Groundwater Recharge Symposium

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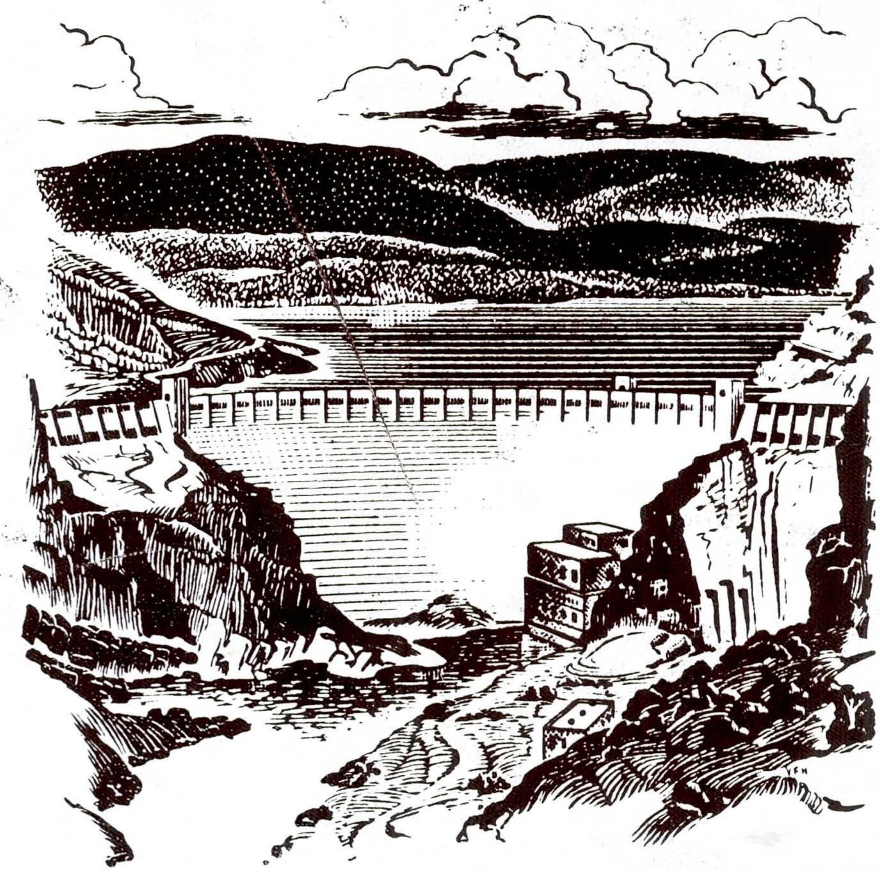

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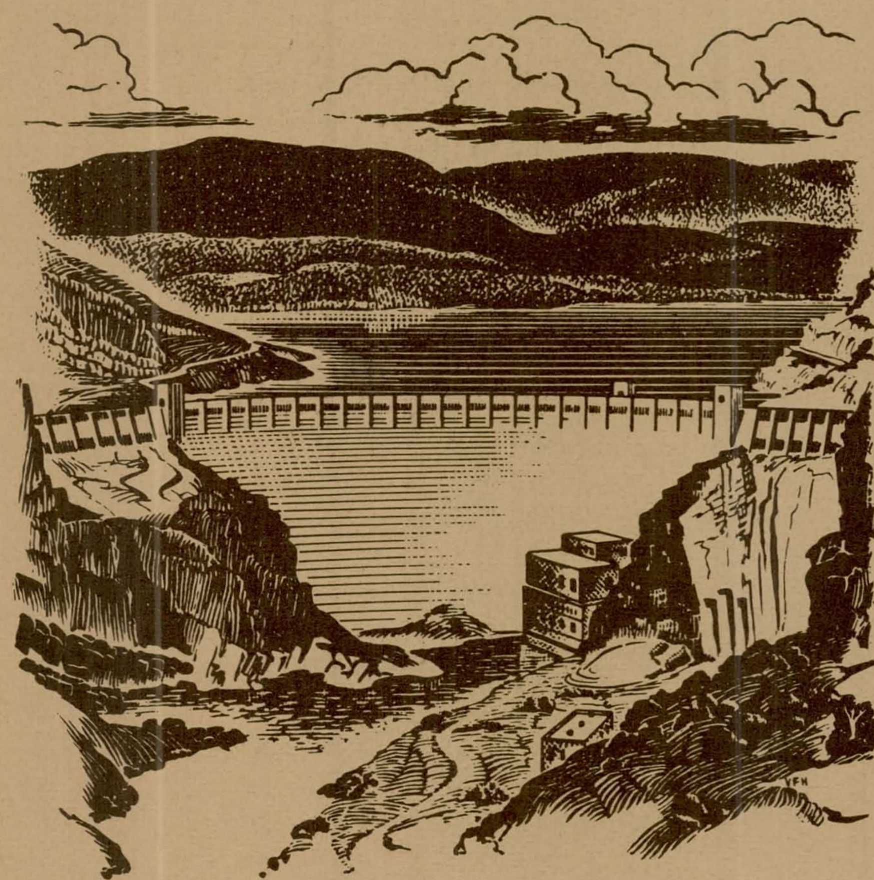


GROUNDWATER RECHARGE SYMPOSIUM

PROGRAM

Environmental Factors of Groundwater Recharge	Harry Nightengale U.S. Department of Agriculture Fresno, California
Panel #2 - Review of Presentations and Questions from Audience	A. J. Pfister Chairman, Panel #2 Salt River Project
Backwater Studies of Hydraulic Structures	Tom Burbey U.S. Bureau of Reclamation Phoenix, Arizona
Case History - Groundwater Recharge in San Joaquin Valley "Leaky Acres Recharge Facility"	William Bianchi U.S. Department of Agriculture Fresno, California
Feasibility of Artificial Groundwater Recharge in the Salt River Valley	J. Dixon - M. Mooradian U.S. Corps of Engineers Phoenix, Arizona
Case History - Groundwater Recharge in Texas Panhandle Area	Don Signor U.S. Geological Survey Lubbock Texas
Case History - Groundwater Recharge in Arizona	L. G. Wilson University of Arizona Tucson, Arizona
Panel #3 - Review of Presentations and Questions from Audience	Wes Steiner Chairman, Panel #3 Arizona Water Commission Phoenix, Arizona
Panel #4 - Symposium Summary	John Harshbarger Harshbarger & Associates Tucson, Arizona

November 27 & 28, 1978

GROUNDWATER RECHARGE SYMPOSIUM

PROGRAM

Topic	Speaker
Statistical Analysis of Flows of Salt & Verde Rivers, and Reservoir Evaporation	Byron Aldridge U.S. Geological Survey Tucson, Arizona
	D. S. Wilson Salt River Project
Flow Process to Underground from Surface Ponds	Herman Bouwer U.S. Conservation Lab Phoenix, Arizona
Flow Above the Underground Water Table	Ed Weeks U.S. Geological Survey Lubbock, Texas
Hydraulics of Wells	Herb Skibitzke Herb Skibitzke & Associates Tempe, Arizona
Panel #1 - Review of Presentations and Questions from Audience	Herb Donald Chairman, Panel #1 Maricopa County Flood Control District Phoenix, Arizona
Legal Considerations of Groundwater Recharge	Harrison Dunning University of California Davis, California
Economics of Groundwater Recharge	Irv Sherman Los Angeles County Flood Control District Los Angeles, California
Effects of Groundwater Recharge on Quality of Groundwater	Ken Schmidt Ken Schmidt & Associates Fresno, California

November 27 & 28, 1978

ACKNOWLEDGMENTS

ACKNOWLEDGEMENTS

The Groundwater Planning Division would like to express their appreciation to Phil Clemons and Richard L. Juetten for their help in organizing the activities of the Groundwater Recharge Symposium. Mr. Juetten also kept the talks and discussions on an orderly and timely schedule. Thanks are extended to Mike Rappoport and his staff for helping compile the initial mailing list and for securing Mr. Gordon Nelson, Coordinator of Farm/Water Alliance, as a luncheon speaker.

Thanks are also extended to Don Womack for his delightful luncheon comments and the introduction of the program film. Expressions of gratitude are extended to Symposium hostesses Jean Alcalde, Hazel Herrington and Edna Wall for their many hours of typing, filing, organizing and operation of the registration desk. They provided the needed touches for implementing a well-organized Symposium.

The Symposium hosts, John Rotert, Terry Turner and Dallas Reigle, are to be commended for their work of setting up the meeting room and keeping the Symposium operating smoothly. Thanks to Marc Norton for his help in reviewing and editing the Groundwater Recharge Symposium Proceedings.

Thanks are also extended to all of those people who spent time helping to develop an educational and thought-provoking Symposium.

Gary G. Small, Supervisor
Groundwater Planning Division

PREFACE

This preface documents the proceedings of a Groundwater Recharge Symposium held in Phoenix, Arizona on November 27 and 28, 1978.

For many years, groundwater recharging in the Salt River Valley Basin has been under discussion by politicians, professional engineers, and the citizenry in general. The purpose of the symposium was to bring together some of the most experienced personnel in the field of groundwater recharge.

We believe the documentation of the expertise of the participants, along with the questions and answers, provides an exceptional reference book for future use.

We appreciate all who participated, either as a speaker or a listener, at this symposium.

