CAPTURING ADDITIONAL WATER
IN THE TUCSON AREA

By

The Rillito Creek Hydrologic Research Committee

of

The University of Arizona

and

The U. S. Geological Survey

June 1959

59-49

Open-file Report

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ABSTRACT

This report represents a preliminary study on the possibilities of increasing available water supplies within the Tucson basin to meet the anticipated water demand resulting from the rapid increase in population. The study was made by the University of Arizona and the U. S. Geological Survey.

The Tucson basin is a depressed structural block between the surrounding mountain masses. The impermeable Pantano beds and the crystalline complex compose the mountain masses and form the margin and floor of the ground-water basin. The sediments which constitute the actual ground-water reservoir are of three principal types: (1) alluvial deposits of the Tucson basin, which underlie most of the broad, virtually flat floor of the valley; (2) the inner-valley fill, which underlies the flood plains of the major washes; and (3) the alluvial-fan deposits along the mountain fronts. The thickness and general configuration of the inner-valley fill and the fan deposits are fairly well known; however, the thickness of the deposits of the Tucson basin, the main source of ground water, is not certain, and their relationship to the adjacent and underlying Pantano beds and crystalline complex is one of the principal problems requiring investigation.

Until disturbed by man, the amount of water in storage in the sediments of the Tucson basin remained almost constant. In recent years, however, water has been withdrawn from the basin much faster than it has been replenished by rainfall and runoff; consequently, static water levels have declined as much as 35 feet, and net ground-water storage loss has been estimated as 250,000 acre-feet during the past 12 years. It is apparent that ground-water supplies will become depleted unless measures are taken to replenish the amount in storage.

The runoff potential in Rillito Creek is equal to 80 percent of the amount of water used in the greater Tucson area. Much of this incoming water is lost before it can be used, as the potential evaporation is about nine times the annual precipitation, and vegetation along the stream channels uses an estimated 2,500 acre-feet per year. Moreover, runoff leaving the Rillito Creek basin averages about 12,000 acre-feet per year.

It is believed that additional water, which is now lost by evaporation or outflow from the basin via Rillito Creek during the rainy season, could be captured. Salvage of this water would ease the pressure on the ground-water reserves, through transfer into the distribution system and recharge into the subsurface, where the ground-water reservoir has been partially depleted.

A review of present knowledge of salient features of the Tucson basin indicates the need for further studies along several lines -- the pattern of precipitation throughout the basin, amounts and distribution of runoff, quality of both surface and ground water, amount of water lost by evaporation and transpiration, amount of ground water in storage and its movement within the basin, and the feasibility of artificial recharge of the ground-water reservoir.

INTRODUCTION

The problem of the availability of water to meet the future demand of the greater Tucson area motivated the University of Arizona and the U. S. Geological Survey to initiate preliminary studies on the possibilities of increasing available water supplies. The basic purpose of this report is to determine the feasibility of detailed investigations of methods for capturing additional water in the Tucson area to supplement municipal supplies. As metropolitan Tucson is the fastest growing community in the Southwest, owing to its climatic appeal and commodious living, the population in the next 10 or 15 years may be expected to increase to more than half a million persons; however, the magnitude of such growth and expansion will depend on the availability of adequate water. Preliminary appraisal indicates that it will be necessary to capture additional water within the Tucson basin or import it from elsewhere. As there are many unknown factors relating to the practicability of capturing additional water, it is necessary to make a quantitative appraisal of the pertinent components of the hydrologic system in the Tucson area.

Water in the hydrologic system moves in an ever-continuing cycle. Its circulation speeds up and slows down repeatedly and may vary from year to year, but over the years the system or cycle remains in approximate balance. In effect, no water is added to or lost from the hydrologic system by natural processes in a given region. Water is precipitated from atmospheric vapor as rain or snow. Part becomes surface runoff, from which a portion is stored in the soil or in ground-water reservoirs for varying periods of time. A large part returns to the atmosphere as vapor, evaporating from water or soil surfaces or from foliage of vegetation. Virtually all water that falls as precipitation eventually returns to the atmosphere as vapor.

From this continuous circulation in the hydrologic system, man obtains water for his needs in agriculture, industry, and domestic use. On a continuing basis, water cannot be withdrawn from this hydrologic system at a rate that exceeds replenishment from rainfall and runoff. Withdrawals at greater rates can be made only at the expense of depleting the amount in ground-water or soil-water storage.

These conditions may be expressed in common business words. The water in ground-water and soil-water storage is the basin's capital asset; precipitation is the gross water income. Interception, evaporation, and transpiration are nature's water income tax. Thus, the net water income is runoff, plus that amount that can be recovered or salvaged from the portion that constitutes taxes. The basin's water assets cannot remain "in the black" if these assets are depleted and there is no restoration. In order to establish a business account on the hydrologic system, man must be informed fully on all its components. Such information can be gained from intelligent and unprejudiced research, statistical water records on income and outgo, and analysis of these factors over a period of years. Only when such a commonsense approach is used will it be possible for man not to be taken unaware by a serious water shortage.

Metropolitan Development

Early inhabitants in Tucson settled along the Santa Cruz River where there were small amounts of surface flow or where water could be obtained from shallow wells. As the community grew, the water demand was met by the development of additional wells along the Santa Cruz River and in the area between the Santa Cruz River and Rillito Creek. After World War II the community experienced rapid growth; the population increased sixfold in about 15 years. Business and construction investments presently run into hundreds of millions of dollars. The maintenance of these values and the creation of additional wealth through investment in line with the projected increases in population require an adequate water supply.

Moreover, although it is expected that irrigated acreage in the valley will decrease from the present level, it will be replaced by urban development and new industry which is being attracted to the area by the favorable climate and an adequate labor supply. The present industry, largely concentrated in electronics and aircraft, requires moderate amounts of water for sanitation, air conditioning, and landscaping. Heavy industry would increase the water demands even further.

Metropolitan supplies presently are obtained from ground-water reserves stored in the sediments underlying the area. Undoubtedly there are large amounts of water in storage, but the rate of withdrawal far exceeds annual replenishment. It is quite apparent that this vast storage reservoir will become depleted unless measures are taken to replenish the storage. The rapid decline in water levels after World War II has been documented by Schwalen and Shaw (1957). This trend not only will continue but will be of even greater magnitude. The amount of water that is available perennially for municipal demand will be the governing factor in the ultimate growth of the greater Tucson area. Thus it is necessary to know the rate at which water can be withdrawn from storage and whether additional water can be captured for beneficial use.

On the basis of the assumption that it is feasible to capture additional water which is otherwise lost to the atmosphere, the problem reduces to the question, "How could this captured additional water be stored or used?" There are several ways of utilizing the water after it is captured: (1) direct transfer of water into the distribution system; (2) recharge of water into the subsurface by natural infiltration and percolation into the ground-water reservoir; and (3) storing of water artificially in areas where the ground-water reservoir has been partially depleted.

Arid lands are characterized by a shortage of water and if man wishes to occupy arid lands, such as the Tucson area, his survival depends upon adequate water supplies. Even more important, there is a moisture deficiency as the evaporation potential is about nine times the annual precipitation. Almost every drop of water exposed to solar radiation is quickly changed to vapor. Consequently, man has several choices when his water demand exceeds the natural perennial replenishment. He can (1) transport water into the area; (2) capture additional liquid water from the hydrologic system; or (3) move to areas that have ample water supplies.

Physical Characteristics of Tucson Basin

Rillito Creek and its tributaries drain the northern and eastern parts of the Tucson basin and the adjacent Santa Catalina, Tanque Verde, and Rincon Mountains. Rillito

Creek is tributary to the Santa Cruz River, joining it above the narrows where both surface and subsurface water leave the Tucson basin. The principal tributary of Rillito Creek is Pantano Wash, which, with its tributaries, drains the area east of the Tucson basin between the Rincon, Santa Rita, and Whetstone Mountains. The total drainage area of Rillito Creek is 918 square miles.

The Tucson basin is an intermontane trough typical of the arid Southwest. Such troughs, although they may contain a through-flowing drainage system, were not carved by streams flowing through them, but represent structural basins between mountain ranges. They are partially filled with fan, lake, or floodplain deposits shed from surrounding mountains or brought in from areas upstream.

The valley floor slopes gradually upward, away from the stream channel toward the mountain blocks. These slopes are broken locally by shallow steps or terraces. At the base of the fan material the slopes become steeper, and above the base of the mountains they may be precipitous. The downvalley slope of the Rillito Creek channel near Tucson is more than 20 feet per mile, becoming greater at the higher altitudes.

The stream channel near the confluence of Rillito Creek with the Santa Cruz River is about 2,300 feet above msl (mean sea level). The summits of the Santa Catalina, Rincon, and Santa Rita Mountains extend more than 9,000 feet above msl, and about 220 square miles of the drainage area is more than 5,000 feet above msl.

The mountain slopes are drained through a series of ravines and canyons, some of which discharge water most of the year. Other channels head in the fan material beyond the base of the mountains. Some of these channels are deeply entrenched in the fan material; some may have become obliterated by agricultural and urban development where they originally crossed the valley floor. The lowlands are drained through relatively shallow channels that feed the larger tributaries or the main stem of Rillito Creek. There seems to be a definite relationship between the size, slope, and other geometric features of these channels and the amounts of water discharged by them. These relationships have not yet been established.

Climate in the Tucson basin is typical of that in an arid region. Summer temperatures frequently exceed 105° on the valley floor, and winter temperatures seldom drop below freezing. The dominant features of the rainfall in the lower altitudes are scantiness and extreme variability from one year to the next. At the higher altitudes temperatures are characteristically lower and precipitation is greater than on the valley floor.

With one exception, there have been no unusual, excessively damaging, floods in Tucson basin in recent years. With the passage of years, memories of past events become hazy and people tend to assume that because floods have not occurred recently they cannot happen. Areas along the stream channels that have been flooded in past years begin to appear desirable for residential construction and pressures build up for residential zoning of these areas. Failure to resist these pressures is an invitation to disaster. Are things bad already? They are in Albuquerque where people build on arroyos.

Figure 1 shows Rillito Creek at the Campbell Avenue crossing in Tucson on August 3, 1955. The discharge

Figure 1.--Flood on Rillito Creek, August 3, 1955.

at the time the picture was taken was 6,000 cfs (cubic feet per second). For Rillito Creek, this means that a flood of this magnitude or larger will recur on the average once every 2.33 years. It should be noted that this flood is almost bank full and that any significant increase in flow would cause the stream to spill over its banks.

During 50 years of record, floods have occurred with peak discharge of four times the amount of water shown in the photo. The exception noted previously was a flood of about 40,000 cfs that occurred on Pantano Wash near Vail. The peak of this flood was reduced greatly before it reached Rillito Creek, but there seems to be no logical reason why a flood of equal size or larger should not have occurred in Rillito Creek near Tucson.

The mountains surrounding the Tucson basin are composed of rocks of several types and have a complex history. The Catalina-Tanque Verde-Rincon Mountains mass is largely a metamorphic complex of gneiss, but sedimentary, igneous, and several other types of metamorphic rocks are exposed on the north, east, and south sides of the mountains, and in a few places within the Rillito drainage area itself. The mountainous area drained by Pantano Wash consists of various types of igneous, sedimentary, and metamorphic rocks. The Santa Cruz River on the west side of the Tucson basin flows near the base of the Tucson Mountains, which are composed largely of volcanic rocks. The basal rocks may be thought of as a crystalline complex, of some importance in the present study because they are of low permeability and yield little or no ground water. They, together with the Pantano beds, form the margins, and at some unknown depth, the floor of the Tucson ground-water basin (fig. 2).

The Pantano beds are a sequence of conglomerate, siltstone, sandstone, and claystone, originally deposited as basin-fill material. That it was not deposited in the surficial basin is shown by the fact that it is tilted and broken by faults, and that beds believed to be correlative with it form part of the actual mountain masses, as along the top of Redington Pass. The Pantano beds are tightly cemented and of low permeability, a pertinent fact in appraising the water potential for metropolitan Tucson.

The sediments in the basin constitute the actual ground-water reservoir and are of three principal types, as follows: (1) deposits of the Tucson basin, which underlie most of the broad, virtually flat floor of the trough between the surrounding mountains; (2) inner-valley fill, which underlies the present channels and flood plains of the Santa Cruz River and Rillito Creek and their tributaries; and (3) alluvial-fan deposits along the mountain fronts (fig. 3).

The thickness and general configuration of the inner-valley fill and the alluvial fans are fairly well known, as they can be determined by observation and from the records of shallow wells. The thickness of the deposits of the Tucson basin, however, is not certain, and their nature and relation to the adjacent and underlying crystalline complex and Pantano beds form one of the principal problems requiring investigation in the present study.

SURFICIAL WATER SUPPLIES

Precipitation

As in all arid or semiarid regions of the world, the dominant features of the rainfall in most of Arizona are scantiness and extreme variability from one year to the next. On the desert floor in the vicinity of Tucson, at a mean altitude of about 2,500 feet, the average precipitation is only about 10 inches a year. Forty percent of this occurs in the two months of July and August (fig. 4), whereas a large part of the remaining 60 percent falls as heavy showers scattered almost randomly through the rest of the year.

Although the same rainfall regime is present at higher altitudes, amounts are characteristically greater. For example, the Mount Lemmon rain gage, at slightly over 7,500 feet, receives an average of about 30 inches of precipitation each year -- almost exactly three times that falling on the desert floor. However, monthly amounts (fig. 4) are extremely variable from one year to the next, perhaps even more so than at lower altitudes. On Mount Lemmon 9.55 inches of precipitation was recorded in March 1954, but the very next year, in March 1955, none at all fell. The same pattern holds for almost every other month -- for example, August rainfall has ranged from 0.55 inch (1958) to 11.71 inches (1955). Only in May, which is normally dry, and July, which is normally wet, does the average really have much meaning.

Most of the rainfall in southern Arizona can be attributed to one of four sources, depending mainly on the season of the year. A large percentage of the summer thundershowers is associated with very warm, moist, and unstable air which has swept around the southern margins of the Atlantic Ocean high-pressure cell and advanced into Arizona from the Gulf of Mexico. This air, in passing over the strongly heated land masses, is made even more unstable, and when it is forced to ascend over the numerous mountain ranges of southern Arizona copious showers result. These showers have a very marked diurnal variation, being most intense over the mountains during the midafternoon when surface heating and the general convergence of air associated with the upslope mountain winds are at a maximum. In the valleys the heaviest summer rains usually do not occur until the late afternoon or early evening, at which time the desert floor is considerably warmer than the surrounding cloud-covered mountains.

Not all the warm-season rainfall is the result of simple convective activity of the type described above. A small, but important, part is associated with tropical disturbances which form off the west coast of Mexico at about 15°N. latitude. These storms usually dissipate as they move northward into middle latitudes, but they are normally still intense and extensive enough when they reach the 30th parallel to produce heavy rainfall in southern Arizona. This type of rainfall differs from the normal convective type in several respects. It is more widespread, has a lesser intensity but longer duration, and is only rarely associated with thunder and lightning. Some of the heaviest rainfalls on record, particularly in September, are associated with these tropical disturbances.

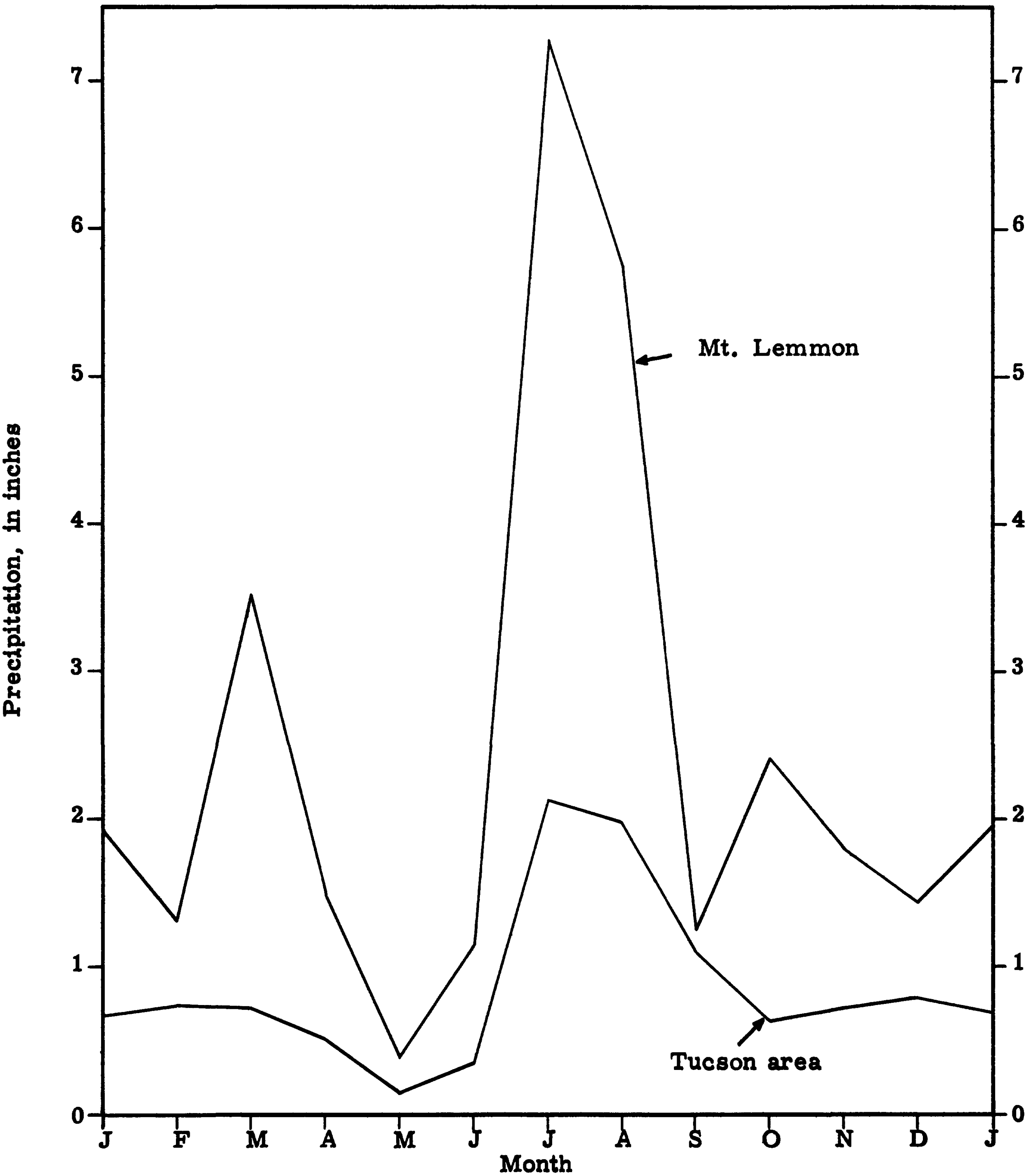

Figure 4.--Mean monthly precipitation in the Tucson area and at Mount Lemmon

Winter, or cool-season, rains are generally less intense but more widespread than those of summer. They also show a smaller variation with ground elevation, sometimes being heavier on the desert floor than in the mountains. Part of this precipitation is associated with the middle-latitude stormbelt, which occasionally moves far enough toward the equator in winter for its southern margins to affect Arizona. It is only when these cyclonic storms move in directly from the Pacific Ocean across the northern and central parts of the country that measurable amounts of rain can occur. When the path of the storm is more nearly north to south, east of the 105th meridian, about all that southern Arizona can expect is plenty of wind and subnormal temperatures.

