and subsequent contaminant migration. Although ground water flows from higher elevation to lower elevation, it will also follow the zone of highest permeability. As a result, ground water entering this zone will flow northward. Another explanation for the zone of high permeability is the presence of a buried stream channel. Although buried stream channels have been identified along the Santa Cruz River in the Cortaro Basin, insufficient data were available to identify these deposits in the study area.

## CHAPTER 6

### CONCLUSIONS

A high degree of variability was found in the results of the chemical analyses conducted for this investigation. The high variability was attributed to incomplete well development in the shallow observation wells and poor analytical procedures. A postmortem review of the analytical procedures indicated that concentrations of bicarbonate, chloride, and sulfate, as well as all field measurements, were generally reliable. Using these constituents as primary indicators of ground-water contamination, a usable interpretation of the data, that was qualitatively accurate, was possible.

Cell 1 of the Ina Road landfill is believed to be a source of contamination to ground water in the region. High concentrations of bicarbonate, manganese, iron, lead, chromium, and cadmium as well as values of specific conductance in well IRT3, are the primary indicators of this contamination. Major runoff events in the Santa Cruz River are the most likely source of water necessary for the generation of leachate in the landfill and its subsequent migration to the water table. Previous investigations by Wilson and Small (1973), and Wilson and Schmidt (1979) indicate that percolating runoff flows laterally above a layer of low permeability and into the landfill. Water reacts with carbon dioxide and reduced sulfur species resulting from various types of microbial decomposition, and acids are produced which reduce the pH of the environment and increase the mobility of certain metals. With a

sufficient volume of water, the field capacity of the landfill bottom and vadose zone will be reached allowing contaminants to migrate to the water table. Estimates of ground-water velocity provided evidence that the October 1978 flood was the source of leachate generation that resulted in the high concentration of various chemical constituents in the ground water.

The abandoned sand and gravel pit west of the landfill is believed to be recharging the ground water in the study area. Concentrations of chloride, sulfate, bicarbonate, and TDS extend northward instead of northwesterly along the regional direction of ground-water flow. Flood waters of good quality in the pit percolate to the water table and interact with ground water of poor quality, resulting in the chemical gradients found in the study area.

The chemical characteristics of ground water in the study area were found to vary with depth. Deeper ground water exhibited characteristics of regional flow, whereas ground water in the shallow portion of the aquifer appeared to be influenced by local conditions. Ground-water contamination from the landfill was found only in the shallow observation wells in the study area. The continued pumping of production wells screened at multiple intervals may cause sufficient mixing to induce contamination in the deeper portion of the aquifer.

The case study of the Ina Road landfill provides evidence that landfills adjacent to ephemeral streams have a high potential for polluting ground water. Runoff from major storm events represents an intermittent but significant source of water for the generation of leachate and the migration of pollutants to the water table.

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Figure 17. Map showing concentration of bicarbonate in ground water in the Ina Road landfill study area, Fall 1979.

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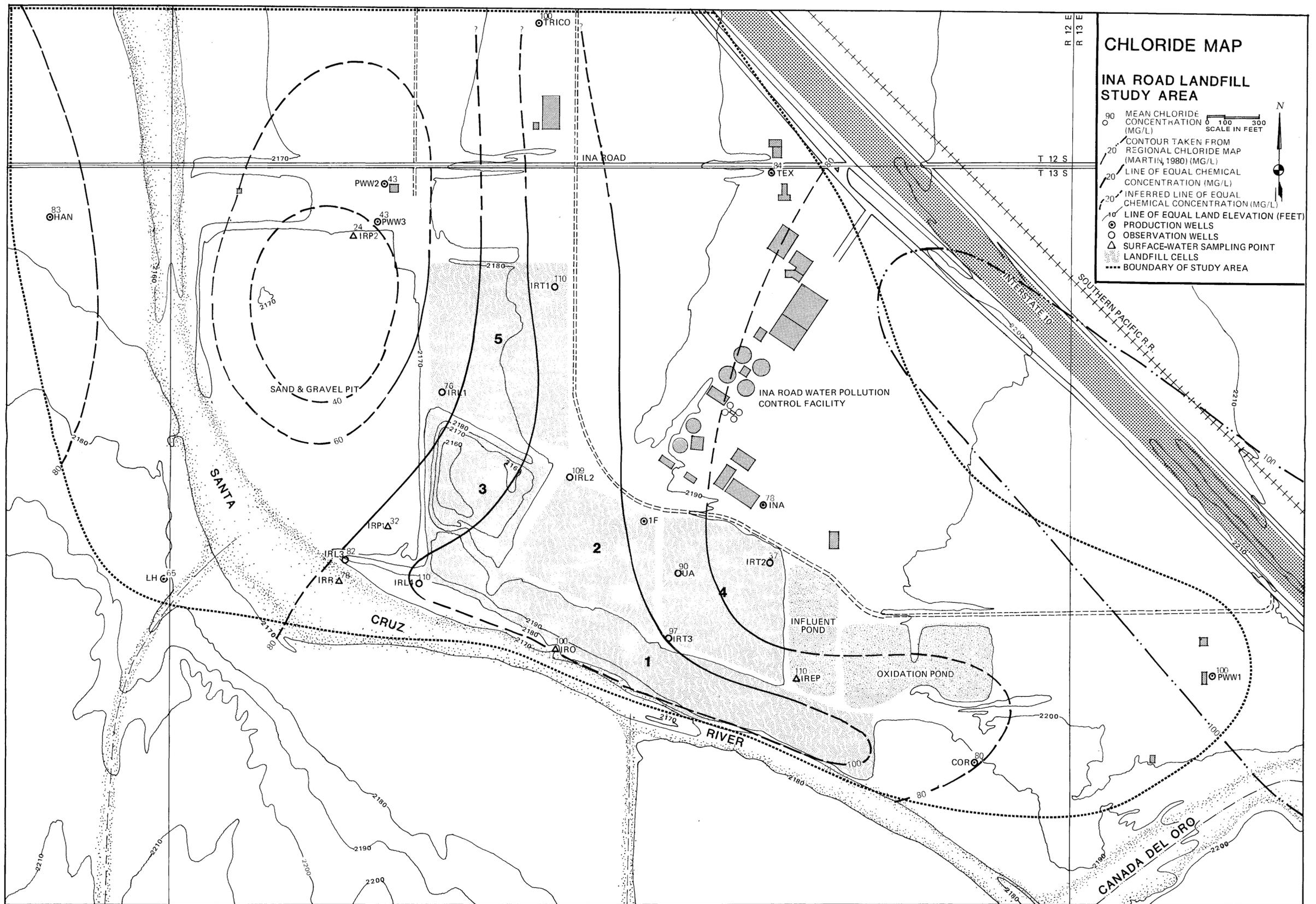