Reid Teeples

Reid W. Teeples
Associate General Manager-Water
Salt River Project

SPEAKERS & PANEL MEMBERS

GROUNDWATER RECHARGE SYMPOSIUM SPEAKERS

D. S. Wilson, Jr.
Salt River Project
P. O. Box 1980
Phoenix, Arizona 85001

Herman Bouwer
U.S. Water Conservation Lab
4331 E. Broadway
Phoenix, Arizona 85040

Ed Weeks
U.S. Geological Survey
P. O. Box 3355
Lubbock, Texas 79452

Herb Skibitzke
P. O. Box 27334
Tempe, Arizona 85282

Harrison Dunning
Governor's Commission
P. O. Box 100
Sacramento, California 95801

Irv Sherman
24030 Killion Street
Woodland Hills, California 91367

Ken Schmidt
Valley Bank Center
Suite 2390
Phoenix, Arizona 85073

Tom Burbey
U.S.B.R.
Arizona Projects Office
Suite 2200, Valley Center
201 N. Central Avenue
Phoenix, Arizona 85716

Mike Mooradian
2509 E. Sylvia
Tucson, Arizona 85716

Harry Nightingale
Water Management Research Lab
SEA-AR U.S. Department of Ag
4816 E. Shields Avenue
Fresno, California 93726

William Bianchi
Water Management Research Lab
SEA-AR U.S. Department of Ag
4816 E. Shields Avenue
Fresno, California 93726

Joe Dixon
U.S. Corps of Engineers
2721 N. Central Ave., Suite 800
Phoenix, Arizona 85004

Don Signor
3225 E. Flower Avenue
Tucson, Arizona 85716

L. G. Wilson
WRRC
University of Arizona
Tucson, Arizona 85721

Byron Aldridge
U.S. Geological Survey
301 W. Congress
Tucson, Arizona 85701

GROUNDWATER RECHARGE SYMPOSIUM PANEL MEMBERS

Panel #1

Herb Donald
Flood Control District
3335 W. Durango
Phoenix, Arizona 85009

Leonard Halpenny
Water Development Corp.
3938 Santa Barbara
Tucson, Arizona 85711

Jim Attebery
City of Phoenix
251 W. Washington
Phoenix, Arizona 85003

Ben Dibble
3625 N. 16th Street
Phoenix, Arizona 85014

Phil Briggs
Arizona Water Commission
222 N. Central
Suite 800
Phoenix, Arizona 85004

Dennis Duffy
ECF 154
Dept. of Civil Engineering
ASU
Tempe, Arizona 85281

Andy Bettwy, Commissioner
State Land Department
Capitol Annex East
Phoenix, Arizona 85007

Panel #2

A. J. Pfister
Salt River Project
P. O. Box 1980
Phoenix, Arizona 85001

Al Colton
Salt River Project
P. O. Box 1980
Phoenix, Arizona 85001

Eva Patton
333 E. Geneva Drive
Tempe, Arizona 85282

Paul Ruff
Engineering Center
ASU
Tempe, Arizona 85281

Meade Stirland
State Bureau of Water
Quality Control
1740 W. Adams
Phoenix, Arizona 85007

Elijah Cardon
134 W. Broadway
Mesa, Arizona 85202

Roger Evans
Salt River Pima-Maricopa
Indian Community
Rt. 1, Box 216
Scottsdale, Arizona 85256

Panel #3

Wes Steiner
Arizona Water Commission
222 N. Central
Suite 800
Phoenix, Arizona 85004

Herb Schumann
U.S. Geological Survey
Suite 1880, Valley Center
Phoenix, Arizona 85073

Brent Brown
Office of Economic
Planning & Development
1700 W. Washington
Room 505
Phoenix, Arizona 85007

Charlie Downs
ECF 154
Dept. of Civil Engineering
ASU
Tempe, Arizona 85281

Ed Kirdar
Salt River Project
P. O. Box 1980
Phoenix, Arizona 85001

John Replogle
U.S. Water Conservation Lab
4331 E. Broadway
Phoenix, Arizona 85040

Bob Moore, Exec. Vice President
Agri-Business Council of Arizona
222 W. Osborne, Suite 116
Phoenix, Arizona 85013

Panel #4

John Harshbarger
Harshbarger & Associates
1525 E. Kleindale
Tucson, Arizona 85719

Herb Donald
Flood Control District
3335 W. Durango
Phoenix, Arizona 85000

Manny Lopez
Bureau of Reclamation
P. O. Box 427
Boulder City, Nevada 89005

Wes Steiner
Arizona Water Commission
222 N. Central
Suite 800
Phoenix, Arizona 85004

OPENING COMMENTS

KARL ABEL: (President of the Salt River Project)

We, from the Salt River Project, would like to welcome you to this Groundwater Recharge Symposium.

About the only thing I know about groundwater recharging are the old wise tales that I've heard over the years so, personally, I'm really looking forward to the talent that we have on this program. We're very fortunate to get these people here to educate us and help us along with the knowledge of groundwater recharging, and there are a goodly number of experts in this audience. I can see from here that we'll also be able to add to the total situation and I think that with a combination like that, we're bound to know a lot more about this particular subject by tomorrow evening. I would hope that this proves to be a very informative and interesting experience for all of you. Thank you.

JACK PFISTER: (General Manager of the Salt River Project)

Good morning ladies and gentlemen. For those of us whose job it is to conserve and store water, nothing is more frustrating then to watch flood waters flow down the usually dry Salt River. The six reservoirs on the Salt and Verde Rivers do a pretty good job of balancing the good water years with the poor ones. However, periodically the flows exceed the storage capacity of the dams and during such periods the potential for even more water conservation exists. One possibility may be recharging the underground. In recent years, recharging the underground has been suggested as a partial solution to Orme Dam. Indeed there are a few who have suggested that it may be a complete solution.

The concept of underground recharge sounds simple. All you have to do is let the excess waters percolate into the underground and pump them out when they're needed. The realities of groundwater recharge are far more complex. We at the Salt River Project decided that a minimum of information was available on the subject as it relates to the Salt River Valley.

Recognizing that other areas in the west have had some successes at recharging, we thought it would be advantageous for the Water Resource Planners in Arizona to benefit from their experience.

Some of the questions that we hope to explore during this two-day symposium include the following:

Is groundwater recharge a viable tool in conserving flood waters in the Salt River Valley?

Is it technically feasible?

How much water is available for recharging the underground water supply in this area?

Is it economically feasible?

What are the legal problems involved?

Will it be compatible with our environment?

Is there sufficient land available for this purpose? And finally, and very importantly, How much will it cost?

The program has been carefully designed to develop as much information as is possible in the two-day period to help answer some of the many questions that exist in the application of groundwater recharge to this area. We're extremely pleased with the group of experts that have been assembled to help shed some light on these questions. We certainly appreciate their participation in what I hope will be one of the best symposiums you ever attended. In order to help maximize the benefits from having a group of such distinguished guests available for questions, we've also assembled into panels, groups of individuals who have some responsibility for water resource planning in the Valley, to ask questions and to develop a symposium summary. We feel that this technique will help us to meet our objective of gaining as much information as is possible during the next two days. Finally, let me express my appreciation to Reid Teeples, Salt River Project's Associate General Manager for Water, and to the many Salt River Project employees that have worked on arranging for this symposium. They've all done an outstanding job and you're about to benefit from the fruits of their labor. The attendance at this symposium is a fitting reward for their efforts. We very much appreciate your coming. Thank you.

AUTHOR'S BIOGRAPHICAL SKETCH

NAME: Byron N. Aldridge

EDUCATION: B.S. Degree in Civil Engineering from Washington State University

JOB POSITION: Surface Water Specialist for the U.S. Geological Survey, Tucson, Arizona

EXPERIENCE: Worked as a Hydrologist on a Department of Interior interdiscipline team studying the impacts of mining in Wyoming

Chief of Arizona District's Special Hydrologic Study Section for the U.S. Geological Survey

Prepared flood reports for the December 1965 and the September 1970 floods in the Salt River Basin

Chief of the U.S. Geological Survey Highway & Flood Section in Tacoma, Washington

STATISTICAL ANALYSIS OF FLOWS OF THE SALT & VERDE RIVERS, & RESERVOIR EVAPORATION (PART 1)

by

BYRON ALDRIDGE

The Water Resources Division of the U. S. Geological Survey, has collected water-related data for nearly a century. Its present data collection program includes surface water runoff, water quality measurements, groundwater data, and several other related items. We also measure sediment loads, chemical constituents, biological content, and radioactivity. During the years of data collection, methods and instrumentation have improved so that we can produce more with the same number of people, yet many of the proven methods have been retained and standardized so that the user knows that the records are of a good quality and collected basically the same way throughout the country. Records from one region are essentially comparable with those of another. The Arizona District operates a network of streamflow stations, many with the facilities for measuring water quality parameters. It measures groundwater levels in many wells, and provides basic data on the three aspects of water. The distribution of annual funds for the three aspects is about 60% for surface water data and studies, 20% each for groundwater and water quality. Basic data collection accounts for about 63% of the expenditures; and projects, interpretive studies (either research or to define water supply), flood potential and other water related characteristics, amount to about 37%.

A streamflow station consists of a stilling well where a float moves up and down with rises and falls in the water levels. The float drives a recorder that either draws a continuous trace of water level in the well or punches a record on paper tape. The streamflow stations operated by the Arizona District provide a record of water levels at sites at approximately 160 natural streams, 60 canals and several reservoirs. Many other sites have been gauged and water quality data are obtained at about 20 to 30% of the stations. The data collection program and interpretive studies are financed largely through cooperative agreements with Federal, State, County and City agencies; Irrigation Districts; Water Districts and groups like the Salt River Project. Forty-one of the streamflow stations are located in the Salt River Basin. Four of these are financed completely by Federal funds, 15 are financed jointly by the Survey and the Salt River Project, and 20 are financed through agreements with the Arizona Water Commission. One station is supported jointly by the Arizona Water Commission, the Salt River Project and U. S. Geological Survey.

The stations provide a record of where runoff originates and how the amounts change in downstream direction. Key stations for measuring inflow to the Salt and Verde reservoirs are those on the Salt River near Roosevelt, Tonto Creek above Gun Creek and the Verde above Tangle Creek. Key stations for measuring outflow are those on the Salt River below Stewart Mountain Dam and the

Verde River below Bartlett Dam. Several other stations provide advance warning of inflow to the reservoirs.

I mentioned that the program is cooperative; but a cooperating agency does not tell the U. S. Geological Survey what data to collect, or how to collect it. The cooperator's responsibilities are to specify the location where data is wanted, the type of data required for their needs and to tell the U. S. Geological Survey if the data fails to meet their needs. Otherwise, the data collection is a complete U. S. Geological Survey function. Whereas a cooperator may be interested in only one aspect of the hydrologic regime; example, flood flows or low flows; the U. S. Geological Survey has found that the station operated for one purpose may be a very key station for some other need. Therefore, we collect a complete record from low through high flows of every stream unless there is some very special reason that we cannot do so. Occasionally, if a station isn't suitable for records over an entire range, we may collect data over just part of the range, but that is only rarely done.