Probably the heaviest rains of winter are associated with the so-called "Kona" storms or "cold lows" of the subtropical Pacific Ocean. These intense disturbances form in the vicinity of the Hawaiian Islands and move very slowly eastward to the coast of southern California. In this region or slightly inland they often remain stationary for several days. But once they get caught in the strong upper-level westerlies, they move rapidly northeastward across the United States. As these storms normally pass directly over Arizona, frequently advancing very slowly, and as they retain most of their moisture supply while moving in from the Pacific, they can produce several days of moderate to heavy precipitation, which is often accompanied by lightning and thunder.

In conclusion, it might be stated that, as a general rule, the atmospheric conditions most conducive to summer precipitation in Arizona are a northward displacement of the upper-level middle-latitude westerly wind belt and a westward displacement of the Atlantic high-pressure cell and its attendant moist unstable airmass. On the other hand, winter precipitation is encouraged by a southward displacement of the middle-latitude westerlies, in which at that time of year are well-developed cyclonic storms.

The rain-gage network in the area for which long-term published records exist is that of Cooperative Observers for the U. S. Weather Bureau. The rainfall data from these observers are published in "Climatological Data, Arizona" and "Hourly Precipitation Data, Arizona," monthly publications of the U. S. Weather Bureau. Past records of precipitation were published in Bulletin W, "Climatic Summary of the United States, Southern Arizona," which tabulated precipitation data to 1930, and the "Supplement to Bulletin W, Arizona," which contains the data for 1931 through 1952.

Table 1 lists the U. S. Weather Bureau Cooperative Observer stations, which are indicated on the map by a four-number designation. Those stations listed under Hourly Precipitation Data have recording gages, and hourly values of rainfall are published as noted above. The record of one station, University of Arizona, Tucson, has been put on IBM punch cards and is available from the Institute of Atmospheric Physics (IAP in map explanation).

There is an excellent small-scale network in the area which can be denoted as the Atterbury Reservoir Drainage Area network (fig. 5). This network is operated by the Department of Agricultural Engineering of the University of Arizona. The area covered, indicated on figure 3, is between the Benson Highway and Pantano Wash, northwest of Vail and southeast of Davis-Monthan Air Force Base. It covers about 18 square miles.

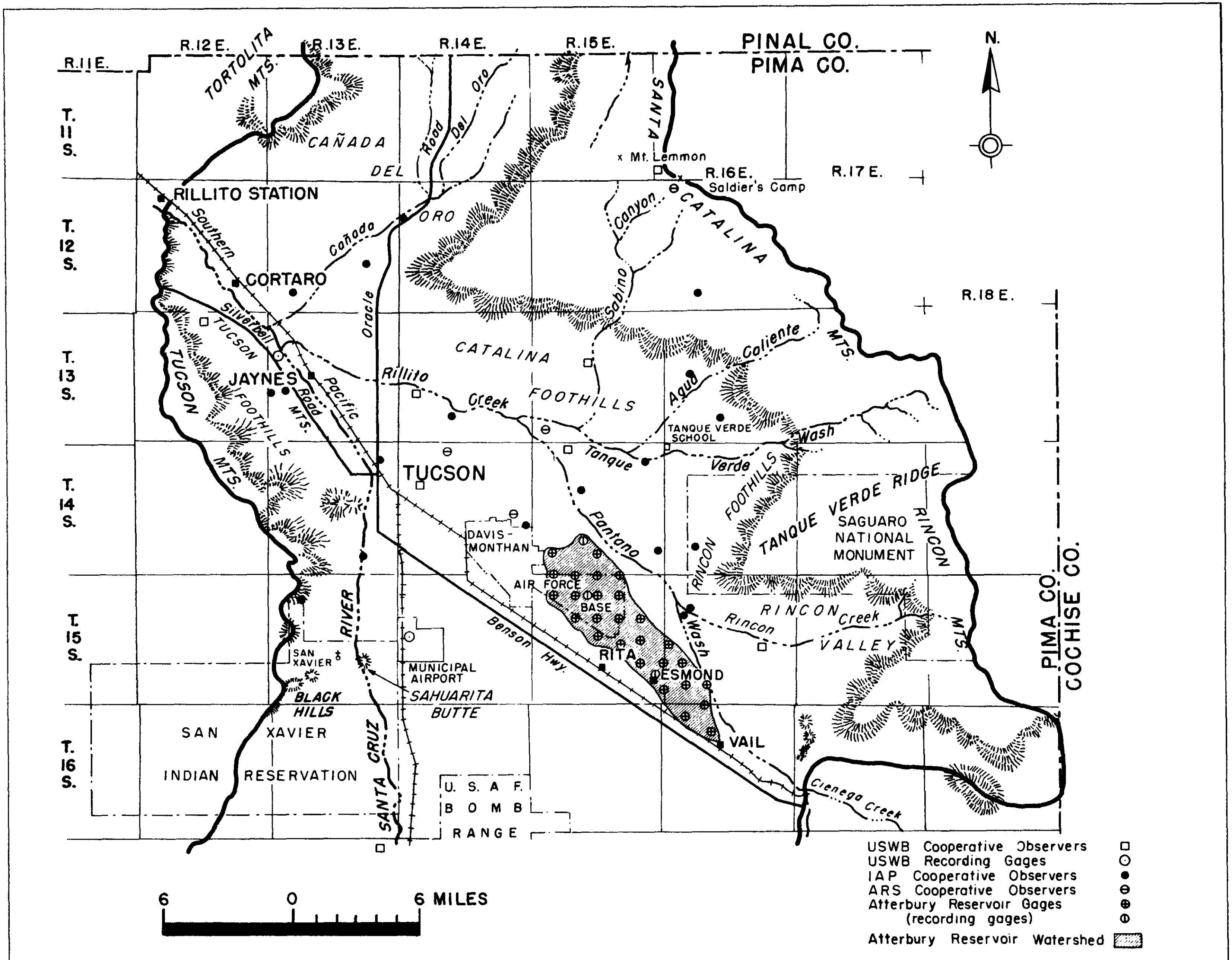

Figure 5.--Rain gages in the Tucson basin.

Table 1.--Cooperative Observer, U. S. Weather Bureau

Number	Name	Period of record*** (as of 11/58)
2159	*Cortaro, 3 SW	1945 to present
5732	Mount Lemmon Inn	10/58 to present
	Mount Lemmon Summit	1957 to 1958
	Mount Lemmon	1950 to 1957
5908	*N-Lazy-H Ranch	1941 to present
7355	*Sabino Canyon	1941 to present
7403	Sahuarita, 2 NW	1956 to present
8796	Tucson Campbell Expt. Farm	1949 to present
8800	*Tucson Magnetic Observatory	1912-16; 1934 to present
8805	*Tucson Mountain Park	1948 to 2/56
8815	**Tucson, U. of Arizona	1867 to present
8820	Tucson, W. B., Airport	1940 to present
Hourly Precipitation Data		
8810	Tucson Nursery	1948 to present
8820	Tucson, W. B., Airport	1940 to present

* Records in Supplement, Bulletin W
** Records in Bulletin W and Supplement
*** Occasional short breaks may exist in these periods

This network was established by the Department of Agricultural Engineering to study the relationship between rainfall and runoff. Data have been collected since 1956 and it is expected that the network will remain in operation. It consists of 30 standard rain gages, of which 3 are recording. Plans exist for the placement of additional Larsen-type rain gages in selected small areas. The gages are regularly maintained, and rainfall is measured after each storm. Complete records for the period of operation are kept by the Department of Agricultural Engineering. These data have been analyzed and studied intensively and are in usable form.

The Institute of Atmospheric Physics has been collecting rainfall records from private individuals in the general area of interest. These stations are designated on figure 5. In general, reports are received each month from these Cooperative Observers, and are kept at the Institute. Most of these observers use a small plastic wedge-shaped gage. The records, extending for about $3\frac{1}{2}$ years, are fairly complete, and the observation can be classed as fair to good. These data have not been analyzed or tabulated in any routine manner.

Another group on campus collecting rainfall data from individuals is the Agricultural Research Service of the U. S. Department of Agriculture. Four gages in the area of interest are designated on figure 5.

Runoff

The longest continuous record of streamflow in the Tucson basin is that of Rillito Creek near Tucson.

The gaging station was established in 1908 by the Agricultural Engineering Department, University of Arizona. In January 1926, operation of the station was assumed by the U. S. Geological Survey with cooperative financing by the University and later by the State Land Department. The records from this gaging station show the streamflow in Rillito Creek,and the extreme variability is seen in the tabulation of monthly discharge (table 2).

The average discharge of Rillito Creek near Tucson is 12,330 acre-feet per year for the 50 years of record. This average has been sharply raised by a few wet years,particularly 1915 and 1916. Although factual records are not available prior to 1908, it is important to understand general conditions of this earlier period. Much information is available from historical documents, and the following account has been prepared from some of these.

The changes in ecology and hydrology experienced during the 1880's by the drainage basin of Rillito Creek parallel rather closely those taking place at the same time throughout most of the rest of southeastern Arizona. Rillito Creek used to flow in "an insignificant bed" through a "pretty and well-cultivated little valley" past the site of New Fort Lowell. Rothrock (1875) states that the creek supplied enough water both for the use of the post and for the irrigation of some small fields. Drinking water came from wells, which in 1875 struck water only 25 to 33 feet below the surface.

West of the Fort, sometimes a mile away, sometimes at its junction with the "dry bed of the Santa Cruz," the Rillito ceased to flow, its bed became enlarged, and it took on the characteristics of what Bourke (1891) called a "sand wash." Cottonwood, alder, and sycamore grew along the watercourse; large mesquites inhabited the bottoms. On the mesas above the creek small stunted mesquite,sage brush, cactus, and "excellent grama and sacatone (sic) grasses" prevailed.

The Rillito's largest tributary, Pantano Wash, evidently used to be dry along most of its course. Two marshes, probably perennial, possibly seasonal, existed along the middle reaches. One, below the entrance of Davidson Canyon, occurred in conjunction with a spring which one traveler described as flowing "a hogshead per minute." The other marsh, a favorite stopping place, was located about where the Pantano station of the Southern Pacific Railroad now stands.

Various travelers commented on the tall sacaton grass around the cienegas. As late as 1887 a proposal was made to tap the surplus water by means of a ditch and convey it to Tucson for irrigation use. On the uplands, as well as the bottomlands along Pantano, mesquite seems to have existed well before 1880.

According to customary usage, "Pantano Wash" gives way to "Cienega Creek" above the junction of the main stream with Mescal Arroyo. "Cienega Creek" prior to 1880 flowed for most of its length above the point where its valley widens, some 7 miles south of Mescal Creek. Then, as now, the quantities of native grasses made the Empire Valley a "stockman's paradise." The tradition persists locally that there has been a marked mesquite invasion in the valley in recent years. Historical documentation is too inadequate either to refute or to support the contention.

Even under the conditions that existed prior to 1880 flooding must

Table 2.--Monthly and annual discharge, in acre-feet, of Rillito Creek near Tucson, Ariz.

Water year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	The year
1909	0	0	5,760	168	204	128	0	0	0	6,000	10,220	5,520	28,000
1910	0	0	0	110	0	0	0	0	100	1,100	3,150	150	4,610
1911	0	0	0	2,020	0	300	0	0	0	1,650	4,290	3,030	11,290
1912	0	0	0	0	0	3,740	25	0	0	3,000	5,000	0	11,760
1913	300	0	0	0	420	650	0	0	0	50	200	30	1,650
1914	0	0	0	1.2	821	0	0	0	12	2,470	2,910	2,590	8,800
1915	500	1,360	60,000	21,370	25,450	10,090	1,210	4,240	0	5.0	0	0	120,000
1916	0	0	0	37,060	2,200	3,600	58	0	0	910	7,770	686	52,280
1917	28	0	0	900	272	7.9	0	0	0	5,070	2,850	638	9,770
1918	0	0	0	0	6.9	7,760	0	1,000	483	144	6.7	0	9,400
1919	38	7.9	4.0	12	827	329	662	0	0	30,750	4,120	462	37,210
1920	0	2,350	2,750	4,430	11,630	2,280	555	0	0	0	2,000	30	26,020
1921	0	0	0	0	0	0	0	0	0	25,980	16,150	365	42,500
1922	18	0	0	232	0	0	0	0	105	208	1,870	595	3,030
1923	0	0	0	0	0	0	0	0	0	2,510	4,100	61	6,670
1924	0	335	5,160	87	0	2.0	177	0	0	0	0	0	5,760
1925	0	0	0	0	0	0	0	0	0	708	1,510	2,500	4,720
1926	0	2.0	0	0	0	192	583	0	0	141	52	974	1,940
1927	32	0	71	194	1,490	1,260	0	0	0	38	198	1,300	4,580
1928	0	0	0	0	0	0	0	0	0	397	837	50	1,280
1929	10	0	0	0	0	0	0	0	40	1,840	6,980	17,950	26,820
1930	0	0	0	0	0	3,350	0	0	153	3,150	3,250	688	10,590
1931	0	0	0	0	5,490	109	0	0	18	32	6,280	125	12,050
1932	79	2,390	1,280	403	5,230	1,660	0	0	0	3,600	192	0	14,830
1933	448	0	0	2.0	228	137	0	0	0	40	127	666	1,650
1934	282	0	0	0	0	0	0	0	0	662	895	260	2,100
1935	0	0	16	1,440	3,560	793	0	0	0	373	7,940	4,150	18,270
1936	0	24	0	258	902	0	0	0	0	272	2,130	16	3,600
1937	0	0	2.0	0	3,040	383	0	0	0	184	770	67	4,450
1938	0	0	0	0	0	1,880	0	0	60	83	470	4.0	2,500
1939	0	0	0	0	0	0	0	0	0	1,740	5,090	48	6,880
1940	4	2	0	2	262	0	0	0	446	24	7,100	516	8,360
1941	0	161	12,780	2,740	4,430	6,980	0	0	0	159	1,850	645	29,740
1942	0	2.0	734	468	331	248	0	0	0	0	250	139	2,170
1943	0	0	0	0	0	609	0	2	0	0	1,720	270	2,600
1944	0	0	0	0	0	0	12	0	0	734	2,360	83	3,190
1945	28	56	0	0	73	305	0	0	0	450	2,970	6.0	3,890
1946	71	0	0	4.0	0	0	0	0	0	422	2,470	69	3,040
1947	135	65	0	0	0	0	0	0	0	2.0	3,770	147	4,120
1948	0	14	0	0	0	0	0	0	0	244	427	274	959
1949	0	0	524	1,290	1.8	7.9	.4	0	0	64	259	770	2,920
1950	0	0	0	0	0	0	0	0	579	6,340	339	0	7,260
1951	0	0	0	0	0	0	0	0	0	2,260	1,880	0	4,140
1952	264	1,180	528	2,080	0	1,860	115	6.9	0	53	65	0	6,160
1953	0	0	0	0	0	13	0	0	0	1,730	0	0	1,740
1954	0	0	0	0	0	6,420	0	0	37	3,670	1,760	1,150	13,040
1955	0	0	0	0	0	0	0	0	0	3,870	8,430	0	12,300
1956	18	0	0	26	0	0	0	0	0	257	14	0	315
1957	0	0	0	2,760	186	54	0	12	0	45	1,020	137	4,210
1958	282	230	36	0	79	6,580	278	0	0	1,320	2,430	29	11,260

have occurred as part of the normal regime of the Tucson basin. Because no well-defined channel existed, however, the water evidently spread out in a shallow sheet across the valley floor, doing relatively little damage.

The first disastrous recorded flood came in August 1880, when Pantano Wash destroyed several sections of the Southern Pacific Railroad track. In 1885 a similar flood wrecked 6 miles of track, and the Rillito for a time became unfordable. In 1887 a flood "fully fifteen feet in depth" coursed down Cienega Creek, drowning numerous cattle. Through July and August of that year intermittent flooding continued, culminating September 11, 1887, in a torrent which destroyed bridges across the Rillito and caused water to stand "two miles wide" in the valley north of Tucson.

These floods on Rillito Creek and its tributaries, like those on the Santa Cruz River during the same years, seem to have indicated a transition between past and present conditions. The runoff pattern had evidently changed; at the same time, river channels had not yet accommodated themselves to the new loads by trenching. The earliest channel cutting that can be documented occurred on the Rillito immediately prior to August 5, 1890. The parallel to conditions along the Santa Cruz is striking; the channel trench along the latter stream began forming August 4, 1890.

Kirk Bryan (1925), drawing heavily on a study by Smith (1910), summarizes the story as follows:

> The valley of Rillito Creek...was...an unbroken forest of mesquite in 1858, when the first settlement was made. Between the trees was a good growth of grass and the river course was indefinite and lined by an almost continuous growth of cottonwood, ash, walnut and willow trees. These conditions continued until 1872, when the United States Army post was moved from Tucson to Fort Lowell on the Rillito largely because natural grass could be cut for hay. Thereafter the Rillito cut a wide channel from ten to fifteen feet deep.

The adjectives "unbroken", "indefinite", and "almost continuous" are perhaps questionable. Otherwise, the descriptive material can be confirmed--at least generally--by historical evidence. However, any direct relationship as that postulated between the relocation of Lowell and the trenching of Rillito Creek must be strongly questioned. Old Fort Lowell, 7 miles away, also had horses to feed and grass to be cut. The move, at best, would have affected only a few additional of the 918 square miles in the Rillito drainage area.

Even more important, strikingly similar processes of change were going on at the same time in the more general areas of the Santa Cruz basin and, with some modifications, in the San Pedro basin. Far from being merely local, the fundamental determinants of erosion and ecological change along the Rillito Creek appear to have been wider--perhaps even regional in extent.