Figure 18. Map showing concentration of chloride in ground water in the Ina Road landfill study area, Fall 1979.

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 University of Arizona

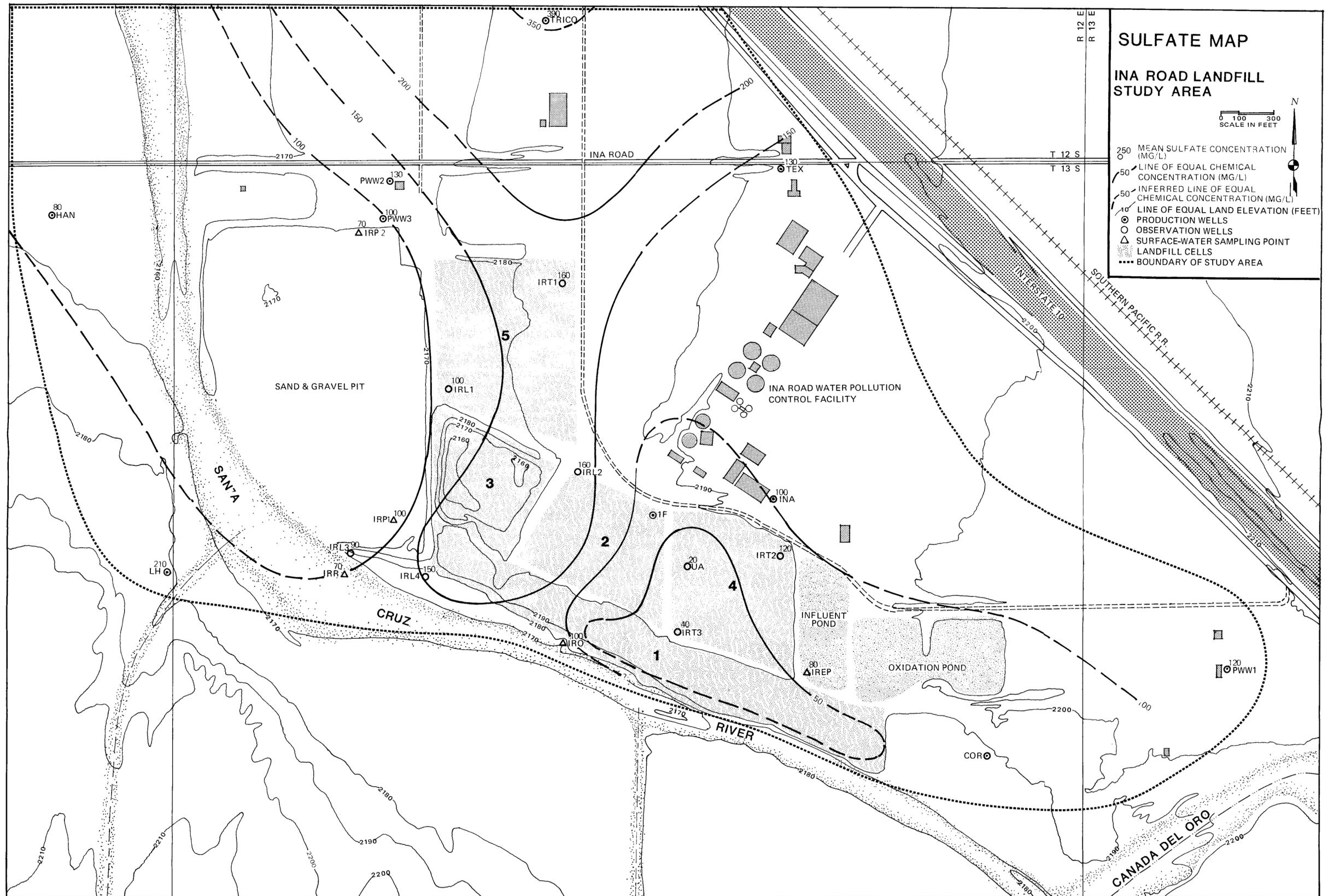


Figure 19. Map showing concentration of sulfate in ground water in the Ina Road landfill study area, Fall 1979.

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Figure 20. Map showing specific conductance of ground water in the Ina Road landfill study area, Fall 1979.

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