The hydrologist in the field makes discharge measurements. These discharge measurements are related to a stage so that a rating curve can be developed. This rating curve then is applied to the recorded gauge heights to obtain a daily record of discharge and the maximum flows and low flows during the period. The streamflow data are published annually in a report of water resources for Arizona. The published data includes daily, monthly, annual mean discharges, peaks above the specified base and minimum flow. Water Quality data for surface streams are published in the same report. The data are also stored in computer files that serve as input for several programs to generate statistical parameters that are more usable than the basic data. One program generates tables showing the number of days and percent of time discharge occurs for a given streamflow within certain ranges. The total range in discharge of the stream is generally divided into 32 increments. The data are known as Flow Duration Data. There's a program to extract the highest and lowest mean discharges for periods varying from 1 to 183 days. This data can be ranked for plotting frequency curves, or used as input for computing mathematical distributions according to frequency of occurrence. Frequency distributions of annual maximum discharge during each year can also be computed directly from the computer stored data. Another program computes monthly and yearly means. It also ranks means for each calendar month and computes flows that will occur 25%, 50%, and 75% of the time. It computes arithmetic and logarithmic means, standard deviation of the data for each month and year, and serial correlation between months. Output from these programs can be transferred to another file that provides stream flow and basin characteristics required for making regression analysis for one or more specific geographical areas. Such an analysis relates the streamflow characteristics to measurable basin characteristics.

Surface runoff is the most significant source of water for recharge. There's very little recharge from direct rainfall; recharge is all from surface water leaving the mountains and entering the Salt River Valley. Knowledge of the distribution of surface runoff, both with respect to time and geographical area, is a must for planning and managing any recharge project. A successful recharge project must account for the chemistry and sediment load of the water being used.

A knowledge of groundwater is also essential to the successful recharge project. The U. S. Geological Survey has collected, published, and stored in computer files, immense amounts of data regarding the groundwater system. Water levels are measured at least annually at index wells that are considered representative of geographical regions. A statewide summary of water levels, changes in water levels, and pumpage is published annually. Individual groundwater basins are being studied more thoroughly at the rate of 3 to 5 basins per year. For each study, wells are inventoried, and groundwater levels are measured in as many wells as possible. Water levels are contoured, and changes in water level since the last complete study are computed. One of the reports that's been done is for the Eastern Salt River Valley. This study shows declines of up to 350 feet in some places in the last 50 years, which leaves a very immense area that could be recharged if the other factors could be worked out. Interpretive studies on water supply, movement, operative characteristics are made for either geographical regions such as groundwater basins or for political subdivisions such as a county or an area within a reasonable distance of a metropolitan area. Bob Laney of our Phoenix Office is presently working on another study of the Eastern Salt River Valley to get more detail than what our present study shows. This study will show the potential yield of aquifers, permeability of alluvium, and amount of alluvium that has been dewatered. It fits very well into a recharge study because it can be used to determine how receptive the aquifers would be and volume of storage space available. Laney has found that some of the dewatered alluvium is highly permeable and very receptive to water.

Other studies that we have made in the past show some of the floodflows contribute large amounts of water to this area. The April 1955 release from the reservoirs was about 39,000 acre feet; 20,000 acre feet went past Granite Reef. The flow was down to a little over 5,000 acre feet by the time it reached 48th Street, and almost nothing went past 7th Avenue. During the December 1965 and January 1966 flood, there was over 600,000 second feet released from the reservoirs. About 200,000 second feet went into infiltration, and only 400,000 second feet reached Gillespie Dam. So, we know that there's very high infiltration capacity. In the time permitted, I've only been able to highlight the various types of data and work that the U. S. Geological Survey does. But, there's much more data in the files; more specific information and data can be obtained either from the Phoenix Office, or those in Flagstaff, Thatcher and Tucson.

AUTHOR'S BIOGRAPHICAL SKETCH

NAME: David S. Wilson, Jr.

EDUCATION: B.S. Degree in Watershed Management from the University of Arizona

JOB POSITION: Manager of Water Resource Operations for the Salt River Project

EXPERIENCE: Supervisor of the Surface Water Division at the Salt River Project

Supervisor of User Services Division at the Salt River Project

Watershed Specialist at the Salt River Project

STATISTICAL ANALYSIS OF FLOWS OF SALT AND

VERDE RIVERS, AND RESERVOIR EVAPORATION (PART 2)

by

D. S. WILSON

My presentation will cover three key areas: first, the review of the management of surface waters from the Salt and Verde River drainage basins and the past and present uses of this water in the Salt River Valley; secondly, the Salt River Project's (SRP) approach to conjunctive management of both surface and groundwater supplies; thirdly, provide information concerning what the realistic opportunities are for groundwater recharge from flood flows that are released at Granite Reef Dam.

To put things into perspective, there has been management and use of water in the Salt River Valley for many, many years. In fact, hundreds of years before the first white settlers arrived there was a flourishing, irrigated agricultural community here in the Salt River Valley which was maintained and operated by Indians known as the Hohokam (Figure 1). But for one or more reasons (a suspected cause is drought), this community vanished from the Salt River Valley (Figure 2). It was replaced in later years by the first white settlers who put in diversion works of their own and redeveloped many of the old Hohokam irrigation canals. These early pioneers had their problems. Conflicts caused by water shortage during drought periods were common (Figure 3). At the other extreme, high spring runoff and large amounts of flood water occasionally flowed down the river and washed out their diversion works (Figure 4). It wasn't until the early 1900's when the Salt River Valley Water User's Association was formed and Roosevelt Dam was constructed on the Salt River that man was able to exert some regulation and management of the surface flows originating on the Salt River Watershed (Figures 5 & 6). Later, as additional reservoirs were constructed, regulation of Verde River runoff was possible. With the control and added management flexibility provided by the reservoirs, a thriving agricultural community developed here in the Salt River Valley (Figure 7). Today, agricultural areas are rapidly being urbanized with attendent needs for water for municipal, industrial and domestic uses as well as agriculture. Additional benefits of surface water conservation and management include a variety of recreational opportunities, wildlife enhancement, and the generation of hydroelectric power at some of the reservoirs (Figure 8-11). Where does this water come from? It originates as precipatation which falls on the 13,000 square mile watershed which is drained by the Verde and Salt Rivers and Tonto Creek (Figure 12).

Most of the water flowing from the watershed results from melting snow that is deposited during the fall and winter. This source typically accounts for more than two-thirds of the runoff received in a normal year (Figure 13). That water is monitored at key gauging points, and the information is used for routine inflow analysis and operation of the reservoirs. Certain gauges are of particular importance during potential flooding periods because they provide lead time information before the water gets to the reservoirs (Figure 14).

Once the water flows into the reservoir system, it is stored, managed and released from a system of six reservoirs; the largest and oldest being Roosevelt, completed in 1911 with a storage capacity of almost 1.4 million acre feet. The most recent addition to the reservoir systems is Horseshoe, completed in 1946 on the Verde River system. Water stored in the four reservoirs on the Salt River and two reservoirs on the Verde River, is ultimately released for use here in the Salt River Valley. Those reservoirs' releases are diverted into the SRP canal system at the Granite Reef Diversion Dam located below the confluence of the Salt and Verde Rivers.

Each year the Salt River Project establishes a reservoir operations plan. Some of the plan considerations include: the total water demand that is anticipated and what kind of reservoir releases and pumping might be required to meet that user demand; the amount of water in storage at the start of the year; and projected runoff for the year. One of the key objectives of reservoir operations is to provide carry-over storage for low runoff years. Actual operation includes maximizing releases from the Salt River system during the summer, to provide optimum benefits from hydroelectric generation. The Salt River reservoirs are the only ones presently equipped to generate power. Releases from the Verde River reservoirs are maximized during the wintertime to provide adequate storage capacity in the Verde system to capture spring runoff. The highest groundwater pumping regiment is maintained during the spring and summer months to supplement surface water deliveries.

The ultimate objective is to ensure dependable water supplies for the Salt River Valley. Groundwater is used to supplement surface water only to the extent necessary to provide carry-over storage in low runoff years. Therefore, pumping is less when the most surface water is available, and conversely, the most pumping occurs when the least surface water is available.

Looking at surface water supplies more closely, there was an extremely large runoff event on both the Salt and Verde Rivers in March of 1978 and that's what most of us remember. But if we look at the past 89 years of runoff record, the wide range of variability in the runoff events is clearly evident (Figures 15-15E).

Watershed and weather conditions sometimes produce peak flows that are quite dramatic, but routinely, river flows are moderate to very low for extended periods of time. The annual demand for water in the Salt River Project delivery area is about 1.2 million acre feet. During the 65 year period of record since the first flood release was made in 1913, there have been 18 years in which the annual inflow to the reservoir system exceeded that demand of 1.2 million acre feet. There have been only five years when flows equalled the demand, and there have been 42 years when the annual inflows were below the annual demand - some 64% of the record period (Table 1).

What about the flood releases that have been made. These releases are measured at Granite Reef Diversion Dam. The first release in 1913 peaked at 3,700 cfs. There were three different release periods in that year; February, March and April. Water ran at Granite Reef Dam into the Salt River channel during those three release periods for some 30 days. Reviewing the record from 1913 to present, there have been several relatively large peak releases: 1916 - 79,000 cfs; 1919 - 46,000 cfs; 1932 - 48,000; 1938 - 58,000 cfs; 1965 - 67,000 cfs; 1966 - 53,000 cfs and 113,000 cfs in 1978. The total record indicates different release events over a period of 65 years, with a total number of release days at 899 (Tables 2 & 3).

What about opportunities for groundwater recharge using surplus water. Looking at the complete record from 1911 (when Roosevelt Dam was completed) and assuming that there will be no more additional releases in 1978; there have been 96 total release events during the 68 year period with a total of 899 release days out of 24,820 possible days. This means that there was surplus flood water available at Granite Reef Dam which could have been used for groundwater recharge only 3.6% of the time during the 68 year period. However, the reservoir system wasn't completed until 1946. Since completion of the total reservoir system, surplus flood water has been available to Granite Reef Dam for recharge programs only 1.7% of the time (Tables 4 & 5).