A summary of all available streamflow records in Rillito Creek is presented in table 3. Average annual runoff at the various stations was computed for the periods shown to provide comparisons between records for comparable periods. The discharge from 35 square miles of Sabino Canyon drainage area is a little more than the discharge of Rillito Creek from its entire 918

Table 3.--Summary of streamflow records available in Rillito Creek drainage

Gaging station	Drainage area (sq.mi.)	Records available	Runoff, in acre-feet Avg. 50 yrs. 1908-58	Avg. 26 yrs. 1932-58	Avg. 6 yrs. 1952-58	Total for period
Rillito Creek near Tucson	918	Oct. 1908-Sept.1958	12,310	6,180	7,150	----
Sabino Creek near Tucson	35.5	July 1904-June 1912	----	----	----	----
		July 1932-Sept.1958		6,230	7,530	----
Sabino Creek near Mt. Lemmon	3.19	May 1951-Sept.1958	----	----	941	----
Rincon Creek near Tucson	44.8	Oct. 1952-Sept.1958	----	----	2,950	----
Atterbury Reservoir near Tucson	18	Jan. 1956-Dec. 1958	----	----	----	807
Rillito Creek near Wrightstown	221	June 1940-Dec. 1946	----	----	----	
Pantano Wash near Tucson	602	June 1940-June 1941	----	----	----	6,760

square miles. Records from other stations within the basin tend to confirm that the basin potential is greater than shown by the records of Rillito Creek near Tucson.

Most of this discharge is floodwater produced by summer cloudbursts causing high flows of short duration. Only a part of it is the result of snowmelt from the high altitudes. Flood peaks resulting from storms in the upper part of the basin may be wholly or partially dissipated before they reach the mouth of Rillito Creek. The reduction in peak discharge is caused by temporary channel storage or by channel retention. Channel storage results from filling of the channel with water. It causes a lag of time in the travel of the flood wave, but it does not create a loss of total flow. Channel retention, which is caused by sponging up of water by porous material in the channel, causes a reduction in total flow.

A striking example of reduction of flood peaks occurred during the flood of August 12, 1958, on Pantano Wash near Vail. The peak of 40,000 cfs was reduced to 8,930 cfs at the Rillito Creek gaging station, 29 miles downstream. Another example is illustrated by figure 6. A peak of 2,250 cfs and total runoff of 226 acre-feet passed the Sabino Creek gaging station on July 7, 1950. The same rise with presumably no tributary inflow reached the Rillito Creek gage 5 hours later. The peak had been reduced to 310 cfs and runoff for the ensuing 13 hours was only 42 acre-feet.

It is possible to use available discharge records to approximate the unit runoff from various parts of the basin. Records from Atterbury Wash show annual runoff from the basin floor as 16 acre-feet per square mile. Rincon Creek has average annual runoff of 66 acre-feet per square mile, while that of Sabino Creek is 212 acre-feet per square mile. These records cover the extremes of runoff that may be expected in the basin. By interpolating between these unit runoff values and applying values so determined to the drainage area of each section, it is possible to estimate the total inflow to Rillito Creek. As shown in table 4, this inflow for the period 1952-58 averaged 38,220 acre-feet annually. During the same period only 7,150 acre-feet discharged past the Rillito Creek near Tucson gaging station as surface flow out of the basin. The areas listed in table 4 are delineated in figure 7.

It must be emphasized that the figures of inflow are estimates and as such are subject to large error. This stresses the need for additional gaging-station records to provide a more accurate determination of the basin potential. However, it is certain that the basin potential of Rillito Creek is considerably greater than is shown by records of outflow from the basin.

Most of the water in Rillito Creek results from heavy storms over the basin. Although these floodwaters could supplement the groundwater reserves if they could be captured and utilized, they also present a definite hazard in their present uncontrolled state. Since 1915, the greatest flood on Rillito Creek near Tucson was 24,000 cfs on September 23, 1929. How this compares with some of the earlier floods of 1880, 1885, and 1887 is not known. The description of water standing "two miles wide" north of Tucson at the culmination of the 1887 flood indicates that it must have exceeded the 1929 flood considerably. Without control, such a flood can recur and, with encroachment of the flood plain by residential development and as a result of deterioration of the channel, recurrence of a flood of similar magnitude to that of 1887 could create a disaster.

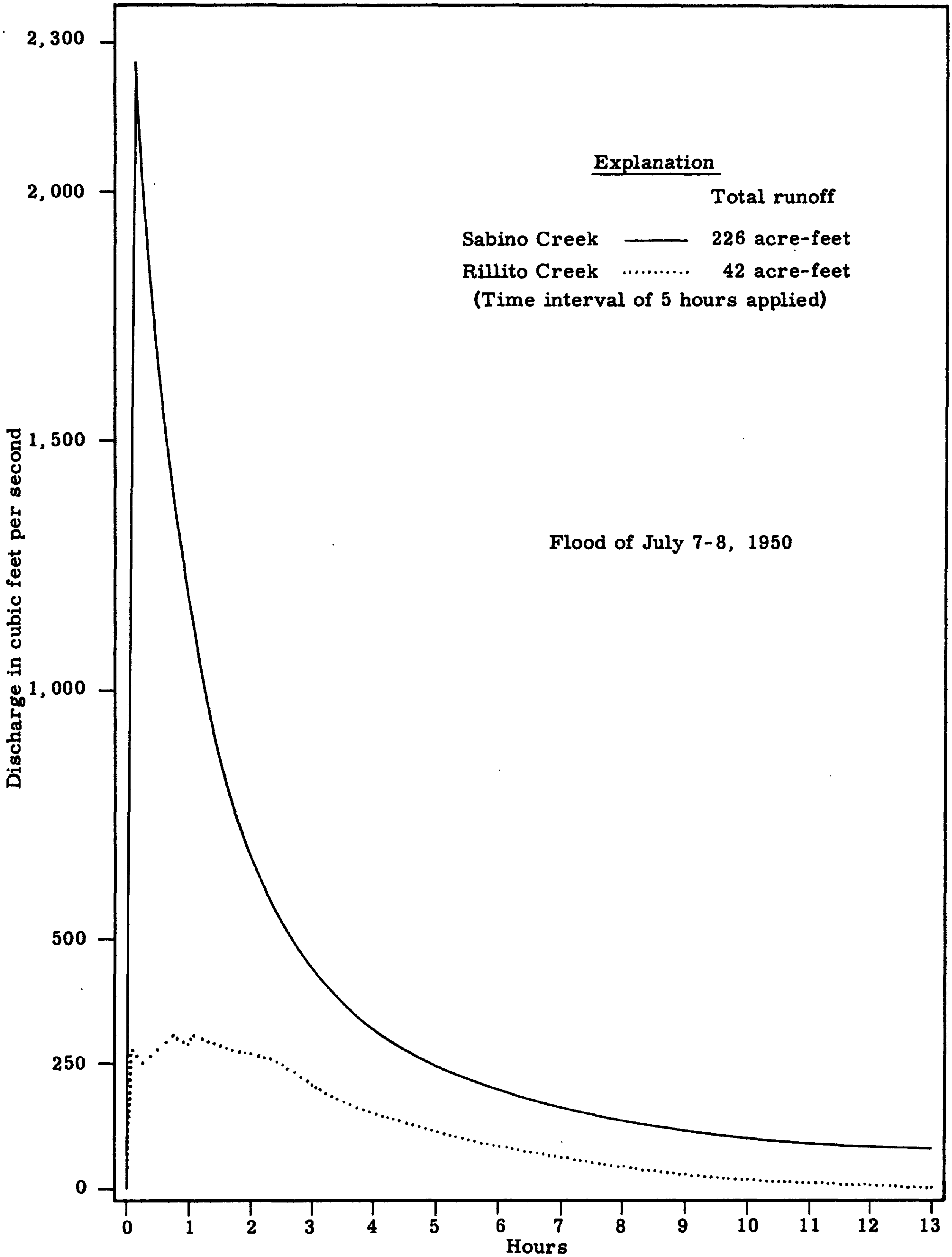

Figure 6.--Streamflow depletion between Sabino Creek and Rillito Creek at Oracle Road bridge.

Table 4.--Tributaries and their estimated inflow into Rillito Creek drainage

Tributary	Drainage area (sq.mi.)	Average runoff in acre-ft. per sq. mi. 1952-58 (estimated)	Average runoff of tributaries in acre-ft. 1952-58 (estimated)
S. Slope of Catalina Mts.	60.8	50	3,040
Sabino Creek at gage	35.5	a/212	a/7,530
Bear Canyon at mouth	16.6	200	2,490
Sabino Creek below Bear Canyon	20.0	30	600
Agua Caliente & Tanque Verde W.	140.0	50	7,000
East Bank of Pantano Wash No. 1	22.4	16	360
S. Slope Tanque Verde Ridge	25.4	16	410
Rincon Creek at gage	44.8	a/66	a/2,960
East Bank of Pantano Wash No. 2	32.0	16	510
Agua Verde Creek at mouth	37.9	50	1,900
Tucson Urban	25.0	25	620
Cienega Creek near Vail	418.6	30	10,460
West bank of Pantano No. 3	b/21.0	16	340
Total contribution from tributaries	918.0		38,220
Rillito Creek at gage	918	a/7.8	a/7,150

a/ Based on gaging station records.

b/ Does not include 18 sq. mi. comprising Atterbury Reservoir drainage area.

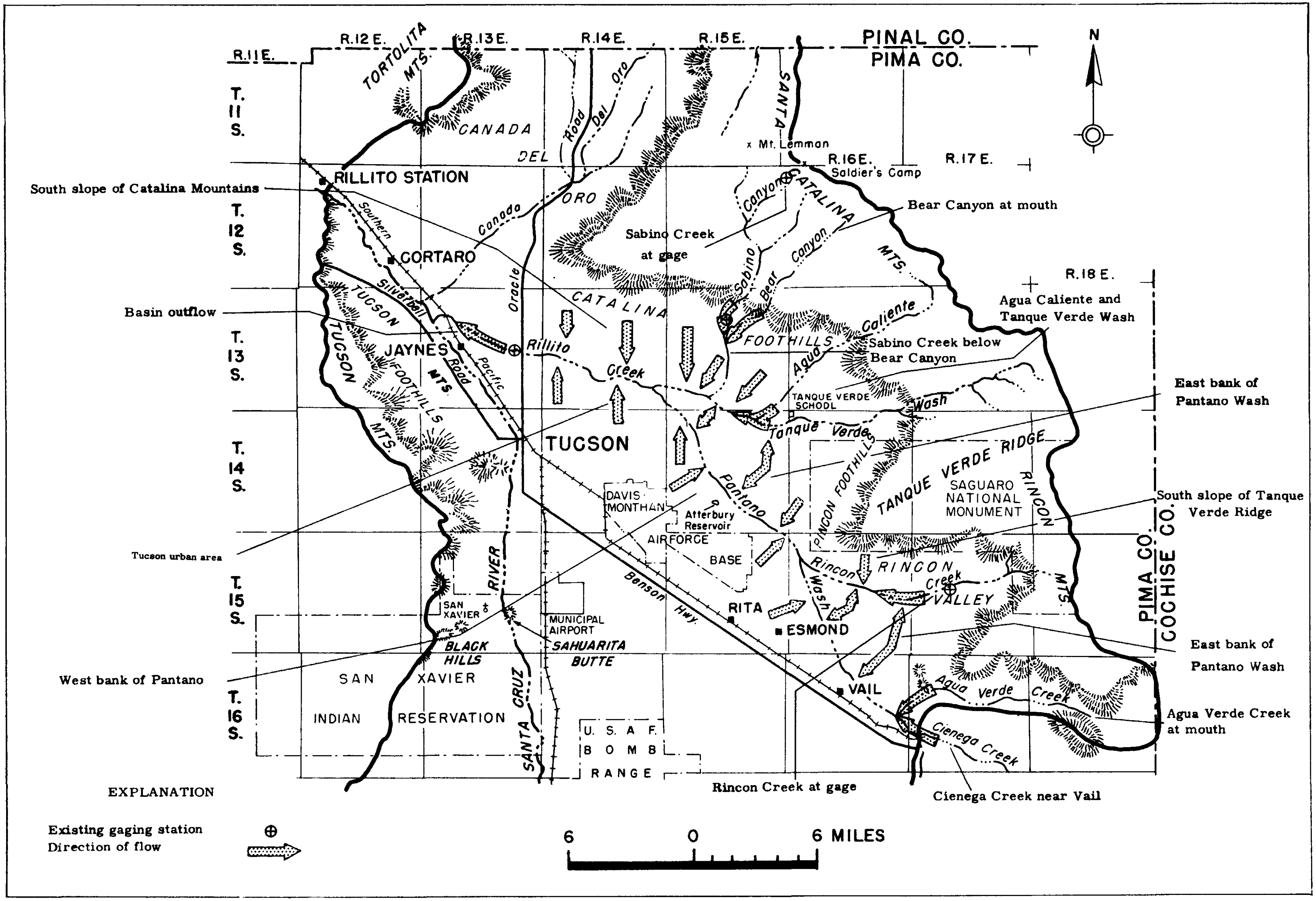

Figure 7.--Surface inflow and outflow of Rillito Creek drainage.

Through the use of Gumbel plotting, a device used by many hydrologists, the maximum annual floods since 1915 are portrayed in figure 8. The mean annual flood is determined as 6,000 cfs. According to this plotting, a flood of 24,000 cfs can be expected to recur on the average of about once every 50 years.

Sediment Content of Floodwaters

The capture of water in arid lands requires that knowledge be obtained on the transport of sediment by floodwaters. Salvage of presently wasted floodwaters would involve the problem of sediment removal. Information concerning the sediment load carried by Rillito Creek and its tributaries is almost completely lacking. However, observation of floodflows reveals that there is wide variation in the amount and the physical character of sediment transported. The following factors are particularly important in their effect upon the sediment load: (1) geologic and textural character of the soil surface in the source area; (2) amount and type of vegetative cover in the source area; (3) physiographic and topographic character of the source area; (4) stream channel condition and character of streambed material; (5) storm characteristics---intensity, duration, and areal extent; and (6) discharge peaks and variation in flow as shown by the shape of flood hydrographs.

It is important that studies be made that will provide sufficient information to permit an appraisal of engineering feasibility and probable cost of the treatment of floodwaters for recharge, or to determine the approximate life of a storage reservoir.

The sediment content of floodwaters resulting from the short, intense summer rainfall on desert areas is known to be relatively high. This is particularly true when stream-bank undercutting and headward erosion of the stream channels occur. Floodflows from Pantano Wash, the principal tributary of Rillito Creek, have long been distinctive for their dark color and high silt content as compared to the flow from other tributaries.

Open-bottle samples from three floods with estimated discharge of 400 to 1,000 cfs in the Pantano Wash ranged in silt content from 3.9 to 5.4 percent, and averaged 4.2 percent (J. E. Fletcher, 1959, oral communication). The estimated maximum velocity was slightly more than 9 feet per second. Samples collected in a similar manner from floodflows in the Santa Cruz River had sediment contents of as much as 4 percent. In comparison with the relatively high sediment content in these two streams, the following results were obtained from samples collected from a floodflow eminating from Sabino Canyon on March 22, 1958:

Location of sampling	Percent of sediment
Sabino Road Bridge on Rillito Creek	0.0004
Dodge Blvd. Bridge on Rillito Creek	0.023
Oracle Road Bridge on Rillito Creek	0.084
Cortaro Road Bridge over Santa Cruz River	0.100

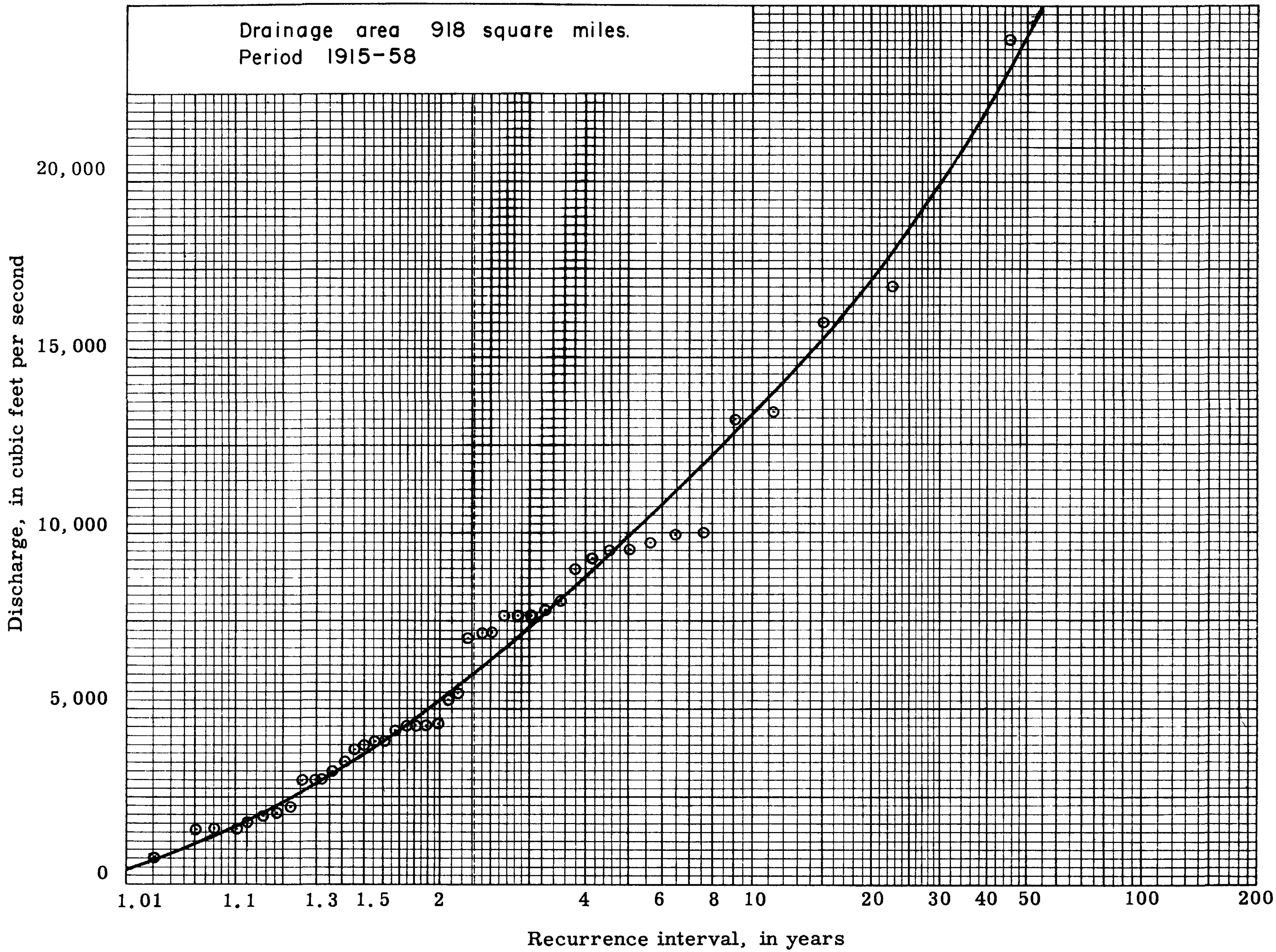

Figure 8.--Annual floods of Rillito Creek near Tucson, Ariz.

The samples indicate that as the flow, which amounted to about 750 cfs, issued from the canyon mouth the silt content was negligible but that it progressively increased as a sediment load was picked up from the stream channel of Rillito Creek and the Santa Cruz River.

A comparatively large number of open-bottle silt samples have been collected from the San Pedro River at Charleston over a period of years by the U. S. Geological Survey for the Agricultural Engineering Department, University of Arizona. A correlation of sediment content with discharge is shown in figure 9. The points show rather wide variation from the curve but represent average conditions. The sediment content increases with discharge in the lower range and levels off at about 5 percent. It is believed that sediment contents of floodflows from Pantano Wash will show an equally wide variation in relation to discharge, as conditions in the drainage area are somewhat comparable to those on the San Pedro River above Charleston. Mechanical analysis of suspended sediment samples and correlation with streambed and channel conditions should permit an estimate of the total sediment load.

The computation of the dry weights of the sediment collected or stored in reservoirs vary considerably, depending upon the mechanical analysis of the sediments and even upon the composition of the clay fraction, as well as the conditions under which the storage takes place --that is, under water continuously, or alternately submersed and exposed to the atmosphere. For example, the density of the Lake Mead sediment has been determined to be 65 lb. per cu. ft., and those in the Roosevelt and San Carlos Reservoirs estimated at 70 lb. per cu. ft. (Interagency Committee on Water Resources, 1957).

Quality of Floodwaters

Although floodwaters from mountain canyons have not been analyzed chemically, it is certain that those in granitic or gneissic areas have an extremely low content of soluble salts and should be classed as soft waters.

Floodwaters from rainfall on the valley slopes within the Tucson basin, and those entering the area in Pantano Wash, may be expected to have a salt content of several hundred parts per million. No chemical analyses of these floodwaters are available, but the waters may be comparable in quality to those sampled from the San Pedro River at Charleston. These waters average about 300 ppm (parts per million) in total soluble salts and have an average hardness of about 130 ppm. A few samples have been collected from the Atterbury Reservoir and stock ponds in this drainage area. They have an average soluble salt content of about 160 ppm and a hardness of 98 ppm.

A sample representative of the base flow of Cienega Creek at a point where it enters the Tucson basin had a total soluble salt content of 875 ppm and a hardness of 368 ppm. This is effluent ground water from an area with considerable limestone and gypsum deposits.

Soils

The available soils data on the Tucson basin and vicinity are as follows:

1. A detailed soil survey of the Tucson area was made by the Bureau of Chemistry and Soils, U. S. Department of Agriculture (Youngs and others, 1931). The report covers parts of the Santa Cruz River and

Rillito Creek, the area designated "A" on figure 10.

Detailed descriptions of the soils in the area mapped are given in the above report. In general, the soils represent two broad groups: (1) the older upland soils, which have a very definite accumulation of lime or caliche in the subsoil, such as the soils of the Pinal series; and (2) those on the more recently deposited stream-bottom lands or lower alluvial fans, such as the soils in the Gila and Pima series, most of which are mellow and friable throughout and lack a very definite horizon of lime accumulation. In the Pima series, however, the subsoil is rather heavy in texture and somewhat compact and tough in places.

The stony or gravelly alluvial fans, which have been badly cut by erosion, are underlain by subsoil material that is highly calcareous and more or less firmly cemented.

2. Data were obtained from detailed soil surveys of areas designated "B" on figure 10. The data from these surveys made by the Soil Conservation Service, U. S. Department of Agriculture, since 1931 are available in its Tucson office.

3. Data from a 1936 soil survey made by the Soil Conservation Service also are available at its Tucson office. The areas covered by this survey are designated "C" on figure 10.

4. Data from a range site and condition survey, collected by the Soil Conservation Service, are available at its Tucson office. The areas covered by these surveys (which are complete only for small parts of the Rillito drainage basin) are designated "D" on figure 10. This type of survey includes taking sufficient soil borings to determine surface and subsurface soil types, noting land-use practices, estimating slopes and amounts of erosion, and noting vegetative cover.

Range site and condition surveys are being continued by the Soil Conservation Service upon requests from ranchers. However, there are no surveys being made or pending at the present time in the Rillito drainage basin above Vail.

Evaporation

As the Tucson basin study is chiefly concerned with the total water budget, evaporation from surfaces of soil (including streambeds), water, vegetation, snow, and ice must be considered. In fact, evaporation plays an important role in the hydrologic cycle in that it generally accounts for a large part of the water lost, especially in semiarid and arid regions.

The factors controlling evaporation are known, but an accurate quantitative analysis of the relative effectiveness of each is difficult because of their interrelations (Linsley, Kohler, and Paulhus, 1949). The following factors have to be considered:

1. Vapor-pressure differences. The rate of evaporation depends on the difference between the vapor pressure of the water and the saturation vapor pressure in the air above the water surface.

2. Temperature. The rate of emission of molecules from liquid water is a function of the temperature--the higher the temperature, the greater the rate of emission.

3. Wind. There is a relation between evaporation and wind movement, but its exact nature has not been determined.

4. Atmospheric pressure. Evap-

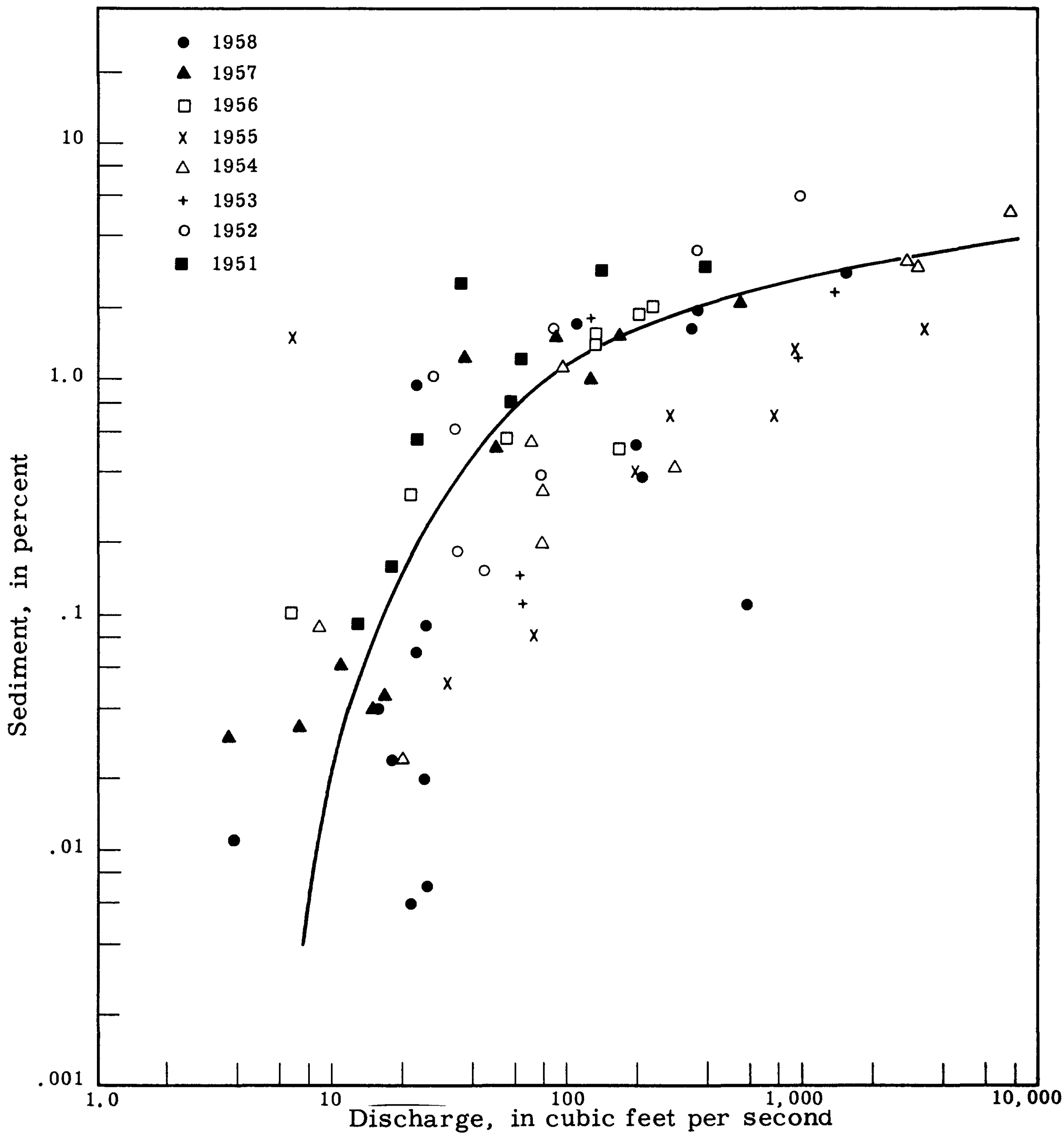

Figure 9.--Sediment rating curve, San Pedro River at Charleston, Ariz.

oration decreases as atmospheric pressure increases.

5. Quality of water. Evaporation decreases as the specific gravity increases.

The above factors affecting evaporation as discussed apply chiefly to a free-water surface. Evaporation from soil, vegetation, snow, and ice is affected by these same factors but requires special consideration.

An important factor affecting the volume of evaporation from a soil surface is the evaporation opportunity, or the availability of water. As long as the soil surface is saturated, the evaporation rates are probably not greatly different from those which would be observed from a water surface at the same temperature. However, if the soil surface is not saturated, the rate of evaporation is limited by the rate at which moisture is transferred to the surface from below, even though existing meteorological conditions might favor a greater rate.

A part of all precipitation is temporarily retained on the exposed surfaces of vegetation. The water thus retained is returned to the atmosphere by evaporation. Like evaporation from the soil, this loss is greatly dependent on the evaporation opportunity.

The evaporation opportunity from both snow and ice is practically 100 percent, and the rate of evaporation is substantially the same as the evaporation from shallow water.

A number of different methods have been utilized for measuring water transfer to the atmosphere (Bernard and others, 1949). These may be grouped into the following four distinct approaches to the problem.

1. The amount of water lost from a container, whether it be a lake or a pan, is measured. As evaporation from free-water surfaces in pans is greater than from adjacent water bodies, an adjustment is required to estimate evaporation from lakes on the basis of nearby pan measurements.

Attempts have been made to determine evaporation from natural soils and from snow by exposing samples in small pans and determining their loss in weight. Such exposures are probably no better index to evaporation from snow or soil in place than the measured loss from an exposed water surface.

2. The vapor-pressure gradient for the determination of the flow of moisture through a layer of the atmosphere above the evaporating surface is measured. The above basic data and wind velocities are used in formulas for computing evaporation.

3. Heat-budget analysis, which requires a measurement of net radiation, heat transfer by soil conduction, and air temperature and vapor-pressure gradients above the surface, will account for the fraction of solar energy used hourly or daily for evaporation or evapotranspiration. Hence the water loss at the earth's surface can be estimated with good accuracy from the disposition of energy at the earth-air interface (Suomi and Tanner, 1958).

4. The changes of moisture in soils and streambeds following rainfall on the area or changes of flow in the stream channels are measured. These changes in soil moisture can be measured by weighing soil samples before and after heating; or by using bouyoucos blocks in the lower ranges of moisture and tensiometers in the higher ranges near the field capacity; or by the neutron method, in which a measurement is made of the number of hydrogen nuclei present per unit volume of soil.

P 26 IS BIG SIZE

For an estimate of the evaporation from free-water surfaces in the basin, the evaporation data from the U. S. Weather Bureau Class A Land Pan at Tucson could be used. The average yearly evaporation for the period 1928-58 at this station was 87.8 inches; this, of course, far exceeds the average rainfall of 10.8 inches at this same station. Figure 11 shows the relation of evaporation to temperature for the station at Tucson, and figure 12 shows the moisture deficiency of the basin created by the evaporation potential.

There are no data available for the Tucson basin regarding evaporation from surfaces of snow, ice, and vegetation; however, available data from other areas could possibly be adapted for use in making rough estimates of the evaporation from the basin.

Vegetation

Vegetation within the Tucson basin ranges from Sonoran desert flora at low altitudes on the valley floor to pine-fir forested areas on the mountain tops. Prior to development by pumping, mesquite forests and cottonwood groves, together with batamote, were the predominant types of vegetation on the bottom lands adjacent to stream channels. Creosote bush, cacti, paloverde, mesquite, and desert shrubs with some grasslands are found on the valley slopes. Oak, juniper, piñon pine, and grasslands occupy the lower mountain slopes and pine and fir are at the higher altitudes.

Vegetation types are closely correlated with temperature and precipitation, and within the drainage basin these are directly related to altitude. Table 5 lists the predominant types, the altitudes in which they are commonly found, and the approximate acreages of each in that part of the drainage basin north of Cienega Creek.

Table 5.--Vegetation in the lower Rillito drainage area

Type	Altitude (feet)	Area sq. miles	Percent
Creosote bush, cacti, desert shrubs, and grasses; mesquite, cottonwood, and other trees along stream channels and on bottom lands..............	2,000-3,000	148	32
Cacti, paloverde, desert shrubs, and grasses..............	3,000-4,000	152	33
Grasses, and some chaparral......	4,000-5,000	69	15
Oak, piñon pine, juniper, and grasses......................	5,000-6,300	37	8
Arizona pine and Douglas fir......	6,300-9,000	55	12
		461	100

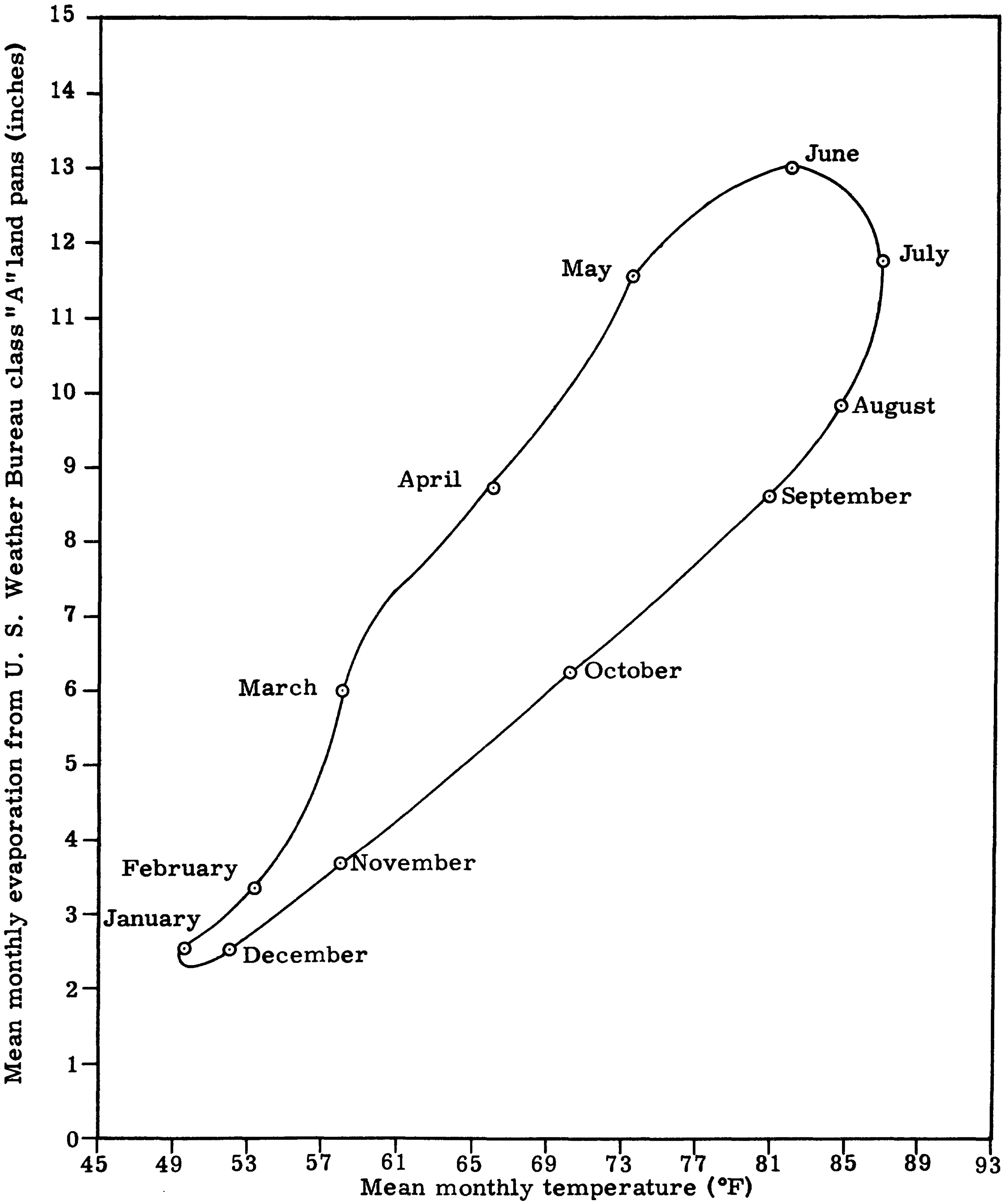

Figure 11.--Relation of evaporation to temperature, Tucson, Ariz., 1928-58.
(Based on U. S. Weather Bureau data)

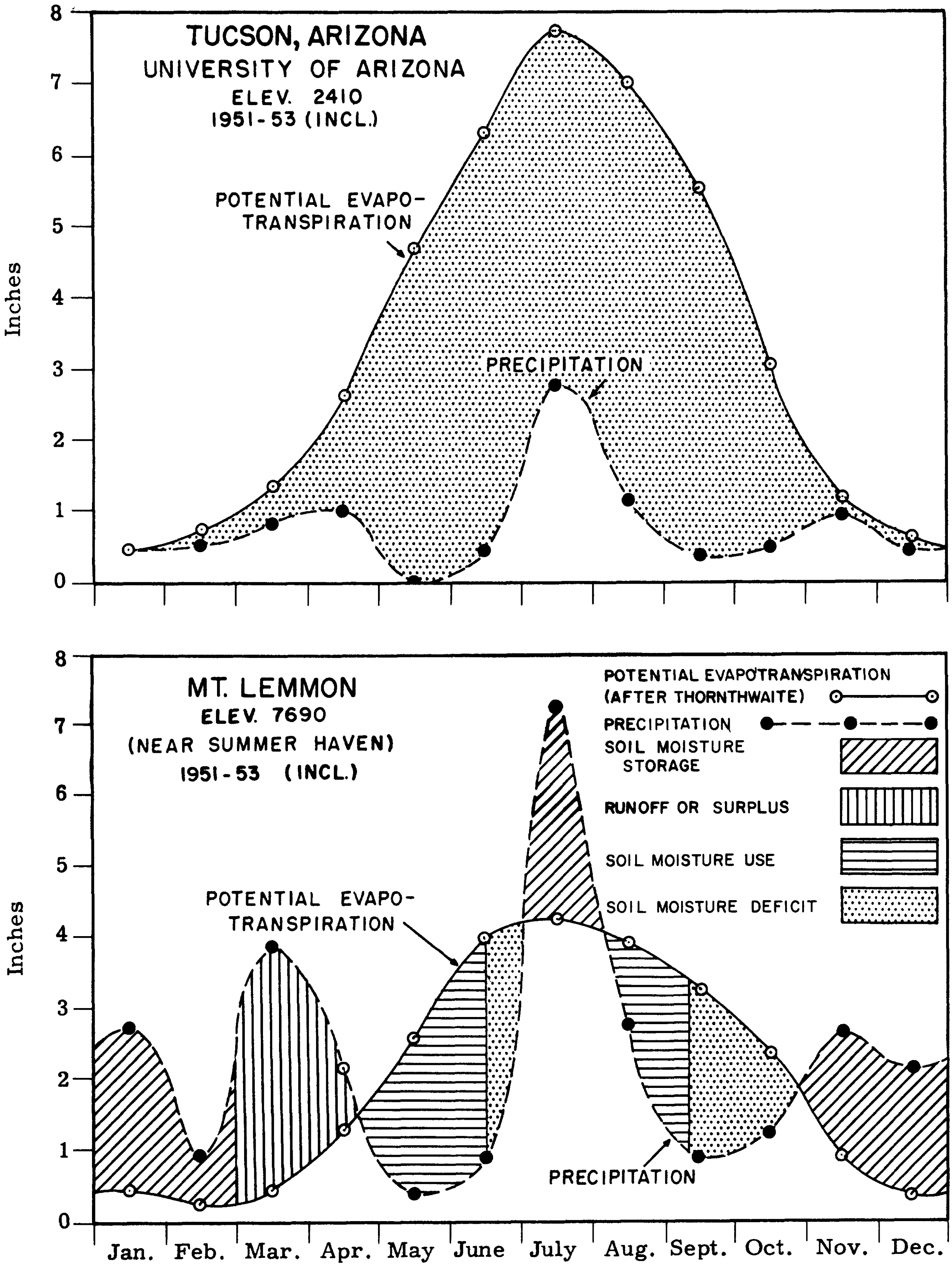

Figure 12.--Precipitation and potential evapotranspiration at Tucson and Mount Lemmon.