A lot of concern developed as a result of the releases that had to be made in March of 1978. When that storm developed, the Verde River system was about 50% empty. During that runoff event, some 652,000 acre feet of inflow was received. What happened to the 652,000 acre feet? 102,000 of it was stored in the Verde reservoir sytem. Some 21,000 acre feet was diverted at Granite Reef Diversion Dam and delivered to users here in the Valley. 529,000 acre feet was released to the Salt River channel. The interesting point is that some 526,000 acre feet or 99.5% of the total water released to the river bed was released during a short eight day period from March 1st through March 8th (Table 6).

This dramatized the point to be made. There are very few events in which flood flow releases from the reservoir system go to the river below Granite Reef. These flows are usually of large magnitude, short duration, and carry heavy sediment loads. Other releases that occur during any particular year are from local inflows below the reservoirs or from the Salt River Valley area. These are very small in nature. The obvious conclusion is that there is no significant surplus flood water flows available on an annual basis for routine groundwater recharge programs. Our challenge and our concern needs to be directed toward handling the infrequent large flood events!

TABLE 1 SURPLUS (FLOOD) WATER STATISTICS

YEARS	ANNUAL INFLOW	PERCENT
18	EXCEED DEMAND	28
5	EQUAL DEMAND	8
42	BELOW DEMAND	64
65		100

BASED ON 65 YEARS OF RECORD: 1913 - 1977

AVERAGE ANNUAL DEMAND = 1.2 M.A.F.

TABLE 2 SIGNIFICANT WATER RELEASES BELOW GRANITE REEF DIVERSION DAM

In Cubic Feet Per Second

YEAR	CFS PEAK FLOW	DATES	TOTAL RELEASE EVENTS	TOTAL RELEASE DAYS
1965	67,000	APR. DEC.	2	4
1966	53,000	JAN., FEB., MAR.	2	33
1967	2,950	DEC.	1	2
1968	3,703	FEB., MAR., APR.	4	26
1972	10,000	JUNE, OCT., NOV. DEC.	4	9
1973	20,254	JAN., FEB., MAR.-MAY	4	101
1978	113,000	MAR., APR.	2	23
		TOTALS	96	899

(As of Nov. 22, 1978)

TABLE 3 SIGNIFICANT WATER RELEASES
BELOW GRANITE REEF DIVERSION DAM

IN CUBIC FEET PER SECOND

YEAR	PEAK FLOW	DATES	TOTAL RELEASE EVENTS	TOTAL RELEASE DAYS
1913	3,700	FEB. MARCH, APRIL	3	30
1914	15,700	JAN., FEB.,MAR.,DEC.	3	21
1915	18,700	JAN., FEB., MAR., APR., MAY, AUG., SEPT., DEC.	7	80
1916	79,100	JAN.- MAY, SEPT., OCT.	3	128
1917	23,100	JAN, FEB., MAR., APR. MAY	3	39
1918	28,400	FEB., MAR., AUG.	3	19
1919	46,200	FEB., MAR., APR., JULY AUG., NOV., DEC.	5	30
1920	87,800	JAN., FEB.- APR.	3	58
1921	15,900	JULY, AUG., DEC.	4	8
1922	24,100	JAN., FEB., MAR.	4	17
1923	42,300	MAR., SEPT., NOV. DEC.	4	19
1924	5,990	JAN., APR.	3	8
1926	28,800	APRIL	2	15
1928	7,820	FEB.	1	5
1929	17,200	APR., MAY	2	7
1931	22,900	FEB., DEC.	2	9
1932	48,700	FEB., MAR.	3	35
1935	6,827	JAN. FEB. MAR.	5	13
1936	4,000	FEB.	1	1
1937	36,891	FEB. MAR.	3	21
1938	57,554	MAR.	2	10
1940	2,495	DEC.	2	3
1941	32,206	FEB.- MAY	3	95

TABLE 4 SALT RIVER PROJECT

WATER MANAGEMENT FACILITIES

STORAGE DAMS	DATE	CAPACITY (AF)
ROOSEVELT	1905 - 1911	1,381,580
HORSE MESA	1924 - 1927	245,138
MORMON FLAT	1923 - 1925	57,852
STEWART MOUNTAIN	1928 - 1930	69,765
SUBTOTAL SALT SYSTEM		1,754,335
HORSESHOE	1944 - 1946	139,238
BARTLETT	1936 - 1939	178,477
SUBTOTAL VERDE SYSTEM		317,715
TOTAL		2,072,050
DIVERSION DAM		
GRANITE REEF	1906 - 1908	-

TABLE 5 CALCULATIONS FROM TABLE OF SIGNIFICANT RELEASES BELOW GRANITE REEF DIVERSION DAM

PERIOD OF RECORD	68 YEARS (1911-1978*)
TOTAL RELEASE EVENTS	96
TOTAL RELEASE DAYS	899
SURPLUS FLOOD WATER AVAILABLE	3.6% OF RECORD PERIOD

*ASSUMING NO ADDITIONAL RELEASES IN 1978

AFTER COMPLETION OF RESERVOIR SYSTEM
(HORSESHOE DAM, 1946)

PERIOD OF RECORD	32 YEARS (1946-1978*)
TOTAL RELEASE EVENTS	19
TOTAL RELEASE DAYS	198
SURPLUS FLOOD WATER AVAILABLE	1.7% OF RECORD PERIOD

*ASSUMING NO ADDITIONAL RELEASES IN 1978

TABLE 6 STORM OF MARCH 1978

VERDE SYSTEM

INFLOW	652,000 AF
STORED	102,000 AF
USED	21,000 AF
RELEASED	*529,000 AF

*526,000 AF (99.4%) OF TOTAL RELEASE WAS MADE IN 8 DAYS (MARCH 1-8, 1978).

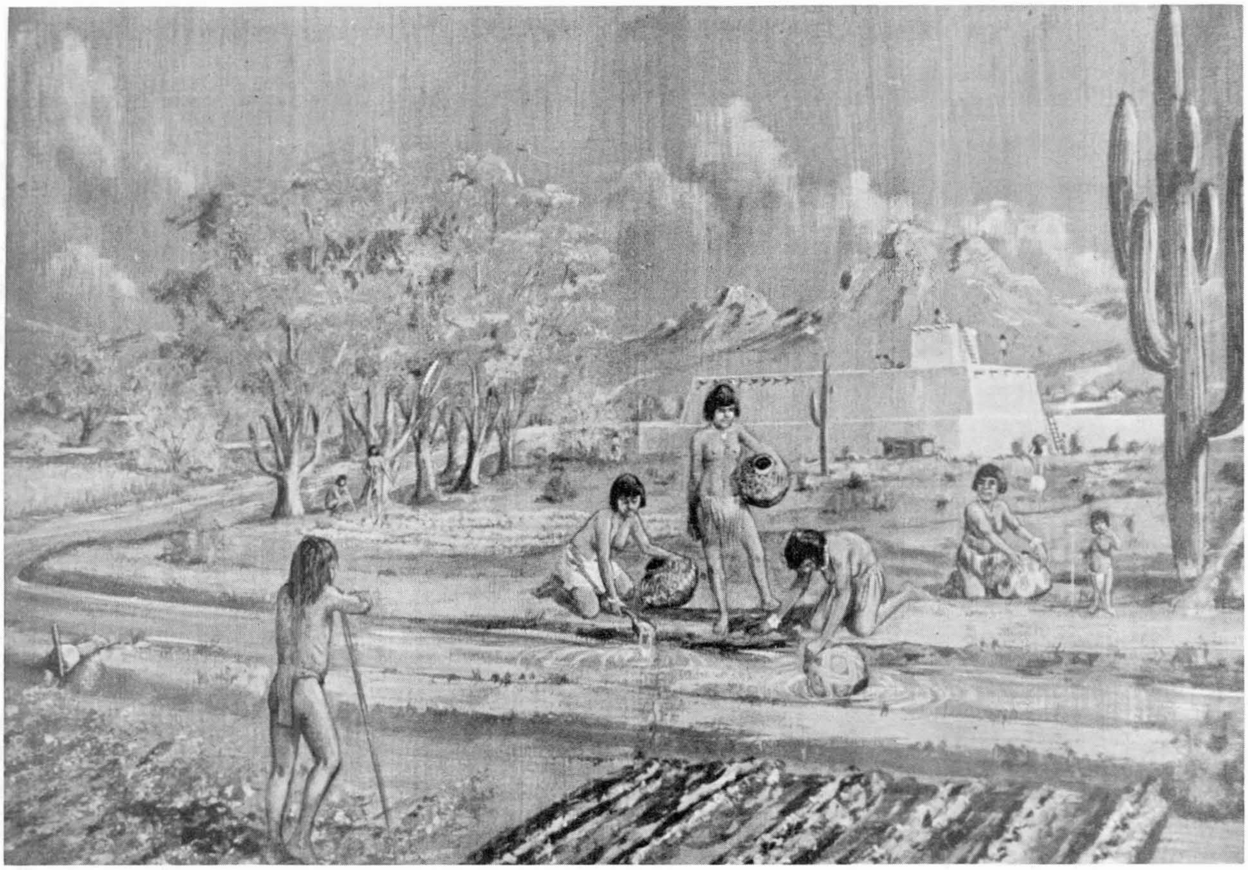


FIGURE 1 - THE HOHOKAM INDIANS PRACTICED FARM IRRIGATION PRIOR TO THE ARRIVAL OF THE FIRST PIONEERS

FIGURE 2 - DROUGHT MAY HAVE DRIVEN THE HOHOKAM FROM THE VALLEY

FIGURE 3 - EARLY-DAY CONFLICTS WERE CREATED BY DROUGHT CONDITIONS

FIGURE 4 - FLOOD FLOWS WASHED AWAY IRRIGATION DIVERSION WORKS

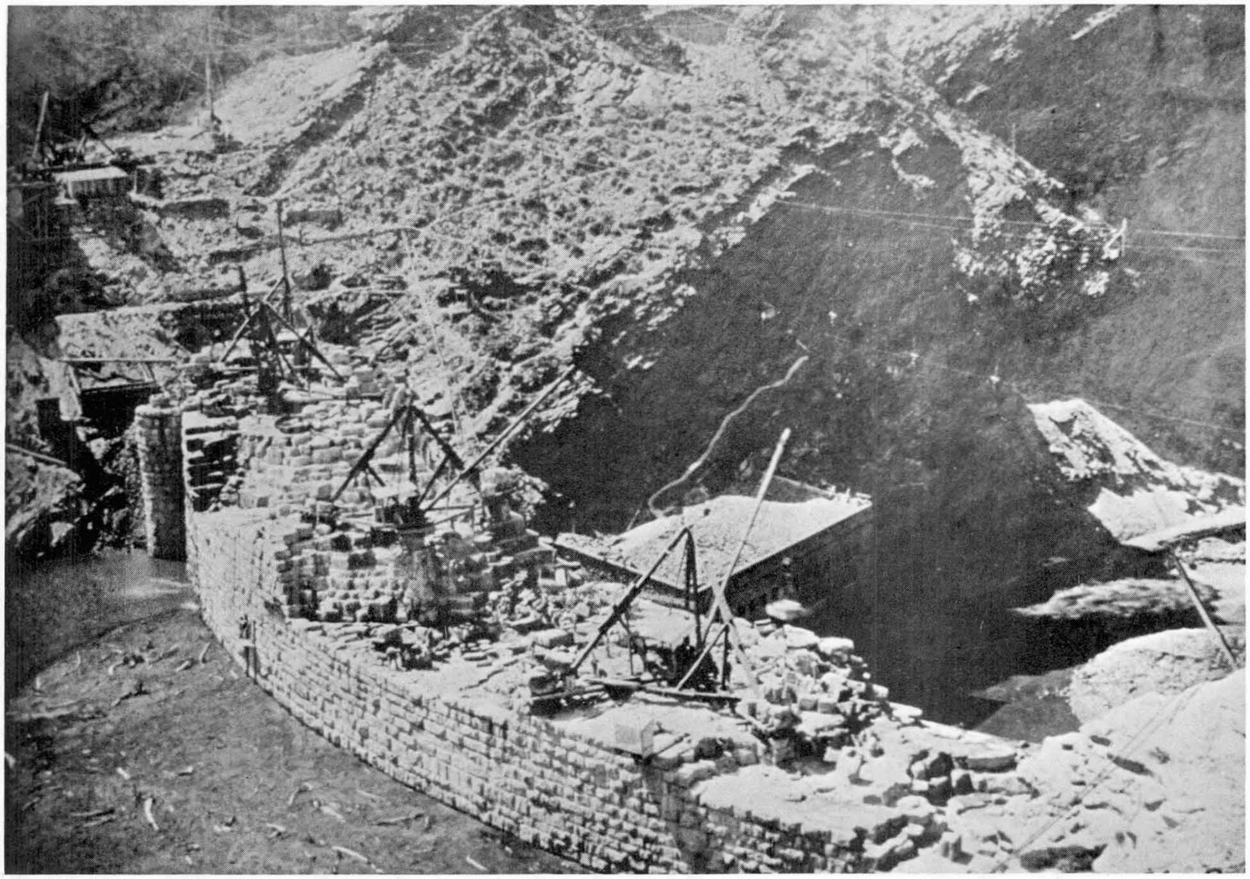


FIGURE 5 - ROOSEVELT DAM UNDER CONSTRUCTION

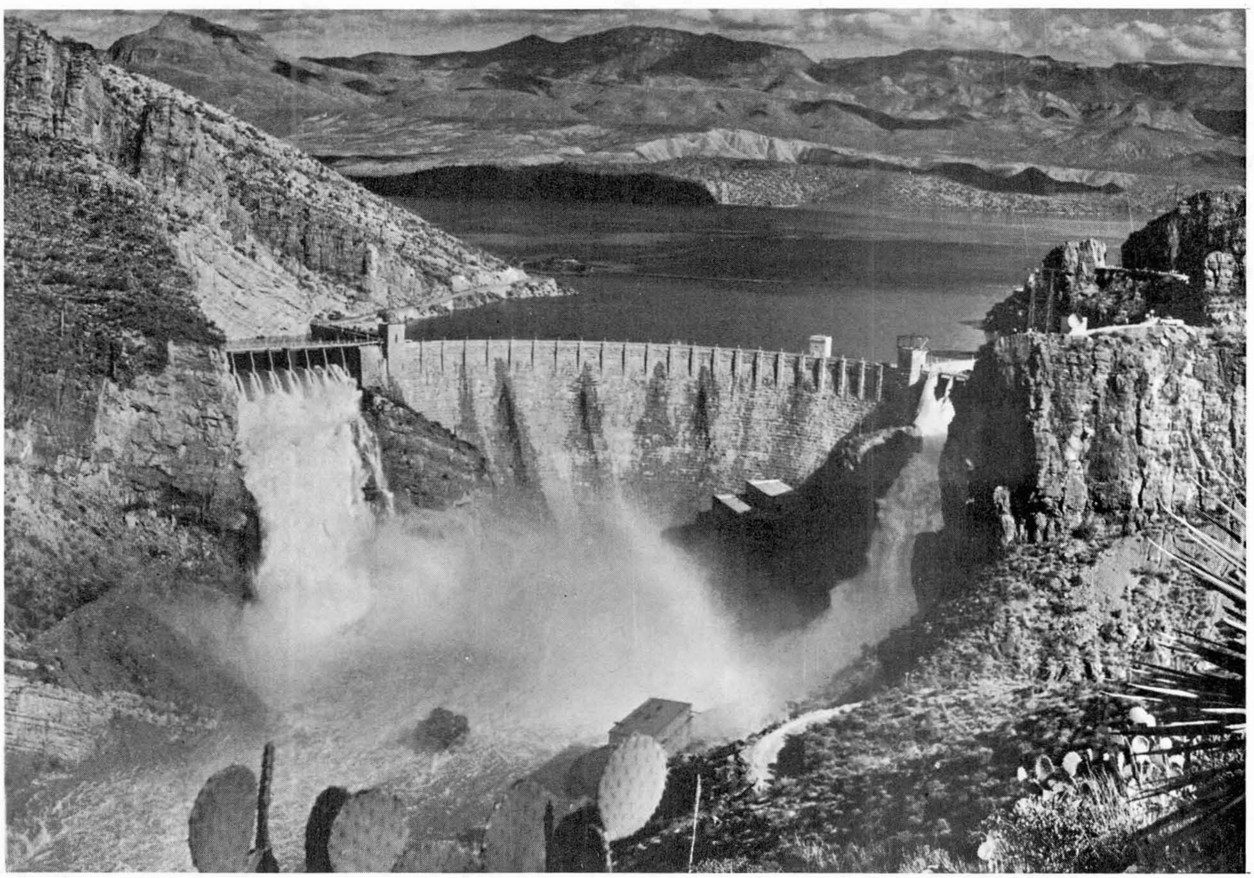