The average annual rainfall ranges from about 10 inches at Tucson to about 35 inches in the Catalina Mountains at an altitude of 8,000 feet (Schwalen, 1942). The small water yield from the drainage area is due to the large excess of potential evapotranspiration over precipitation (Thornthwaite, 1948).

Planned control of vegetation

The increase in water yield that could be expected of vegetation manipulation on the watershed (phreatophytes excepted), assuming such manipulation feasible for an area of high recreational value, probably would be small. In the lower areas the potential evapotranspiration-precipitation ratio is very high and little gain in available water could be expected from changes in density and composition of vegetation. The greatest gain could be expected in the pine-fir zone, but the area is small, the stands are relatively open, and the soil is thin and coarse textured. In addition, much of the area is extremely steep and rocky. These conditions suggest that (1) the surface runoff-soil moisture-storage ratio would be high and (2) the total soil moisture-storage capacity would be low. Under such conditions, changes in vegetation probably would have a relatively small effect on water available for streamflow.

Areas of phreatophytes

The shallow water-table areas within the drainage basin are limited to the bottom land along Rillito Creek upstream from about 2 miles west of the junction with Pantano Wash, the Tanque Verde Wash and narrow strips along lower Sabino and Esperero Canyons, and the Agua Caliente Wash. Esperero Canyon and Agua Caliente Wash maintain free water-table conditions only after wet periods, and function as phreatophytic areas only during these periods. Figure 13 shows the cleared and irrigated acreages, overflow areas, and phreatophytic areas within the basin. The total acreage in each of these classifications is as follows: cleared or cultivated, 1,850 acres; sandy overflow areas, 250 acres; and phreatophytes, 2,750 acres.

In general, the water table within the areas shown on the map (fig. 13) ranges in depth from somewhat less than 10 feet during wet periods to a maximum of 30 feet at the end of dry periods. The average water level is about 20 feet. The direct draft by phreatophytes from the ground-water reservoir probably does not average much more than 1 acre-foot per year. The total amount of water which might possibly be salvaged from this area is further limited by the rather intensive suburban development in that area, and the fact that the native vegetation in the form of mesquite growth, cottonwood trees, and sycamores in the lower canyon reaches is considered by many to be highly beneficial. The present draft upon the ground-water reservoir in this area by phreatophytes may be estimated at roughly 2,500 acre-feet per year.

Natural Recharge of Ground Water

It is evident from the effects of pumping draft upon the Tucson basin ground-water reservoir that only a small percentage of the rainfall on the drainage area is recharged to ground water. By far the greater part of it is lost by evaporation from the soil and vegetative surfaces or, subsequently, by evapotranspiration. That part of the precipitation which finally becomes a part of the main body of ground water comes principally from the following immediate sources (Schwalen and Shaw, 1957): (1) direct infiltration from rainfall; (2) ground-water movement into the basin as underflow; (3) seepage from irrigated lands; and (4) seepage from stream

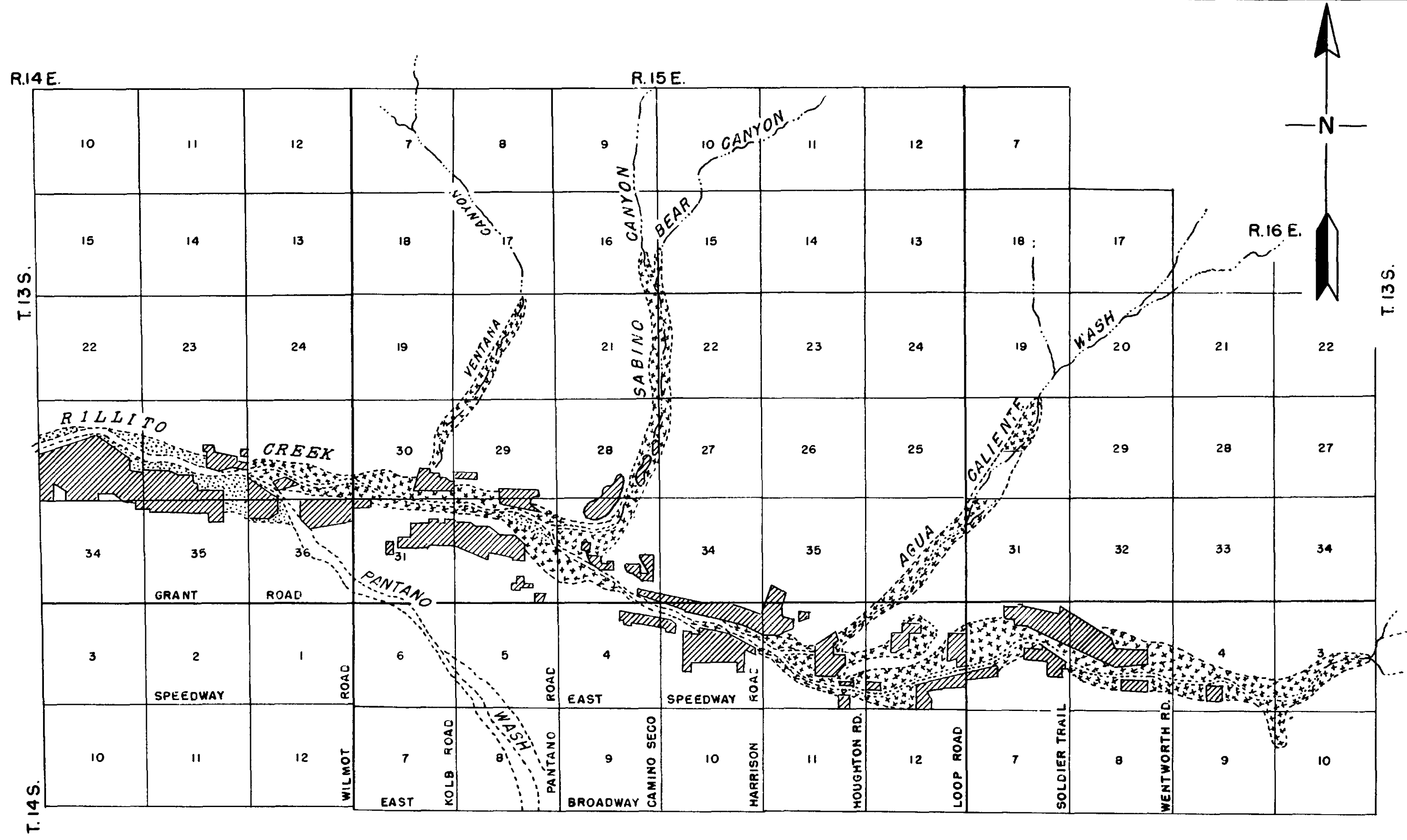

FIGURE 13.--AREAS OF PHREATOPHYTES WITH SHALLOW WATER TABLE ALONG RILLITO CREEK.

AGRICULTURAL ENGINEERING DEPARTMENT UNIVERSITY OF ARIZONA
1959

1 0 1 2
Scale in Miles

LEGEND

- PHREATOPHYTES- MOSTLY MESQUITE COTTONWOOD AND SYCAMORE.
- SANDY OVERFLOW AREAS- MOSTLY BATAMOTE AND SMALL GROWTH.
- CLEARED OR CULTIVATED AREAS.

channels.

Direct recharge to the water table from precipitation is of no importance (Turner and others, 1943). An exceptional rain of 2 inches upon the normally dry desert floor and slopes is sufficient to wet the soil only to a depth of a foot or two. At the end of a long rainy period, and then only under the most favorable conditions for infiltration, the soil will be wet only to a depth of a few feet. Rarely does rainfall upon the valley floor penetrate to a depth below the root zone of native vegetation or wet the soil beyond the depth from which it will be captured by surface vegetation.

Significant, but limited recharge from rainfall does occur through the fractures in the rocks at the base of the mountains and also in some areas of coarse, open detrital outwash adjacent to the mountain base. The generally impermeable character of the mountain rock formations precludes any appreciable movement of ground water from the mountain areas down to the ground-water reservoir.

The determination of ground-water movement into the basin as underflow is normally difficult. Fortuitously, an accurate measurement of underflow into Pantano Wash near Vail has been accomplished. Here a concrete arch dam, anchored to bedrock on bottom and sides, has been placed across a narrow gorge. This barrier causes essentially all the underflow to come to the surface where it is measured. The underflow at this point, water recharged from 460 square miles of surface area, amounts to less than 1,000 acre-feet per year.

Seepage or deep percolation losses from irrigated land and ditches is actually the recirculation of ground water, but it is a source of return flow in the immediate area of use. It may amount to as much as 25 percent of total pumpage, and in permeable soils may be even more. It must be considered in any ground-water inventory, but it does not increase the available water supply by its full amount because of gradual deterioration in quality.

Infiltration from stream channels during periods of flow is the major source of recharge in Rillito Creek. During the winter months some streams such as Sabino Creek and Tanque Verde Wash may flow for long periods of time. Much of this water is retained by the sandy stream channels after leaving the crystalline complex, and wells along lower Rillito Creek may reflect the recharge. However, this is a shallow ground-water reservoir and some of this recharge must be considered temporary, as it will be evaporated or used by native plants.

SUBSURFACE WATER SUPPLIES

Geology

The deposits of the Tucson basin, particularly in the Rillito drainage area, do not extend to the foot of the adjacent mountain front. The area between the Pantano-Rillito drainage and the mountain front is, for the most part, an erosion surface cut on indurated rocks and thinly covered by alluvial outwash on the ridges, by inner-valley fill within tributary arroyos, and by alluvial fans adjacent to the mountains (fig. 2). The alluvial outwash may be a part of the fans, and it is included with them on the map. The rocks underlying the Catalina foothills area, north of Rillito Creek, are mostly the Pantano beds. Between Pantano Wash and the Rincon-Tanque Verde front, the rocks include gneiss, tightly indurated sedimentary rocks of either Paleozoic or Cretaceous age, Cenozoic volcanic rocks, and, in some places, Pantano beds.

Between the mountain front and the area occupied by the main part of Tucson, the surface of the crystalline rocks slopes downward so that the Tucson basin deposits are at least several hundreds of feet thick. The relationship between the crystalline complex under the Tucson basin and the shelf along the mountain front is not clearly known. The transition may be a gradual slope, but it is more likely to be an abrupt dropoff. If the transition is abrupt, the exact position of it is not known, but is a dominant feature of tremendous influence on the occurrence, movement, and volume of water in the Tucson basin. Paucity of information on this critical feature is due partly to the lack of detailed study, but more particularly to the fact that Tucson basin deposits and Pantano beds are similar enough in origin and lithology to make it difficult to distinguish between them in well logs. The critical geologic features have been discussed by Moore, and others (1941), Smith (1938), Turner and others (1943), Johnson (in Halpenny, 1952), Voelger (1953), Kidwai (1957), Brennan (1957), and Schwalen and Shaw (1957). Schwalen and Shaw in particular have outlined the general geologic features and their relations to ground-water hydrology.

Rock Units

Crystalline complex

The Catalina, Rincon, and Tanque Verde Mountains consist chiefly of banded, granitic gneiss, and smaller bodies of granite and sedimentary rocks. Other rocks of the mountain mass represent deposits laid down when Precambrian, Paleozoic, and possibly Cretaceous seas covered the area, and some of them have been converted by metamorphism into new types of rocks. Locally, the crystalline complex is fractured and small quantities of water have been produced from the fractured zones. For the most part, however, the crystalline complex forms an impermeable barrier to movement of ground water. Rain and snowmelt form runoff on the mountain slopes, but do not enter the subsurface until the streams enter areas underlain by permeable inner-valley fill.

Pantano beds

The Pantano beds (Moore and

others, 1941) consist of several thousand feet of tightly cemented conglomerate, sandstone, siltstone, and claystone, deposited in a basin or basins of unknown extent, which predate the modern topography. Voelger (1953) assigned three members to the Pantano beds, separated by unconformities and characterized by different compositions. The lower unit contains fragments of Paleozoic limestone and granite, but no Catalina gneiss. The middle unit contains some granite and limestone fragments, and Catalina gneiss. The upper unit contains a high percentage of Catalina gneiss, and is similar in composition to the alluvium in modern streams leaving the mountains, and to the fans along the mountain front.

Voelger's study implies that the lower part of the Pantano beds was deposited when the ancestral Catalina Mountains were uplifted. At that time the cover consisted of Paleozoic sedimentary rocks, and the Catalina gneiss was not exposed to erosion. The presence of rocks similar to the Pantano in the areas south and east of the Rincon Mountains, and the composition of these rocks, suggest that the Pantano was deposited in a basin or basins flanked by mountains which did not necessarily or entirely coincide with the existing ranges.

Brennan (1957) concluded that at least 8,000 feet or more of Pantano beds were deposited in the area south of the Rincon Mountains. As these beds have had older rocks, such as Paleozoic limestone and gneiss, thrust on top of them, the Pantano probably predates the last major structural activity in the area.

Pantano beds are exposed in the Catalina foothills north of Rillito Creek. Figure 14 shows a typical exposure of the Pantano beds in Pontatoc Wash, showing slight tilting and faulting of the beds. The most common rock in this area is red claystone, but all three of the members recognized by Voelger are present. The beds are so well indurated and impermeable that they do not yield water to wells in any appreciable quantities.

The Pantano beds in the Catalina foothills and along the west and south sides of the Rincon Mountains have been steeply tilted and involved in thrust faulting. This means that the beds are related to the crystalline complex of the mountain blocks, as far as the structural, erosional, and depositional history of the area is concerned. The inclination and relationships of the Pantano beds under the center of the Tucson basin are not known. The beds might be present in complicated fault blocks along with other units of the crystalline complex. On the other hand, the floor under the present Tucson basin might coincide in part with the floor of some part of the original Pantano basin of deposition, and the Pantano beds might overlie the older units of the crystalline complex with only slight dips. Schwalen and Shaw (1957) noted the presence of Pantano beds at a depth of 550 feet in a well south of Davis-Monthan airbase.

Alluvial deposits of the Tucson basin

The Tucson basin is filled with an unknown thickness of gravel, sand, silt, and clay. Most of this material was probably brought into the basin by streams and slope wash from the adjacent mountains and by through-flowing streams that entered the basin from the south and east. The material was deposited largely in flood plains, but some of the clay was possibly laid down in shallow and temporary lakes. The lithology of the material varies

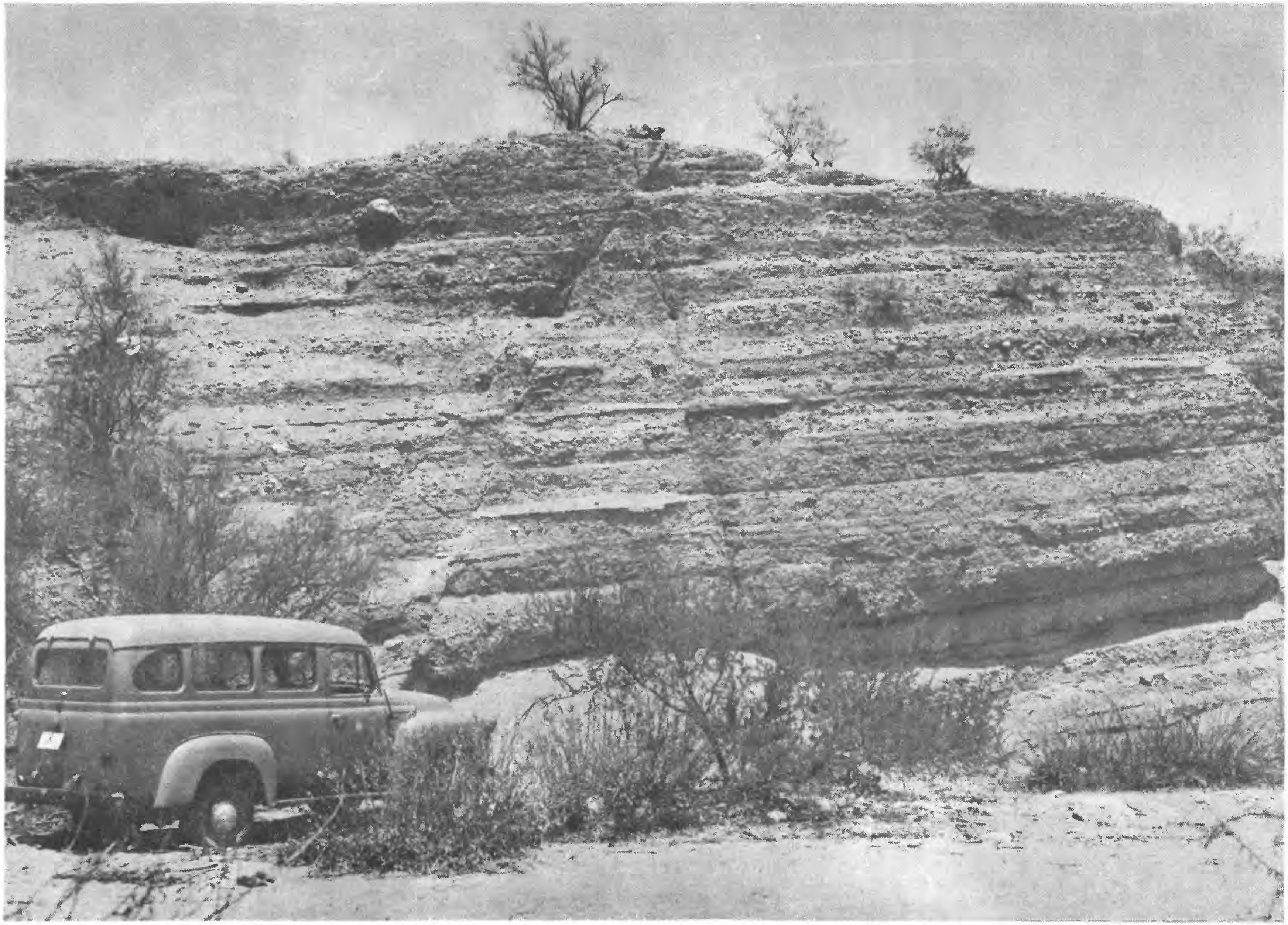

Figure 14. --Conglomerate in Pantano beds.
Exposure in Pontatoc Wash, Catalina Foothills, showing faulting and slight tilting.

considerably, both vertically and horizontally, and correlation between units over any large areas, except in the most general way, has not been possible. Further work in interpreting well logs and samples, however, may result in interpretations of facies relationships that will be useful in establishing the geologic geometry, both vertically and horizontally. These parameters can then be translated into degrees of permeability of various parts of the sediments.

Most of the wells in the Tucson area yield water from the Tucson basin deposits, which are surpassed in permeability only by the younger inner-valley fill along the present streams.

Alluvial fans

Alluvial fans along the margins of the mountains, particularly at the mouths of several canyons, have been formed by coarse material shed from the mountains. For the most part, the fans in the Rillito Creek drainage area are not thick, but remnants of extensive fans occur in parts of the Catalina foothills area, particularly at the western end, and in isolated patches east of Sabino Canyon road.

Outwash from the fan deposits has contributed to the thin layer of gravel and sand that forms a veneer on most of the ridges in the foothill area. The rather abrupt slope from Rillito Creek northward to the Catalina front might imply that the entire foothill area is underlain by a wedge of coarse, permeable fan material, but exposures in the washes and drill records show conclusively that the slope is an erosion surface cut on the tilted Pantano beds and covered with the thin layer of alluvium.

Alluvial-fan deposits along the mountain fronts and at the mouths of canyons are often considered to be important as channels for recharge of mountain runoff into the groundwater basin (fig. 3). It is obvious that most of the fans along the Catalina and Rincon fronts do not provide such avenues of recharge because they are not directly connected with the Tucson basin deposits. The fans at the mouths of canyons in the foothills area, however, probably do serve to channel water into the inner-valley fill of the major streams.

Inner-valley fill

The inner-valley fill is the material underlying the channels and flood plains of existing streams. The more important areas of exposure are along the Santa Cruz and Rillito channels. The thickness of the fill in most places is a few tens of feet, or 100 to 200 at most. The lateral extent of the fill is shown by the flood plains occupied by the streams within historic times. The inner-valley fill consists of sand, silt, and gravel, which has not been greatly cemented by minerals nor greatly compacted. The fill forms the most permeable unit of the area. Shallow wells of relatively large capacity have been developed for domestic and agricultural uses along the flood plains of both the Santa Cruz River and Rillito Creek. Water from such wells is derived mainly from recharge from the respective streams, and the direct relationship of this water to precipitation and runoff is clearly shown by the hydrograph of the well at University farm (fig. 16).

Structure

The Tucson basin represents a depressed block between the surrounding mountain masses, which have been elevated. The extent of structural relief formed by faulting, folding, or a combination of both, is not known. The Catalina Mountains appear to be a great domal upwarp or fold, and their present elevation may be due in part to this doming. Boundary faults, however, surround the Catalina-Rincon Mountain mass, and some of the uplift is probably due to faulting (fig. 2).

The boundary faults trend approximately north-south and east-west in the Rillito Creek drainage area. A conspicuous fault zone along the south face of the Catalinas separates the crystalline complex from Pantano beds. The angulate pattern of the boundary faults, and the fact that the Pantano beds are locally tilted, fractured, and faulted, indicate that some of the boundary faults may extend into the basin. A block mountain topography, on a smaller scale than the modern topography visible, may be present on the floor of the basin where it is covered by the basin deposits.

In particular, an east-west fault might approximately parallel the course of lower Rillito Creek and line up with the boundary fault south of Agua Caliente Hill. The inferred fault near Sabino Canyon might also be projected southward into the basin along a line just east of Wilmot Road. If a fault-block pattern of topography does exist within the basin, the blocks were probably modified by erosion before the old surface was completely buried by Tucson basin deposits. The presence of such a rugged topography might have an influence locally on the capacity of the basin deposits to store and transmit water, and certainly would control the thickness of the fill from place to place.

Physiography

The relationships of the geologic units that control the hydrology of the Tucson basin are expressed in the structural, depositional, and erosional features of the area. There is insufficient information to explain all the details, but a general outline may be given.

The present mountain ranges of the Tucson area were formed by a crustal disturbance which followed deposition of several thousand feet of Pantano beds. Since this disturbance the mountains have been modified by erosion and perhaps by some additional uplift. The basins have been filled to various depths by sediments, and, in some places, by volcanic ash and lava flows.

Some of the mountain fronts that originally formed bold, steep faces, called fault scarps, have retreated during erosion so that they may now be some miles from the original faults bounding the basins, and have been worn down to gentle slopes called fault-line scarps. A typical example is the Sierrita Mountains mass southwest of Tucson. Such erosion or cutting back of the front leaves an erosional surface on the bedrock which slopes from the valley up toward the mountain. This surface, which is called a "pediment," is covered with a thin layer of alluvial debris, only a few feet or a few tens of feet thick, carried from the mountains to the valley by streams and sheet wash during floods. The surface of this pediment cap commonly merges imperceptibly with the valley floor. The distinction between a pediment surface and the valley floor proper, or an alluvial fan, is important because the material overlying the pediment is not thick enough to store or transmit any appreciable amount of water.

The south and west fronts of the Catalina and Rincon Mountains are flanked by pediments, extending to about the positions of Rillito Creek and Pantano Wash. The present mountain fronts are steep and bold, suggesting that they are fresh fault scarps rather than erosional fault-line scarps. The pediments may represent erosion of foothill blocks that were uplifted in the original mountain building to elevations intermediate between those of the basin block and the higher mountain blocks, in a steplike arrangement. If this is so, the basinward side of the pediments should be bounded by faults, now concealed by fill, and the transition from the foothill areas to the basin should be a fairly abrupt dropoff.

While the mountains were being eroded and the pediments were being formed, the basin was filled by detritus shed from the mountains and was brought into the Tucson basin by the Santa Cruz River and Pantano Wash. The basin deposits probably extended to a greater height than the present valley surface during the last stages of filling, and all or parts of the foothill pediments may have been buried. Pantano Wash probably contributed a major portion of the deposits in the area southeast of Tucson, in effect building a delta or fanlike deposit across the Santa Cruz Valley. The course of Pantano Wash probably swung back and forth over the surface as deposits built up, blocking each course in turn. This sort of deposition, of course, causes great irregularities in the character of deposits, both vertically and laterally.

After the basin was filled to the present surface or slightly above, the streams began to cut down rather than to build up. The reason for this change is not known. It may have been caused by climatic changes or by regional tilting of the area, or by both. In any event, a series of erosional pulses carved out some of the original fill, leaving a series of terraced surfaces stepping down to the present valley flood plains. These flood plains occupy troughs cut into the older Tucson basin deposits, and are filled with a few tens of feet of material deposited in Recent time.

Ground Water

The Tucson area obtains its water supply from the ground-water reserves within the Tucson basin. Thus, it is essential to know the amount of water in storage, how much can be withdrawn, and for how long. Such determinations will be difficult; however, it is believed that the amount in storage can be calculated and the more pertinent factors, such as the amount which can be withdrawn and the character of the withdrawal response, can be ascertained. In order to determine these factors, certain geologic information and water records are needed to make the ultimate quantitative analysis. Much of this information is already at hand and a resume of the ground-water conditions in the Tucson basin follows.

Occurrence and movement

The ground-water basin, for the most part, is the area between the Rillito-Pantano drainage and the Santa Cruz River, and the Tucson basin deposits constitute the major aquifer in the area. As the rock units immediately north of Rillito Creek and east of Pantano Wash (fig. 3) form the outer margins of the water basin, there is little hope that any significant amounts of water could be obtained from these less permeable rocks. The thickness of the Tucson basin deposits is not definitely known, but available data indicate that it may range from 500 to 800 feet throughout most of the area. Underlying these deposits are a series of beds of fine material, for the most part the Pantano beds, and although they may contain water their yield may be relatively small.

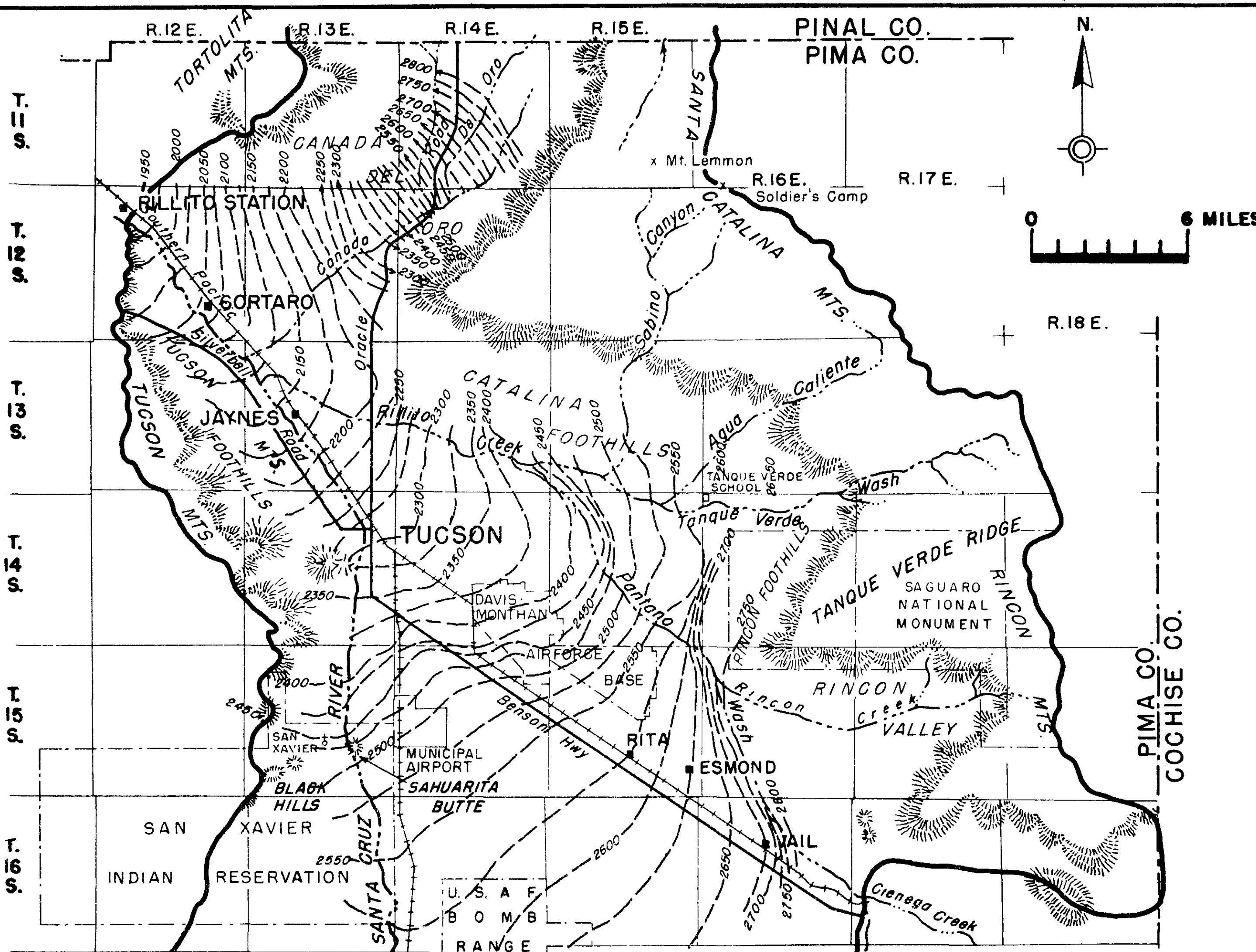

FIGURE 15.--GROUND-WATER CONTOUR MAP OF TUCSON BASIN, SPRING 1959.

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JUNE 6, 1959

A water-table map provides the hydrologist with an excellent document to determine the character of the water reservoir. The distribution and the shape of the water-table contours indicate to the hydrologist many factors such as the permeability of the rocks, direction of movement, effects of natural recharge, and depletion effects of withdrawal. Schwalen and Shaw (1957) have documented much of the information on these factors and the changes that have occurred over the past 40 years.

The ground-water contour map (fig. 15) shows the water-table conditions as of spring 1959. The water table in the Tucson basin ranges from about 10 feet to about 600 feet below the land surface. In greater Tucson the water level ranges from about 10 feet to about 300 feet below the land surface. As water moves at right angles to the contours, the general movement is from the southeast to the northwest; however, in the area along Rillito Creek the movement is from east to west.

In the area between the Catalina Mountains and Tanque Verde Ridge, the contours are more closely spaced, indicating a barrier condition, possibly due to faulting, that accounts for a sharp drop in the water table and may be related to a buried pediment surface. In general, where the contours are closely spaced the rocks are less permeable than in those areas where they are more openly spaced.

The configuration of water-table contours also indicates areas that receive recharge from the land surface. The shape of the contours along Rillito Creek clearly shows that recharge occurs along the inner-valley fill, whereas the contours in the Pantano Wash area clearly indicate that little or no recharge reaches the ground-water reservoir. Along Rillito Creek the water table is shallow, thus enabling only a part of the floodflow to enter the subsurface. There are similar conditions in parts of the Santa Cruz River where surface water enters the subsurface via the inner-valley fill. Little or no recharge enters the ground-water basin from direct precipitation on the land surface. Only after long periods of sustained streamflow do any significant amounts of recharge take place, even along the inner-valley streambeds. Such conditions existed during the winter months of 1958, when a sustained flow of about 6 weeks caused the water table to rise several feet along the Rillito Creek flood plain.

As the amount of annual recharge into the ground-water reservoir is small, it is necessary to remember that the ground-water reserves in Arizona's alluvial basins were emplaced over a period of many centuries, even thousands of years. Also, in the past centuries there may have been more rainfall and runoff available for recharge into the ground-water reservoirs. The amount of net recharge to the basins today is only a small fraction of the amount that is being withdrawn; consequently, there is a decline of the water table and depletion of ground-water reserves.

Water movement in the subsurface is little understood by man, in spite of all his technological knowledge gained in the field of hydrology. The exact nature of how water moves in the subsurface is directly related to the character of the rock materials. As man dwells on the land surface, he is able to observe and understand surficial phenomena better than those in the subsurface. Subterranean observations are necessary in order to understand the ground-water system and these are difficult to obtain. However, there are several basic physical laws and fundamentals that apply to ground-water movement, but they are applicable only in isotropic media. As the subsurface materials never really occur under such conditions, the behavior of water is modified by the character of the materials.

Movement of water in the unsaturated zone, that part between the water table and the land surface, is due primarily to the force of gravity. The dominant vector of movement is directly downward. However, impermeable layers cause the water to move obliquely to the vertical component in certain areas; but it seeks a straight downward path. The movement in the saturated zone is in the direction of maximum hydraulic gradient and the velocity is directly proportional to the magnitude of the gradient. The hydraulic gradient is expressed as the ratio of the vertical difference between any two points of the water-table surface to the flow distance between the points. In the Tucson ground-water basin the hydraulic gradient, in general, ranges from about 10 to 15 feet per mile. Such gradients are common throughout the alluvial basins in the arid Southwest. Examination of the water-table contour map (fig. 15) shows a variance of the hydraulic gradient along the eastern side of the basin, which reflects differences in the permeability. If the subsurface were a homogeneous mass, the contours would be uniformly spaced under natural conditions. Thus, the contour map clearly reflects the inhomogeneous nature of the subsurface rocks.

The rate of movement of water in the subsurface is one of speculation by many persons, even by hydrologists. However, an analysis of some basic fundamental laws and arithmetical calculations indicate that movement in the saturated zone is very slow under the best of conditions. In general, the character of the materials in the subsurface indicates that the velocity of movement in the saturated zone is only several hundred feet per year. It might require several centuries for a drop of water to move from the southeastern part of the basin to downtown Tucson at the prevailing hydraulic gradient. However, when the hydraulic gradient is increased, as by depression cones of withdrawal, the velocity increases proportionately. The velocity of movement in the unsaturated zone is also related to the character of the rock material, but is several hundred times greater than in the saturated zone. The effect of water moving vertically downward in the stream channel material, such as in Rillito Creek and the Santa Cruz River, is well known and the water level rises very quickly, in terms of weeks and even days. But it is necessary to keep in mind that the rate of movement in these areas is not comparable to the velocity in the saturated zone.

A good illustration of movement is shown by the hydrographs (Schwalen and Shaw, 1957 fig. 10) which document the water level from 1916 through 1959 (fig. 16). One well is located in the inner-valley fill of Rillito Creek at the University Farm on Campbell Avenue. The other well is located on the campus of the University. The hydrographs show the effect of withdrawal of ground water and the effect of recharge from surface-water infiltration. The Farm well hydrograph fluctuates widely, showing relationships between withdrawal and recharge to the well field. The recharge effects correspond very well with the years which had above-normal precipitation, particularly 1941 and 1952. An examination of the Campus hydrograph, however, shows no effect of this recharge, as the new water did not move this far southward. The hydrograph clearly shows that the continued decline of the water level is due to withdrawal from storage. The geologic framework corroborates these conditions, as there is a difference in the materials in the inner-valley fill and the materials underlying the University campus. It is unlikely that recharge effects would extend from the inner-valley fill to the Campus well, a distance of a little more than 2 miles, in such a short period of time. There is a noticeable increase in the rate of decline of the water level in the Campus well after 1946.