FIGURE 6 - ROOSEVELT DAM

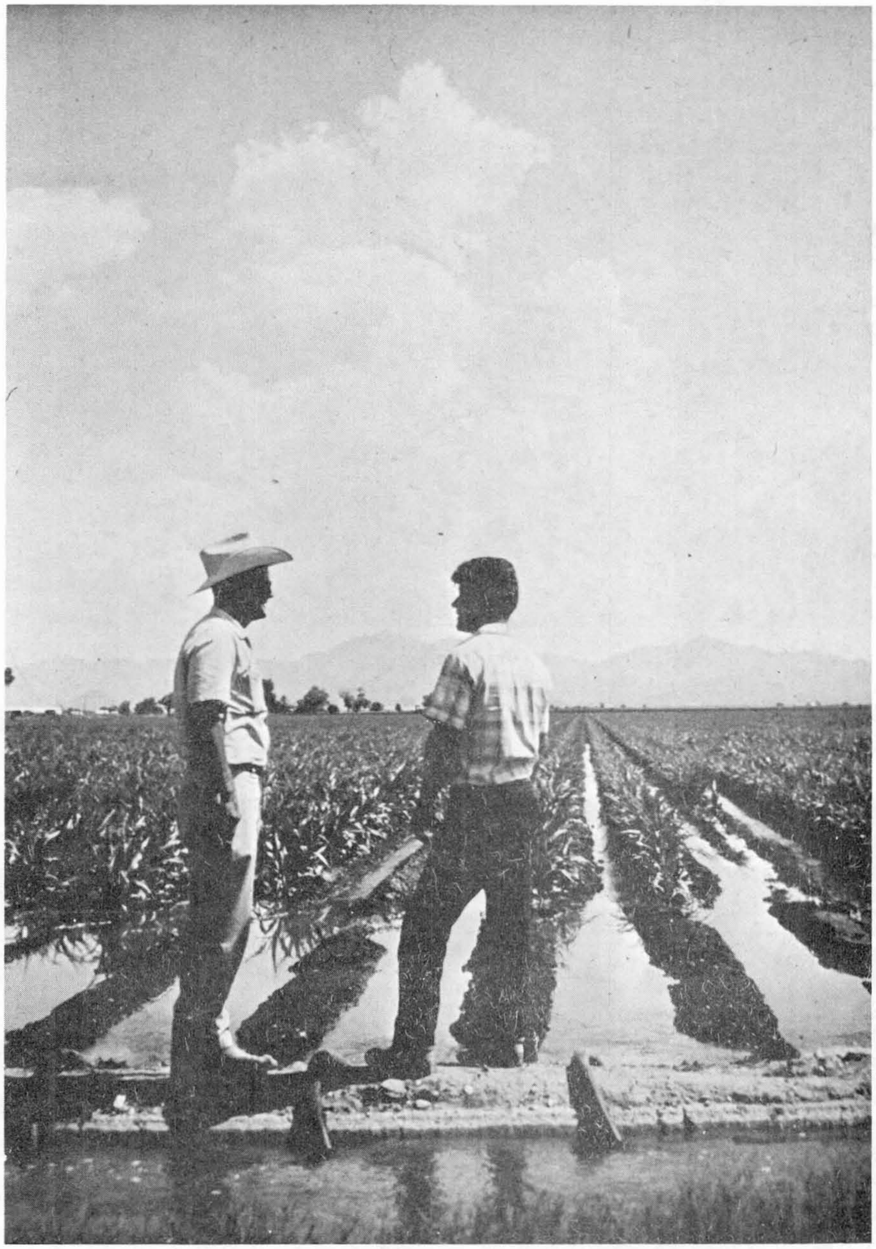


FIGURE 7 - AGRICULTURE

FIGURE 8 - MUNICIPAL

FIGURE 9 - DOMESTIC

FIGURE 10 - RECREATION

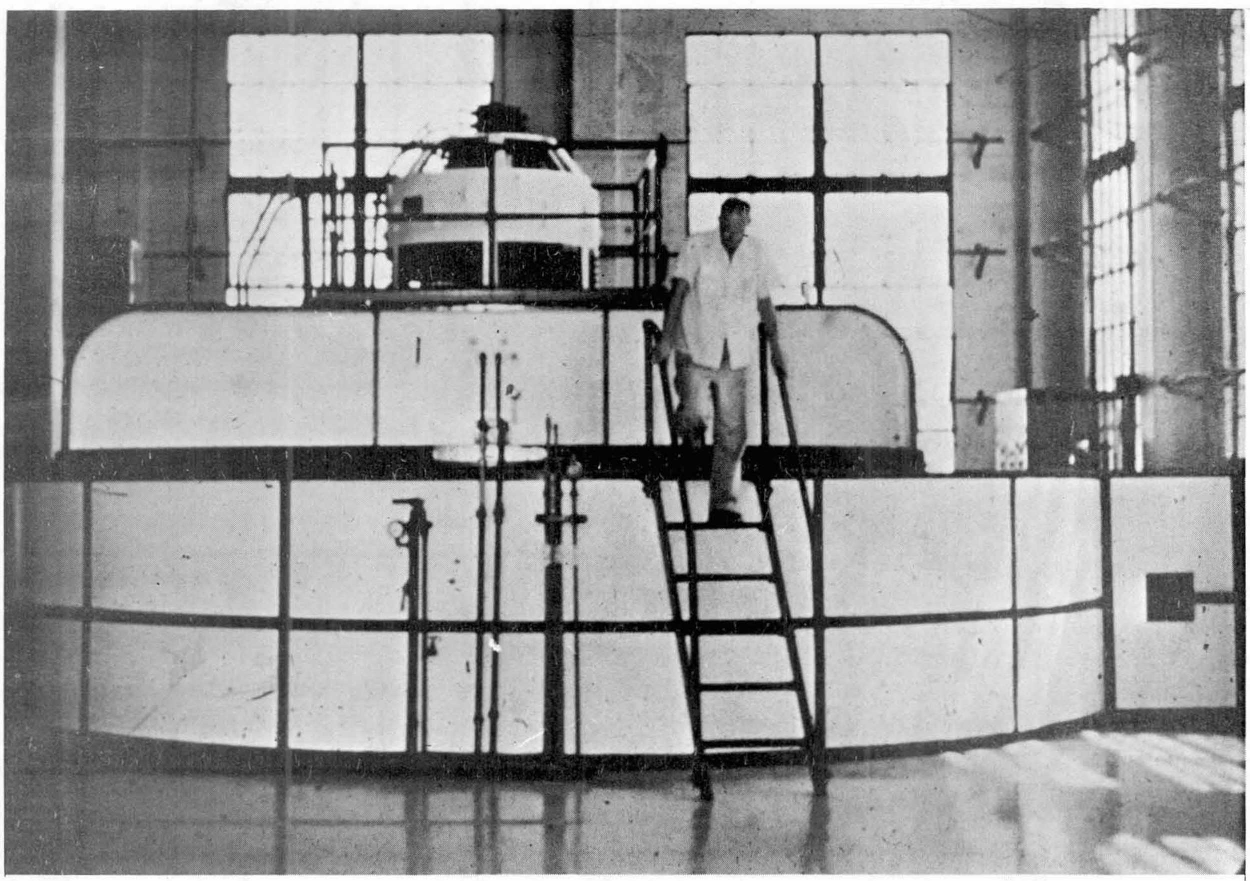


FIGURE 11 - HYDROGENERATION

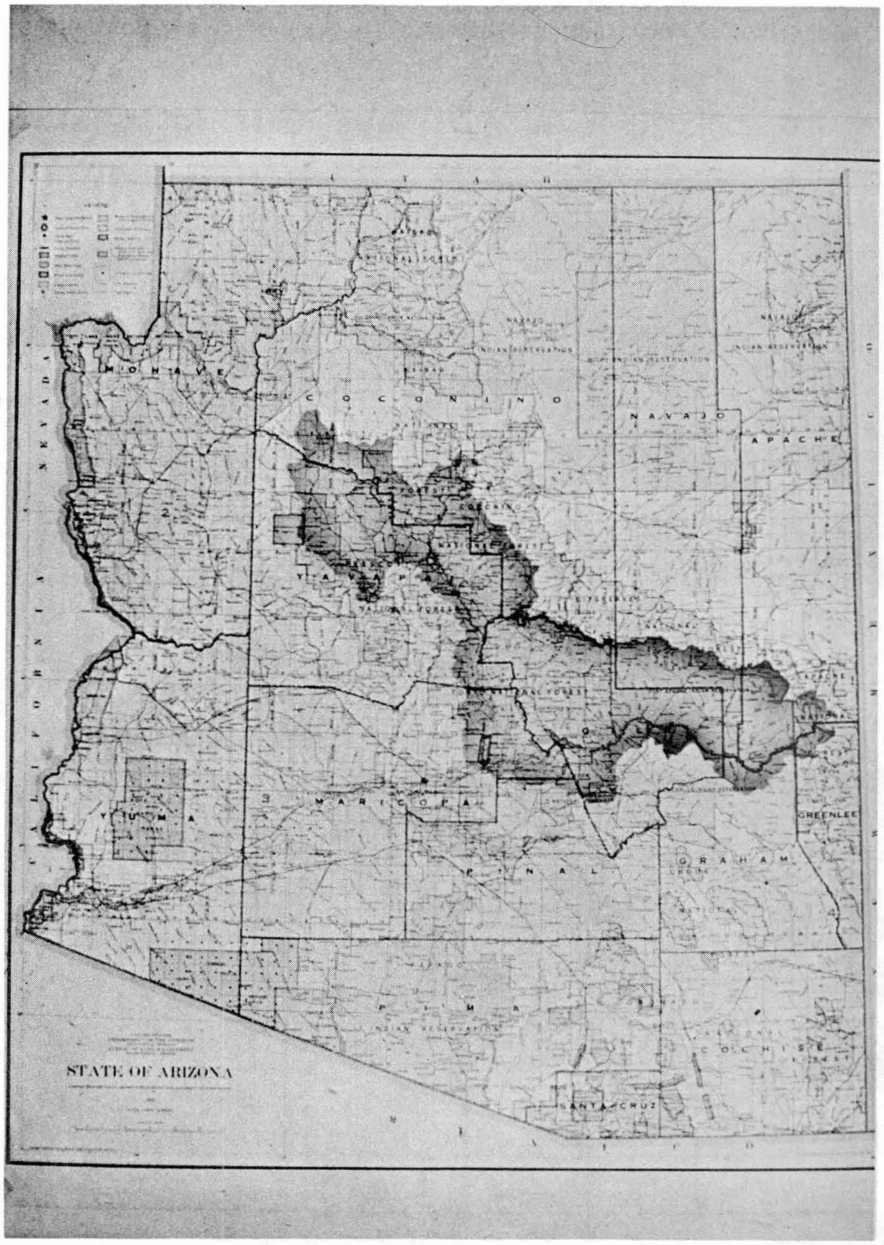


FIGURE 12 - SALT, VERDE & TONTO WATERSHED AREA

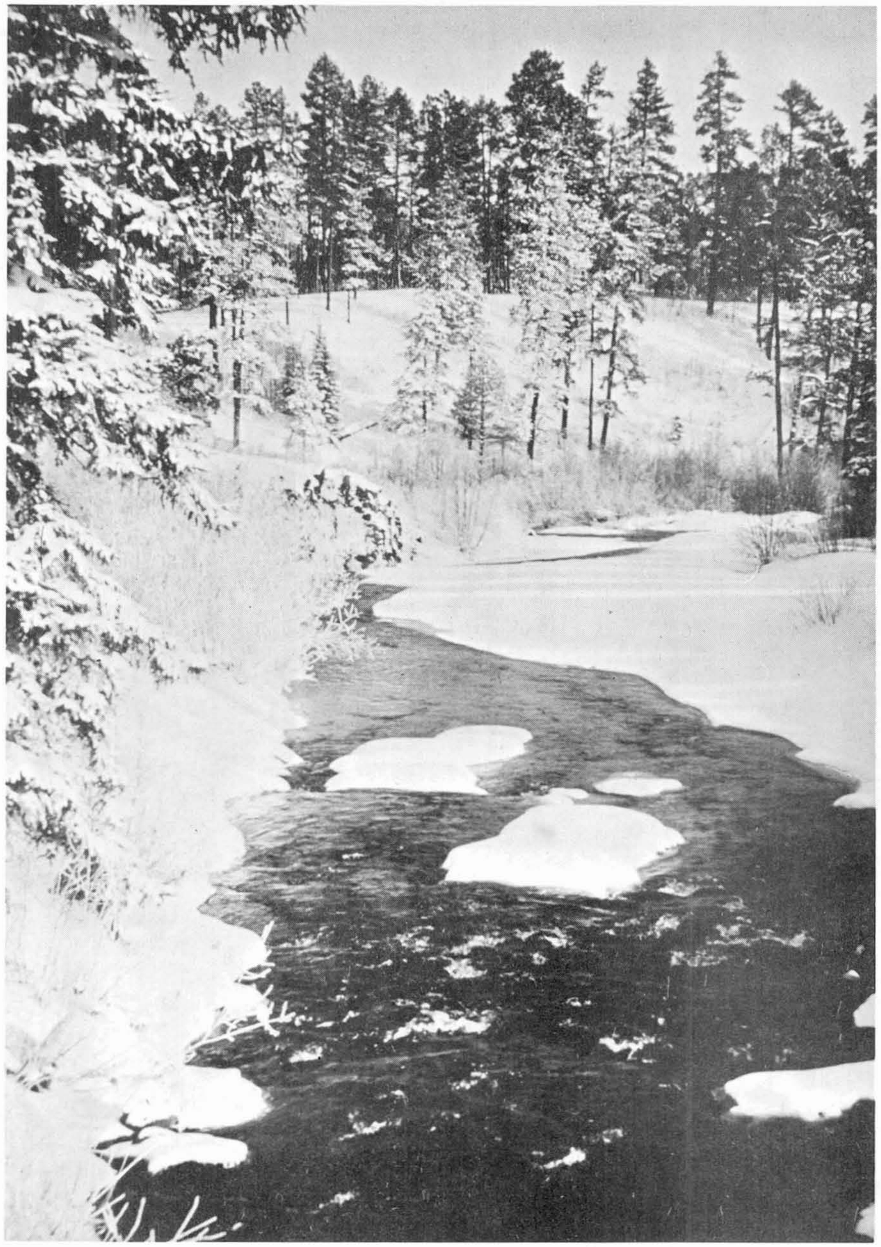


FIGURE 13 - SPRING SNOW MELT

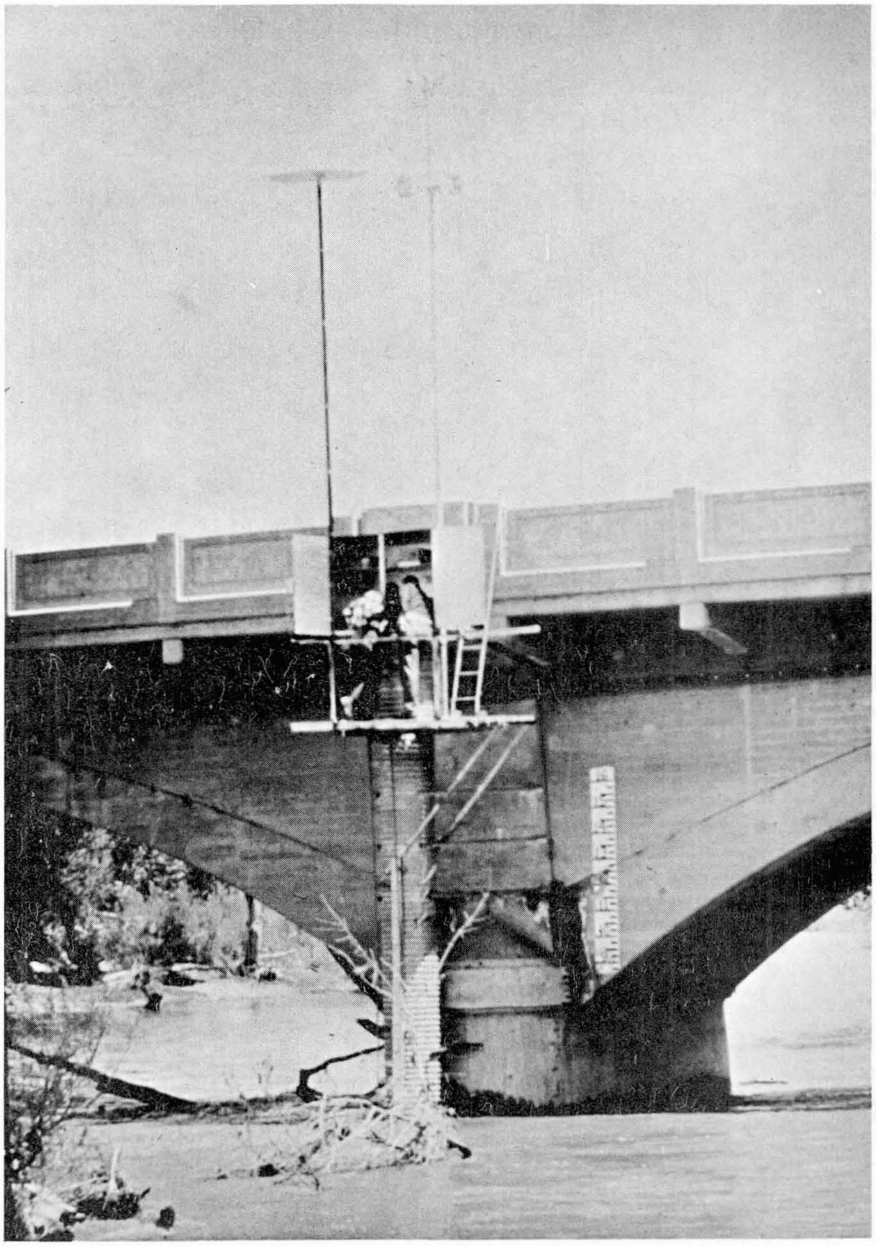
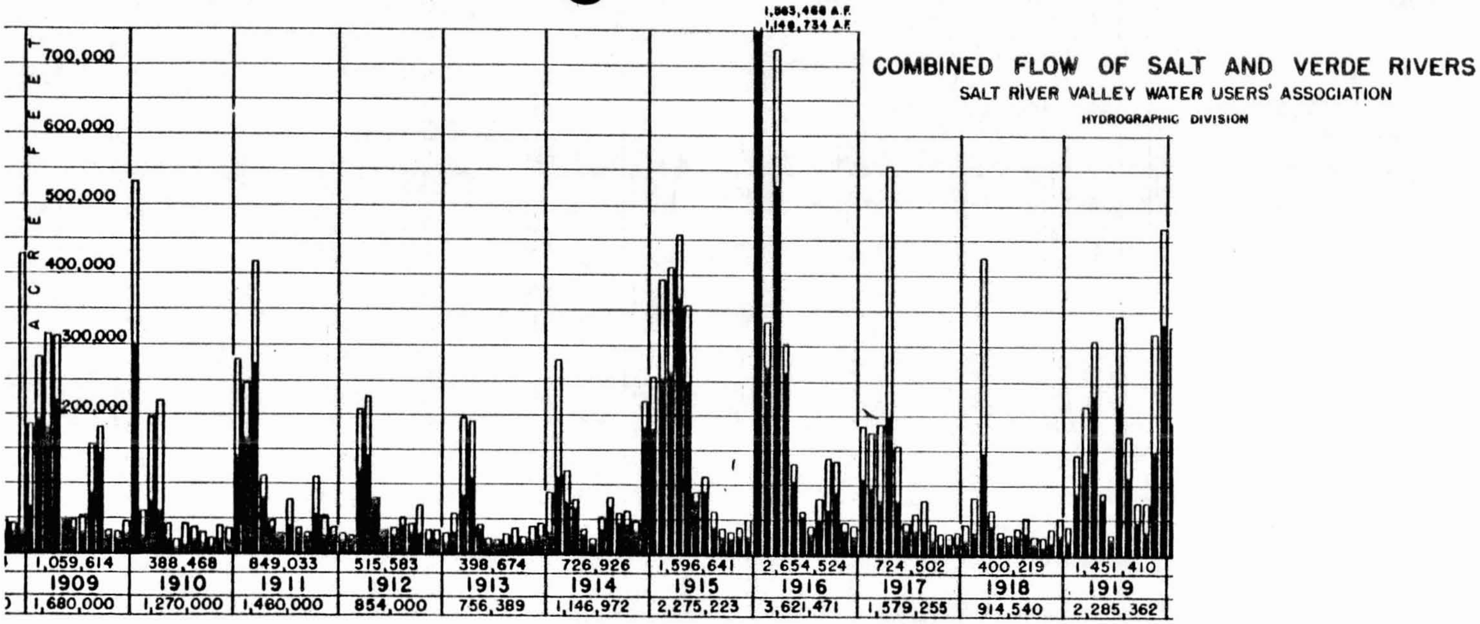


FIGURE 14 - RIVER GAGING STATION


COMBINED FLOW OF SALT AND VERDE RIVERS
SALT RIVER VALLEY WATER USERS' ASSOCIATION
HYDROGRAPHIC DIVISION
ACRE FEET
700,000
600,000
500,000
400,000
300,000
200,000
1,863,466 A.F.
1,149,734 A.F.
1,059,614
1909
1,680,000
388,468
1910
1,270,000
849,033
1911
1,460,000
515,583
1912
854,000
398,674
1913
756,389
726,926
1914
1,146,972
1,596,641
1915
2,275,223
2,654,524
1916
3,621,471
724,502
1917
1,579,255
400,219
1918
914,540
1,451,410
1919
2,285,362