Quality of water

The general character of the ground water within the Tucson basin deposits has been fairly well established from numerous chemical analyses. In the water underlying the major part of the area the total soluble salt content is less than 500 ppm and the hardness is less than 1.70 ppm. Small areas are indicated along Rillito Creek and Tanque Verde Wash in which the hardness is less than 1.35 ppm and the total soluble salts are between 200 and 300 ppm (fig. 17). A similar situation exists in the Canada del Oro area, but the total soluble salt content is less than 200 ppm. These are the waters of best quality found within the Tucson area, and typical analyses of them are given in table 6.

Table 6.--Chemical analyses of ground water in the Tucson basin area

	Rillito Creek Section 25 T.13S., R.14E. (ppm)	Tanque Verde Creek Section 5 T.14S., R.16E. (ppm)	Canada del Oro Section 14 T.12S., R.13E. (ppm)
Total soluble salt	265	233	156
Calcium	30	15	22
Magnesium	0	8	4
Sodium	44	40	14
Chloride	20	12	14
Sulfate	25	30	T
Carbonate	0	0	0
Bicarbonate	146	127	102
Fluoride	0.4	0.9	-
Hardness as $CaCO_3$	74	72	72

Analyses from three wells, rather widely spaced in the central part of the area, have been selected to show the quality of the water where the total soluble salt content is less than 500 ppm, but in which the hardness is between 85 and 170 ppm. The analyses follow.

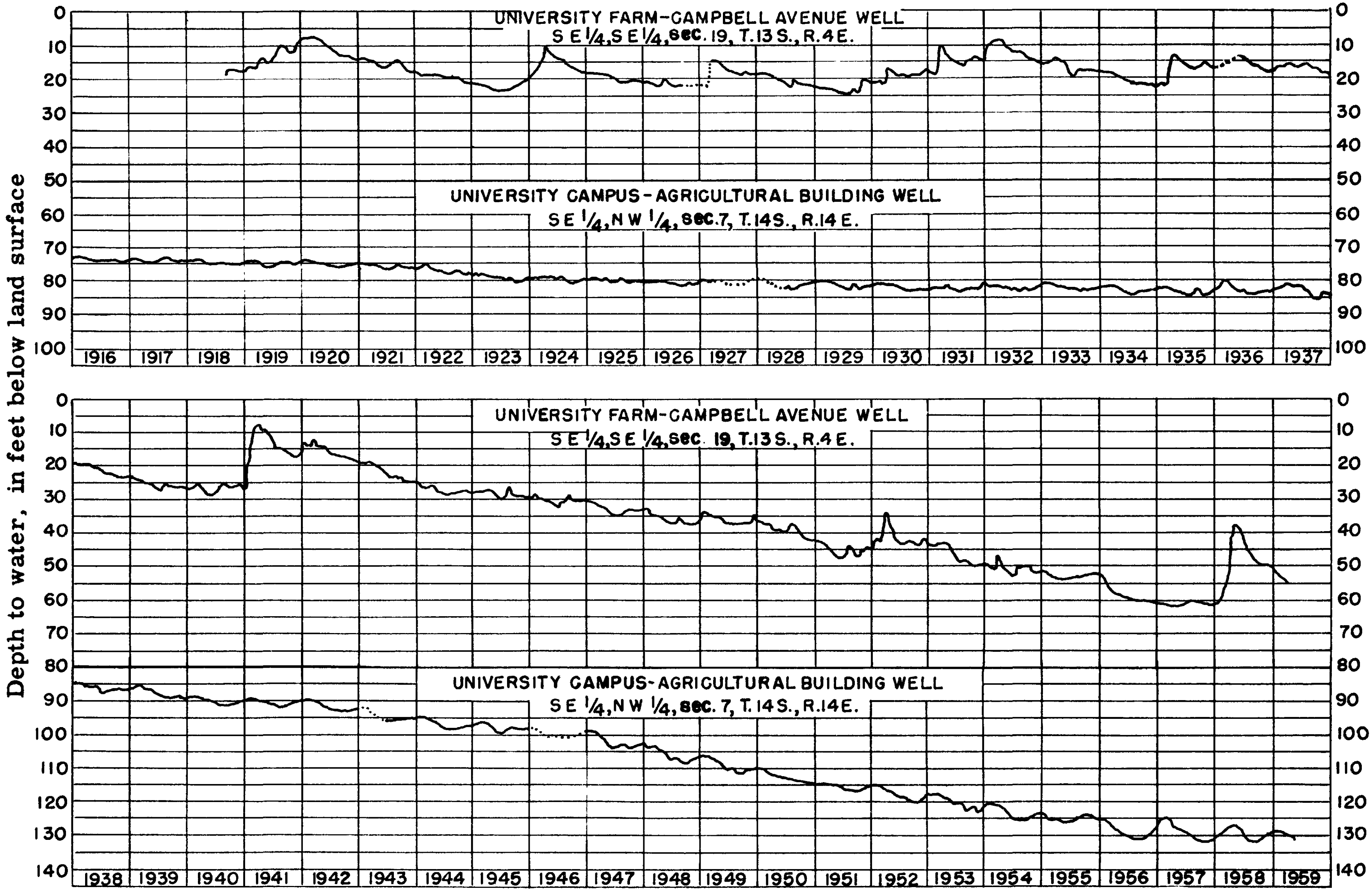

Figure 16.--Hydrograph of water levels in two representative wells, 1916-59.

	Rillito Creek Section 7 T.13S., R.14E. (ppm)	Tanque Verde Creek Section 18 T.14S., R.15E. (ppm)	Canada del Oro Section 13 T.13S., R.13E. (ppm)
Total soluble salt	304	324	370
Calcium	30	46	35
Magnesium	4	10	8
Sodium	50	23	62
Chloride	14	10	36
Sulfate	40	10	70
Carbonate	0	0	0
Bicarbonate	166	225	159
Fluoride	0.4	0.2	0.3
Hardness as Ca CO_3	92	155	121

South of the Southern Pacific Railroad is a zone of ground water in which the total soluble salt content is more than 500 ppm and the hardness exceeds (1.70 ppm). Typical analyses of waters from wells in this area follow.

	Section 4 T.16S., R.15E. (ppm)	Section 13 T.15S., R.14E. (ppm)	Section 12 T.14S., R.13E (ppm)
Total soluble salt	870	585	821
Calcium	127	94	74
Magnesium	7	13	4
Sodium	110	54	170
Chloride	32	22	44
Sulfate	372	214	339
Carbonate	0	0	0
Bicarbonate	220	186	190
Fluoride	0.3	-	0.4
Hardness as Ca CO_3	348	288	202

Along the west edge of the valley and more or less parallel to the Santa Cruz River are waters with a salt content of more than 500 ppm, and in some cases more than 1,000 ppm, and with the typical high sulfate content of the waters of Santa Cruz Valley. The following analyses are typical of the waters in this area.

	Section 17 T.13S., R.13E. (ppm)	Section 15 T.15S., R.13E. (ppm)	Section 19 T.16S., R.14E. (ppm)
Total soluble salt	686	717	784
Calcium	120	60	130
Magnesium	4	8	36
Sodium	60	145	34
Chloride	103	70	38
Sulfate	204	180	206
Carbonate	0	0	0
Bicarbonate	195	254	275
Fluoride	-	-	-
Hardness as Ca CO_3	317	185	473

North of Rillito Creek in the foothills of the Santa Catalina Mountains is an area of Pantano beds, buried in some places and exposed in others. Dry holes or wells of extremely poor yield have been constructed in this formation, but in many places they will not produce sufficient water for a single home, or water of satisfactory quality for household purposes. This may be termed a questionable area, as to both quantity and quality of ground water.

The availability of a water supply in the foothill area adjacent to Tanque Verde Ridge and along the base of the Rincon Mountains is questionable, except along the bottom land adjacent to Rincon Creek. Wells along the creek, in general, have a total salt content of less than 300 ppm, and a hardness of slightly more than 85 ppm.

Practically all ground waters within the area contain small amounts of fluoride, which do not exceed the allowable limit of 1.5 ppm except in the area north of Tanque Verde Wash. In this area all well water should be checked for fluoride where young children are to use the water for drinking. Some water has been found with a fluoride content in excess of 10 ppm.

Storage and yield

In Arizona the ground-water reserves in the arid alluvial basins have been used to meet the water demand, except where available surface supplies have been developed. Since the early existence of the Tucson community its supply has been obtained from ground water. Tucson might not have grown to its present size if these ground-water reserves had not been available. (Turner and others, 1943). The growth of numerous communities throughout the State is limited because of the lack of available water.

The amount of water that is in storage in the Tucson basin is directly related to the areal extent and thickness of the deposits, and to the character of the materials. The Tucson basin is bounded on the north, east, and west sides by impermeable rock barriers, as shown on figure 2. Underflow into the basin comes from the Pantano Wash and the Santa Cruz River. However, the amounts are small compared to the amounts being withdrawn and the water moves at an extremely slow pace. The natural underground outflow from the basin northwest of Tucson also is small and moves very slowly. Under natural conditions inflow is approximately equal to outflow; thus, no water is gained or lost in the subsurface system.

To obtain quantitative data on storage and yield, the character of the materials must be translated into hydrologic terms, such as permeability and specific capacity. Permeability may be expressed in terms of gallons per day moving through a cross section of 1 square foot under unit hydraulic gradient under prevailing field conditions. This coefficient is a measure of the ability of the sediments to transmit water.

Also important is the matter of specific yield, which is defined as the ratio of the volume of water that will drain by gravity from a saturated rock to the total volume of the rock. In a number of Arizona's alluvial basins, the specific yield ranges from 10 to 20 percent, which is considerably less than the actual porosity of the materials. Perhaps half the amount of water in storage drains to wells. Schwalen and Shaw have stated that the specific yield in the Tucson basin is about 10 or 12 percent, which indicates that the materials are less

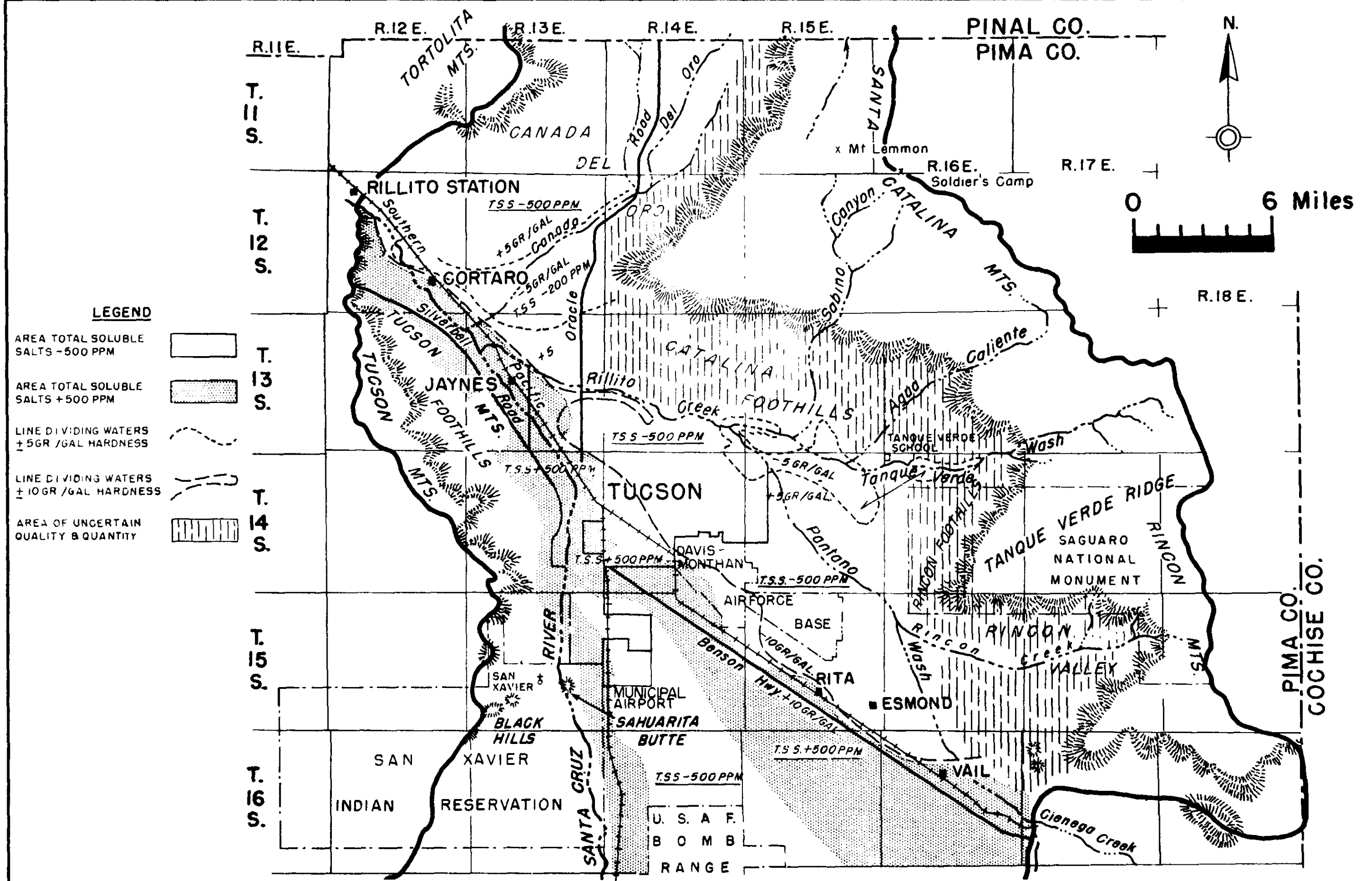

FIGURE 17.--QUALITY OF GROUNDWATER IN RILLITO CREEK PROJECT AREA.

AGRICULTURAL ENGINEERING DEPARTMENT UNIVERSITY OF ARIZONA permeable than in some of the other alluvial basins. This yield appears to be corroborated by the geologic evidence at hand. In the more impermeable layers, at depths below 500 to 800 feet, the specific yield may be something less than 1 percent, which means only limited quantities of ground water are available for withdrawal.

An examination of the ground-water depletion, as shown by the map of water-table decline (fig. 18), documents and corroborates the previous statements. The contours clearly show a cone of depression in the area, and the withdrawal of ground water is directly related to the population density and expansion of metropolitan Tucson. More than 35 feet of decline has taken place in the last 12 years beneath the central part of the city. The cone is spreading outward in all directions, and this trend will continue until it reaches the hard-rock boundary areas, when conditions will worsen because the decline will increase at even a greater rate.

In the northeastern part of the basin along the Pantano Wash near the confluence of Rillito Creek, the decliné contours are already closely spaced, indicating the presence of a barrier in this particular area. Demands for additional amounts of water will greatly accelerate the depletion and a further decline of the water level in this area is inevitable. It has been estimated that in the past 12 years the Tucson basin has suffered a net loss of 250,000 acre-feet of water. As the basin's assets are being depleted and the amount of renewal or replenishment is small, there is reason to be concerned about how long these assets will last.

Volumetric analyses

The rate at which ground water will be pumped from the Tucson basin will generally be determined by the demand for water in the future; however, the nature of the rocks in the subsurface will be a dominant factor in the increased costs and the ultimate specific yield. The magnitude of the hydraulic gradient necessary to cause water to flow into the wells to meet the demand will be determined by the permeability of the deposits. The ultimate question, then, is "How long will it be possible to pump water at a rate to meet the demand?" In part this will be determined by the quantity of water in storage. Analysis of the ground-water reserves indicates that the quantity is more or less fixed, and the rate of withdrawal will be determined by demand.

The quantity of water in reserve in the Tucson basin could be determined logically by a flow-net analysis. The Agricultural Engineering Department of the University of Arizona has collected considerable hydrologic data which would serve as an excellent base with which to make such an analysis. However, further data are needed on the exact amounts of withdrawal over certain periods of time, and these must be correlated with the decline of the water table over the same period. The character of the rocks in the subsurface must be known to make a flow-net analysis. A number of drillers' logs and samples have been collected over the past years during development of wells. Systematic studies of these data may provide adequate information on the rock character, which could then be translated into permeability parameters and also be used for construction of the geologic geometry of the basin. The availability of such basin geologic information would enable evaluation of the water-table-decline data to determine the specific yield of the ground-water reservoir.

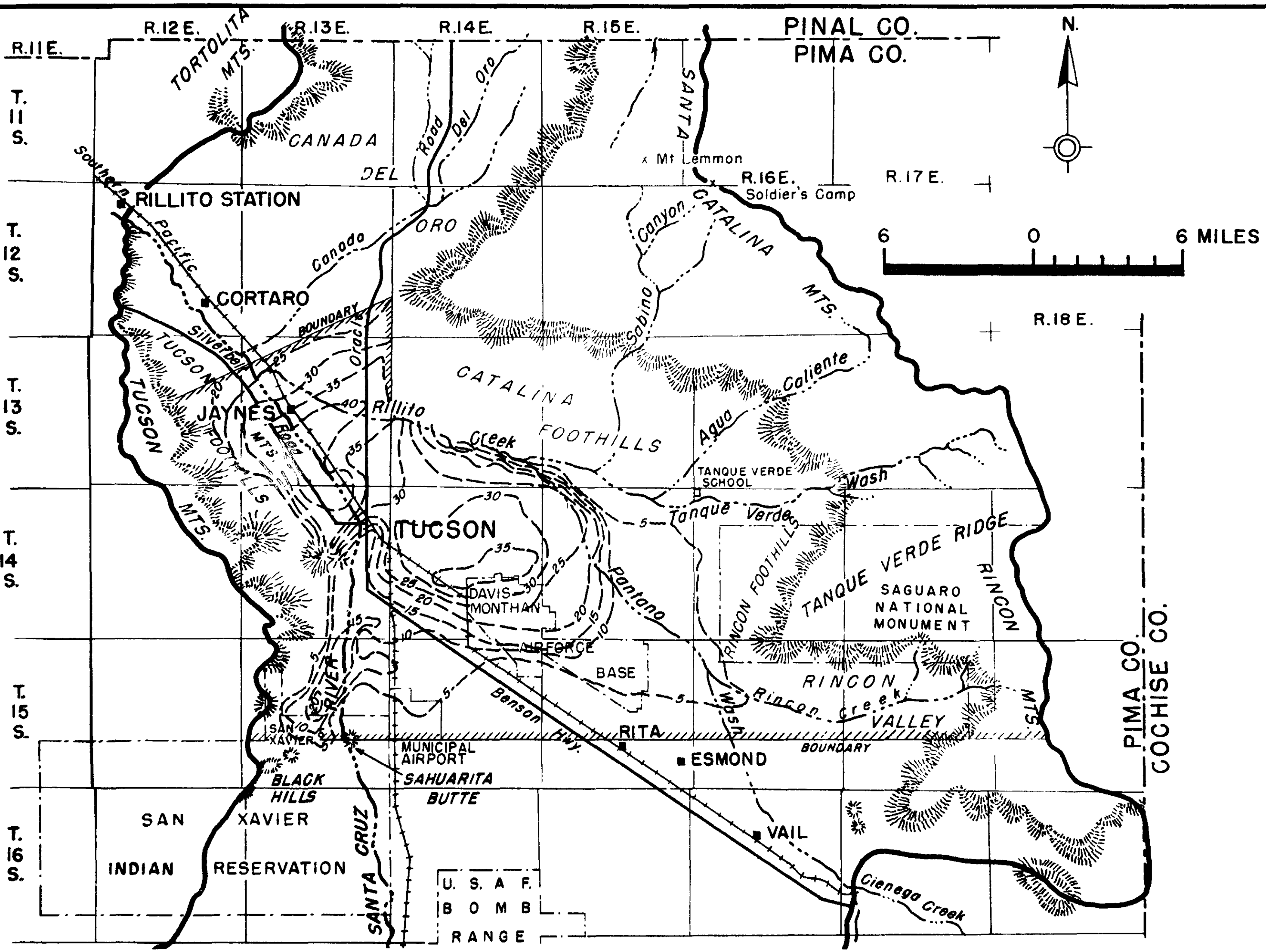

FIGURE 18.--GROUND-WATER LOWERING IN TUCSON BASIN 1947-59.

AGRICULTURAL ENGINEERING DEPARTMENT UNIVERSITY OF ARIZONA
JUNE 6, 1959

The use of an electric analog computer would greatly speed the transformation of the geologic data into hydrologic parameters and would enable the analyst to predict the withdrawal response for any given year in the future. The demand of water for any future year would be in accordance with the projected population of the area. Thus it would be possible to know reasonably well the position of the water table in any particular year.

Subsurface Storage of Water by Artificial Means

It has been estimated that the annual total inflow to Rillito Creek basin may be about 40,000 acre-feet (table 4). A large proportion of the inflow occurs during relatively short flood periods. Therefore, it is unlikely that much of it could be diverted for direct use of any kind; if it is to be used, it will be necessary to detain the water during high stages of flow and put it into temporary storage for future use.

As reservoir facilities are not available for surface storage of the water, consideration may be given to storing increments of it in the subsurface reservoir. Much of the water pumped from wells is withdrawn from storage; recharging water to the ground-water reservoir by artificial means thereby augments the amount in storage.

Many methods of recharging water to subsurface storage reservoirs have been practiced in other areas. Water spreading was started in Germany more than a century ago, and in the United States in 1889. In more recent years much work has been done in several other countries and states. Descriptions of the methods and of technical points involved with them have been published, for example, in Texas (Sundstrom, 1952; Moulder and Frazor, 1957) and in California (Baumann, 1953, Schiff, 1955; Muckel, 1959; see also Todd, 1959).

The method used most commonly in California is ponding or spreading water in surface basins. Water is also spread in natural stream channels, in furrows and ditches, and in abandoned gravel pits. Water is injected directly into the saturated zone by means of pits, shafts, and wells.

The principal advantages of subsurface storage are that the capacity of the reservoir is very large and that water in subsurface storage is not depleted by evaporation losses. On the other hand, several technical questions arise regarding the quality and quantity of the water to be stored. In order to store it most efficiently, much information also must be at hand regarding the physical processes involved in water movement. Some of the essential facts are known, whereas others remain to be determined. The types of information involved are described below.

The source of much of the flood runoff in Rillito Creek during the summer is from thundershowers of high intensity, short duration, and relatively small areal extent. Many of these occur in the upper parts of the drainage area of Pantano Wash, along the Santa Rita, Empire, or southern Rincon Mountains; others occur in the upper tributary drainage areas of Rillito Creek, on the north side of the Tanque Verde Ridge or southern slopes of the Catalina Mountains. This summer flash-flood runoff must first be controlled before being stored or used. This might be done best by structures built in the upstream parts of the main stream channels, near the mountain fronts, and on washes that contribute tributary inflow. From these structures the water could be released through conduits at controlled rates to downstream areas for storage or use.

Runoff during the late winter or spring is commonly not torrential but of longer duration, resulting from snowmelt and winter rains in the higher mountains, such as in the upper Sabino and Bear Canyon drainage areas. This winter runoff, with characteristics of more steady flow, longer duration, and lighter silt load, is believed to be the source of a large part of the natural recharge to the Rillito Creek area. The part of this runoff that is not naturally recharged would be most suitable for artificial recharge, because of these characteristics; however, the quantities of water that may be so utilized have not been determined, and further studies will be needed on this point.

Quality of Water

The physical and chemical character of the water captured for subsurface storage is of utmost importance in planning methods of storing. If the water is not suitable in quality, it must be treated.

Physical properties

The most significant physical property of the water to be considered is its content of suspended sediment. The relatively steady flow of winter runoff is commonly of low enough sediment content for infiltration, as considerable natural recharge of this water takes place. The flash-flood runoff, however, may contain as much as several thousand parts per million of sediment, and little if any of it could be recharged either naturally or artificially without treatment, as it would seal the recharge surfaces.

If floodwater is temporarily detained in a sedimentation basin so that its velocity is reduced, much of the sediment drops to the bottom. Fine particles remain in suspension, commonly in quantities of a few hundred parts per million. Water of this quality can be induced to infiltrate into surface recharge areas, provided the intake areas consist of sediments of suitable permeability, and provided they are periodically cleaned of silt and clay by some means such as suction, sand replacement, or sluicing.

If such water is to be recharged to the subsurface by means of wells, it must have low silt content, as silt in the water tends to clog the aquifer adjacent to the well bore. Intermittent back-pumping removes some of the silt, but it is not known whether this would maintain permeability over a long period of time. If the recharge well is not back-pumped, the water must be treated, by coagulation and filtration, so that the silt content is reduced to a few parts per million or even a fraction of a part per million. It becomes apparent, then, that water treated sufficiently for well injection will likely be of good enough physical quality for use in a domestic or municipal supply, as well as for other purposes, and may be used directly if the existing demand can absorb the quantity available. When the supply of such water temporarily exceeds the current demand, however, it can be stored underground temporarily and pumped back later to meet peak demands.

Chemical properties

Water to be used for recharge to subsurface reservoirs should be analyzed chemically and compared with the soil chemistry of the intake surface as well as the chemical quality of the ground water with which it will come into contact, in order to avoid a chemical combination which would form precipitates such as the relatively insoluble carbonates. The effect of using waters of different chemical quality is illustrated by tests in Kern County, Calif. (Muckel, 1959, p.42). The infiltration rate achieved by using canal water was about half that obtained by using well water, which contained about double the amount of dissolved solids, on the same intake surface. The well water had a conductivity ($K \times 10^6$) of 646, and the canal water, 239; however, the well water had a slightly lower pH and a considerably lower percent sodium, both of which are likely to affect infiltration rates.

Although the choice of water for subsurface storage is based not so much on its chemical quality as on its source and availability, its chemistry should be determined so that proper chemical treatment may be considered.

Microbial activity

When water is spread over a soil surface for a period of many days or weeks, the rate of infiltration commonly decreases with time. This probably is due largely to biological activity in the soil (Muckel, 1959, p. 25). Comparative tests have shown that more nearly constant infiltration rates can be maintained in sterile soil. It appears from this that in ordinary soils the pores become partially clogged by the products of microbial growth, and that permeability reduction is due to partial disintegration of soil aggregates by the attack of microorganisms on organic materials in the aggregates.

Clogging of aquifer pore spaces by bacterial growth is also a problem in water injection through wells. The sands or other water-bearing alluvial strata in the subsurface contain many types of microorganisms, which are relatively dormant or in a state of equilibrium with their environment. If surface water is injected in these strata, it is likely to contain oxygen as well as an abundance of organic material, by which the native organisms are stimulated to activity and growth. Of particular concern are the colonial "slime-forming" bacteria, which secrete pectinlike jelly (slime) which adheres to the aquifer particles and thus reduces permeability (van der Goot and others, 1955).

During well injection experiments in the West Coast Basin near Los Angeles, chlorination of the recharge water has been useful in inhibiting bacterial growth and maintaining injection rates. Chlorine was added at rates ranging from 1.5 to 20 ppm. It was concluded that a constant dosage of 8 to 10 ppm was sufficient to control the bacteria, although initial and periodic "slug" treatments of 20 ppm were recommended to remove accumulations of slime (van der Goot and others, 1957, p. 60). By February 1959 the dosage in one well had been reduced to 5, then to 3 ppm, without impairing the intake rate (John Mitchell, Los Angeles County Flood Control District, 1959, oral communication). It was also found that a dosage of as much as 12 ppm "appeared to impose no special hazard of corrosion" to well casing.

The required chlorination rate at a given recharge or storage site in the Tucson basin would have to be determined empirically, as each environment is likely to be different from others that have been studied. The criteria for determining chlorine dosage should include a rate low enough to avoid corrosion in the well, but high enough to control the bacteria and maintain a relatively constant specific intake of the recharge well.

Location of Storage Areas

The selection of sites for subsurface storage of water is determined by several physical factors, which may be grouped as follows: (1) source, quantity, and quality of water to be stored; (2) geologic features of the ground-water reservoir; and (3) hydraulic characteristics of the ground-water reservoir.

The source, quantity, and quality of water that is potentially available for storage have been described briefly in preceding sections. The channels of Rillito Creek and its main tributaries carry most of the water from its source; by natural processes of seepage some of it is stored in the alluvium beneath the channels, and the quantity thus stored may be increased by controlling the flow and treating the channels. Other storage areas may be located adjacent to these channels, if part of the streamflow is diverted to nearby spreading grounds. Finally, portions of the streamflow may be diverted by canal or pipe to storage sites more remote from the streams but closer to an area of desired use, such as areas of pumpage for the Tucson municipal system. Thus the storage area must be somewhere between the point of availability and the point of eventual use, the exact location depending upon geologic and hydraulic considerations.

The important geologic features that relate to subsurface storage are lithology, structure, and extent of the ground-water reservoir. The potential reservoirs in the Tucson basin are composed of alluvial sedimentary rocks, in which permeability is related to grain size, assortment, and sedimentary structure. A permeable rock unit must also have a structural attitude, thickness, and areal extent such that it will contain a large volume of water in storage. If the permeable sequence of strata extends upward to the land surface, water may be spread directly over the reservoir and allowed to percolate downward; if it is overlain by relatively impermeable strata, however, water would have to be injected to the reservoir through shafts or wells.

The hydraulic properties of the ground-water reservoir also are to be considered in choosing storage sites. Principal among these are the depth to water, the configuration of the water surface or pressure surface, and the ability of the reservoir to transmit and store water. If the water level is too close to the land surface, there is not enough space in the unsaturated zone to store additional water without the danger of losing it by evapotranspiration. Thus the water level should be deep enough so that if more is added it still will be several feet below ground in order to avoid evaporation loss. Or, if phreatophytes grow in the area, it should be perhaps 20, 30, or even 50 feet, according to the plant type, so that the water will not be pumped up and transpired by the plants. On the other hand, if the water table is very deep, there may be relatively impermeable layers between the surface and the saturated zone, and the use of shafts or wells rather than surface spreading areas may be necessary.

The shape of the piezometric surface or water table, which is related to the rate and direction of subsurface water movement, should be considered in planning storage. If water is recharged to a reservoir in which the saturated zone has a uniformly sloping surface, the water table or pressure surface forms a mound or ridge on the former surface. If recharge continues for a long period of time, the mound becomes elongated in a downgradient direction. Observations of this movement should be made in order to determine the best locations for recovering the water by pumping after a given time interval.

The effects of previous withdrawals by pumping may also be evident by the shape of the piesometric surface, and may have a bearing on the location of storage sites. A prolonged pumping draft in excess of natural recharge in several places has created a depressed area in the water table, such as the trough that extends from southeast Tucson toward Rillito Narrows (figs. 15, 18). Storage of excess water in such an area of depression would seem highly desirable from at least two standpoints; (1) The dewatered sediments have been saturated in the past, so that the wetting requirement is relatively low, and a large part of the water injected into them would replace water removed by pumping; and (2) the decline in water levels is evidence that pumping lifts in the area have increased, and possibly that specific capacities of wells have decreased so that water stored there artificially would represent replenishment in a place where it is badly needed.

Finally, the properties of water transmission and storage in the reservoir should be determined. Aquifer tests at a potential site yield information on the recharge rates that may be anticipated for a given cross-sectional area of water-bearing material, and on the quantities of water that may be stored and recovered in a given volume of rock.

Subsurface Distribution and Ultimate Recovery of Water in Storage

Wherever water is recharged to the ground-water reservoir, its disposition underground should be studied and recorded, by means of water-level observations in nearby wells, in order to plan the most efficient withdrawal of the water from storage when needed. Water that has been recharged by infiltration from the surface, either by natural processes or by spreading, can be pumped from wells in the downgradient direction; water injected through wells may be pumped back through the same wells. For example, in Amarillo, Tex., brine was injected periodically into about 90 million gallons of recharge water, and the water later pumped back was tested for chloride content to determine the rate of recovery of stored water. After 90 million gallons had been pumped back, the recovery of injected water was between 78 and 90 percent (Moulder and Frazor, 1957, p. 22). An experiment in El Paso showed that almost all water injected can be recovered (Sundstrom, 1952).

In summary, the feasibility of storing water underground in the Tucson basin by artificial means can presently be viewed from a theoretical standpoint. The process has been proved feasible in other localities, and experience gained there is useful in directing further research locally; but certain assumptions must now be made regarding some of the variable factors at particular locations in the Tucson basin. Actual quantitative evaluations of such operations must be derived empirically through closely controlled experimental work under local conditions. The results of such work would provide water-management agencies the technical data needed for planning or considering actual underground storage operations.

Research and experimentation on this subject should include consideration of all the pertinent physical factors and processes mentioned in the above section--source of water, its quantity and quality, methods of treatment, location of storage sites, methods of storage, and efficient means of recovery and beneficial use.

SUMMARY

This compilation and analysis of data relating to the capture of additional water in the Tucson basin provides preliminary information on many components of the hydrologic system in the area. The report shows, however, that there is a lack of much needed information in numerous fields. It is believed that further intensive research through the coordinated efforts of the several groups which made this study will provide quantitative answers to questions that must be answered before any program to capture additional water can be undertaken. Conclusions reached by this report are as follows:

1. Although precipitation and runoff in the Tucson basin are extremely variable, the basin potential represents a replenishable resource that at present is largely lost. This potential amounts to approximately 40,000 acre-feet per year, which is about 80 percent of the amount of water used by greater Tucson today.

2. Although there are large quantities of ground water in storage, these supplies are assets, or water reserves, of the basin and are definitely limited. The ultimate amount of water that can be withdrawn from this storage is controlled by the character and distribution of the sedimentary rocks in the subsurface. A quantitative analysis of the basin's water assets must be made and from this the life of the reserves can be estimated.

3. Additional surface waters could be captured and recharged into the ground-water basin to prolong the life of the water reserves. The exact methods and operations need to be determined, as to whether the recharge should be accomplished by induced infiltration or through conduits and wells into the subsurface. Experiments in recharge indicate that virtually all recharged water can be recovered.

4. Because the Tucson area is in the arid Southwest it is experiencing an explosive population increase and industrial expansion, and as a result water demands are increasing at alarming rates. Additional water supplies must be made available in order to sustain property values and the economy as a whole. As figure 16 shows, the rate of decline in water levels has markedly increased since 1946.

5. Even though considerable information has been assembled on the hydrologic system in the Tucson area, there is still much to be known and understood about its complexities. The physical processes and the interrelationship of the various components must be known in order to bring about the efficient capture of water for beneficial use in the Tucson area.

INVESTIGATIONS ESSENTIAL TO THE CAPTURE OF ADDITIONAL WATER IN THE TUCSON AREA

Before capture and recharge of surface water can be accomplished, it will be necessary to investigate further certain fundamental problems. Among them are the following:

1. Pattern of precipitation throughout the basin.

2. Amount and distribution of runoff at critical points.

3. Quality of surface water and the amount of sediment it contains.

4. Quality of ground water, particularly from the deep aquifers.

5. Water loss by evaporation and transpiration.

6. Geologic framework with particular reference to the thickness and distribution of the different rocks and their structural attitude.

7. Amount of ground water in storage and its movement within the basin.

8. Amount of natural recharge, and the feasibility and techniques of the best areas for artificial recharge.

The desired studies can best be carried out in an integrated program among the several organizations at the University of Arizona and the U. S. Geological Survey. The results of a comprehensive hydrologic investigation in the Rillito Creek area also would provide useful guidance and information for water management in other parts of greater Tucson. The Santa Cruz River has a drainage area of 2,000 square miles and it is quite reasonable to believe that many factors would be applicable toward the possibility of capturing additional water from this drainage. The Committee believes that the results and objectives stemming from this report deserve serious consideration by the people living in the Tucson basin.

COMMITTEE

The principal persons who participated in preparing "The feasibility of capturing additional water in the Tucson basin" include the members of the Rillito Creek basin research project committee, as follows:

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- Ground Water Branch
  - John W. Harshbarger, Chairman

In addition, many persons have provided substantial assistance to the principal participants. As there was a considerable amount of work in compiling and analyzing the data and in preparing illustrations and tables, the committee gratefully acknowledges the following contributions:

UNIVERSITY OF ARIZONA

Agricultural Engineering Department

Richard J. Shaw compiled data for the water-table-contour map and the water-table-decline map. David Fonken supplied much information on the rainfall-infiltration data from the Atterbury Wash study and on evaporation from stream channels.

Civil Engineering Department

Henry H. Miles compiled information on the natural recharge that might be effective in the Rillito Creek basin.

Department of Geology

Robert Streitz and George E. Maddox compiled considerable information from well logs and drilling samples, in order to compile the subsurface geologic sections.

Institute of Atmospheric Physics

William D. Sellars prepared the section on rainfall characteristics, Clayton H. Reitan compiled much of the precipitation data, and James R. Hastings made the analysis of flood history and channel trenching.

Institute of Water Utilization

George R. Catron assisted in preparation of the soils map.

U. S. GEOLOGICAL SURVEY

Surface Water Branch

Roy B. Sanderson, Louis P. Denis, and George R. Dempster compiled much of the surface-water data on floods and prepared the hydrographs and other illustrations relating to surface-water aspects.

Ground Water Branch

E. Fred Pashley, Jr., compiled the data for the geologic map and prepared the subsurface geologic illustrations from available data. William F. Hardt supplied advice and suggestions on the ground-water volumetric analysis. Leopold A. Heindl supplied much first-hand knowledge of the geology of the Tucson basin.

U. S. DEPARTMENT OF AGRICULTURE

Agricultural Research Service

Joel E. Fletcher assisted in making data available for the report.

In addition, many other persons in the various groups are to be commended for their diligent efforts in the preparation of illustrations and typing of manuscripts in order to meet the completion date.

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