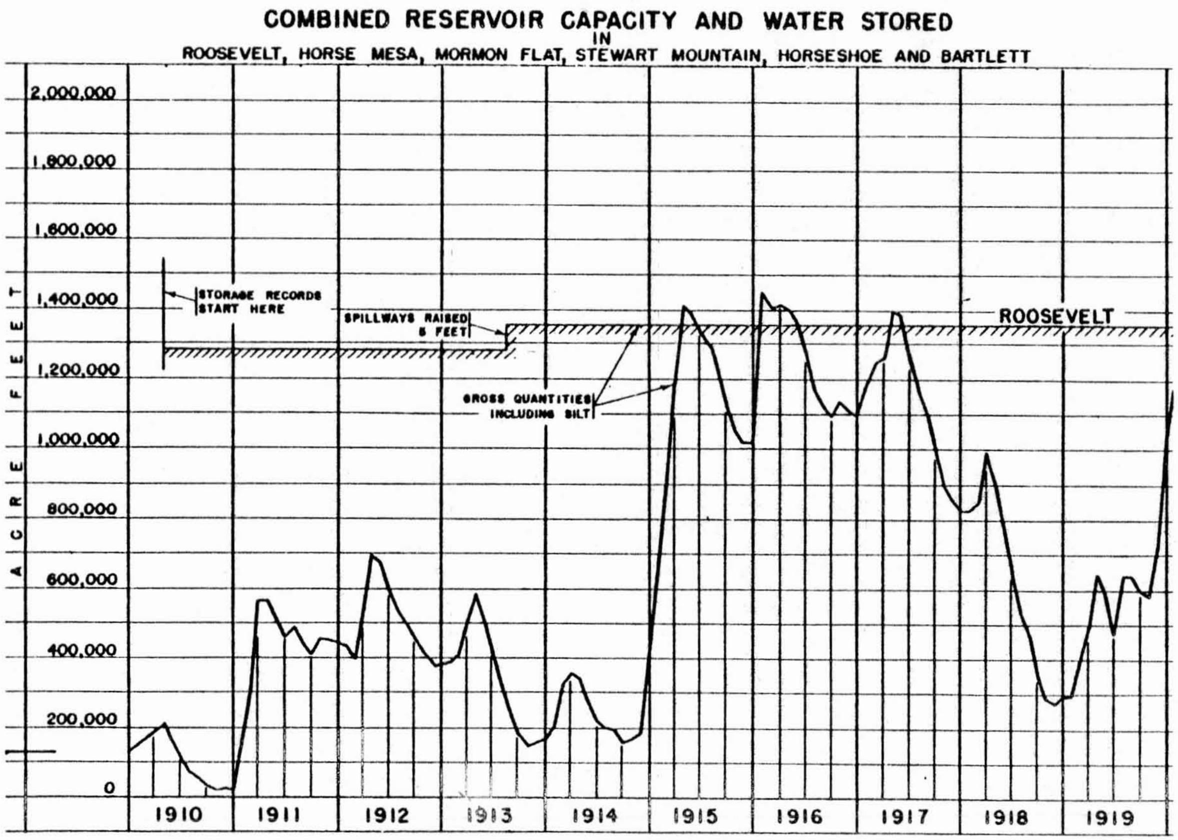
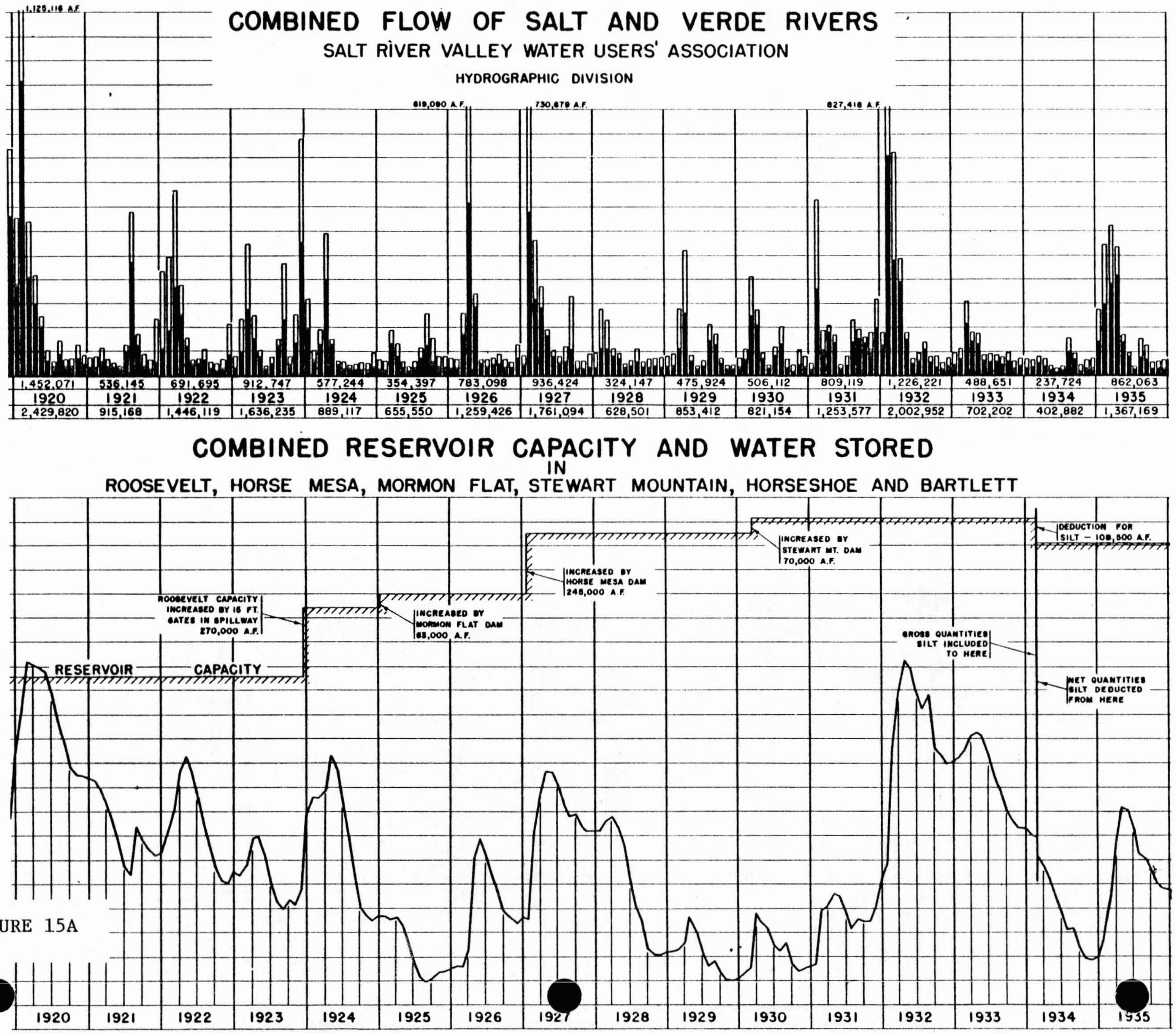

COMBINED RESERVOIR CAPACITY AND WATER STORED
IN
ROOSEVELT, HORSE MESA, MORMON FLAT, STEWART MOUNTAIN, HORSESHOE AND BARTLETT
ACRE FEET
2,000,000
1,800,000
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
STORAGE RECORDS START HERE
SPILLWAYS RAISED 5 FEET
GROSS QUANTITIES INCLUDING SILT
ROOSEVELT
1910
1911
1912
1913
1914
1915
1916
1917
1918
1919

FIGURE 15



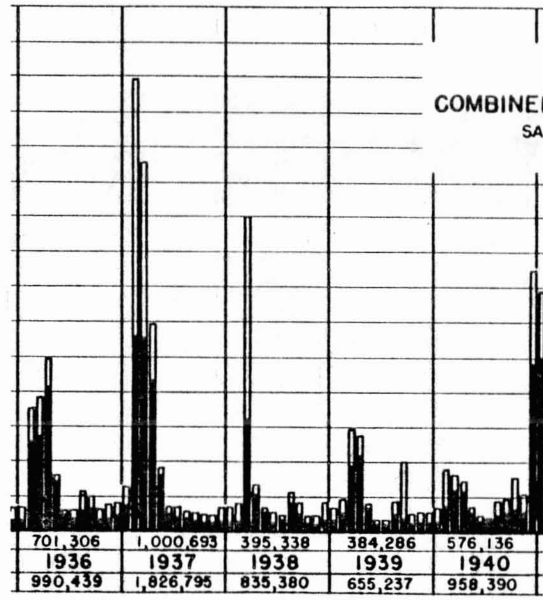
COMBINED FLOW OF SALT AND VERDE RIVERS
SALT RIVER VALLEY WATER USERS' ASSOCIATION
HYDROGRAPHIC DIVISION
1,125,116 A.F.
619,090 A.F.
730,679 A.F.
827,418 A.F.
1,452,071 | 536,145 | 691,695 | 912,747 | 577,244 | 354,397 | 783,098 | 936,424 | 324,147 | 475,924 | 506,112 | 809,119 | 1,226,221 | 488,651 | 237,724 | 862,063
1920 | 1921 | 1922 | 1923 | 1924 | 1925 | 1926 | 1927 | 1928 | 1929 | 1930 | 1931 | 1932 | 1933 | 1934 | 1935
2,429,820 | 915,168 | 1,446,119 | 1,636,235 | 889,117 | 655,550 | 1,259,426 | 1,761,094 | 628,501 | 853,412 | 821,154 | 1,253,577 | 2,002,952 | 702,202 | 402,882 | 1,367,169
COMBINED RESERVOIR CAPACITY AND WATER STORED
IN
ROOSEVELT, HORSE MESA, MORMON FLAT, STEWART MOUNTAIN, HORSESHOE AND BARTLETT
RESERVOIR CAPACITY
ROOSEVELT CAPACITY INCREASED BY 15 FT. GATES IN SPILLWAY 270,000 A.F.
INCREASED BY MORMON FLAT DAM 63,000 A.F.
INCREASED BY HORSE MESA DAM 245,000 A.F.
INCREASED BY STEWART MT. DAM 70,000 A.F.
DEDUCTION FOR SILT – 108,500 A.F.
GROSS QUANTITIES SILT INCLUDED TO HERE
NET QUANTITIES SILT DEDUCTED FROM HERE
1920
1921
1922
1923
1924
1925
1926
1927
1928
1929
1930
1931
1932
1933
1934
1935

FIGURE 15A

COMBINED FLOW OF SALT AND VERDE RIVERS

SALT RIVER VALLEY WATER USERS' ASSOCIATION

HYDROGRAPHIC DIVISION



COMBINED RESERVOIR CAPACITY AND WATER STORED IN ROOSEVELT, HORSE MESA, MORMON FLAT, STEWART MOUNTAIN, HORSESHOE AND BARTLETT

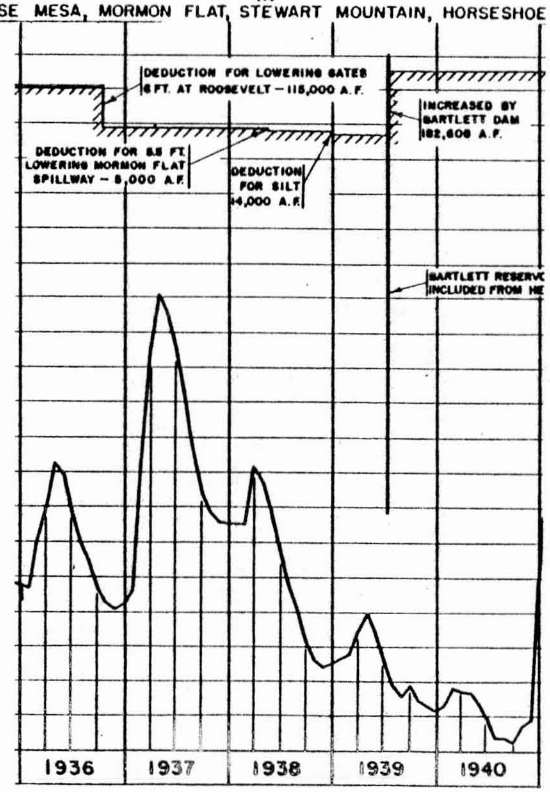
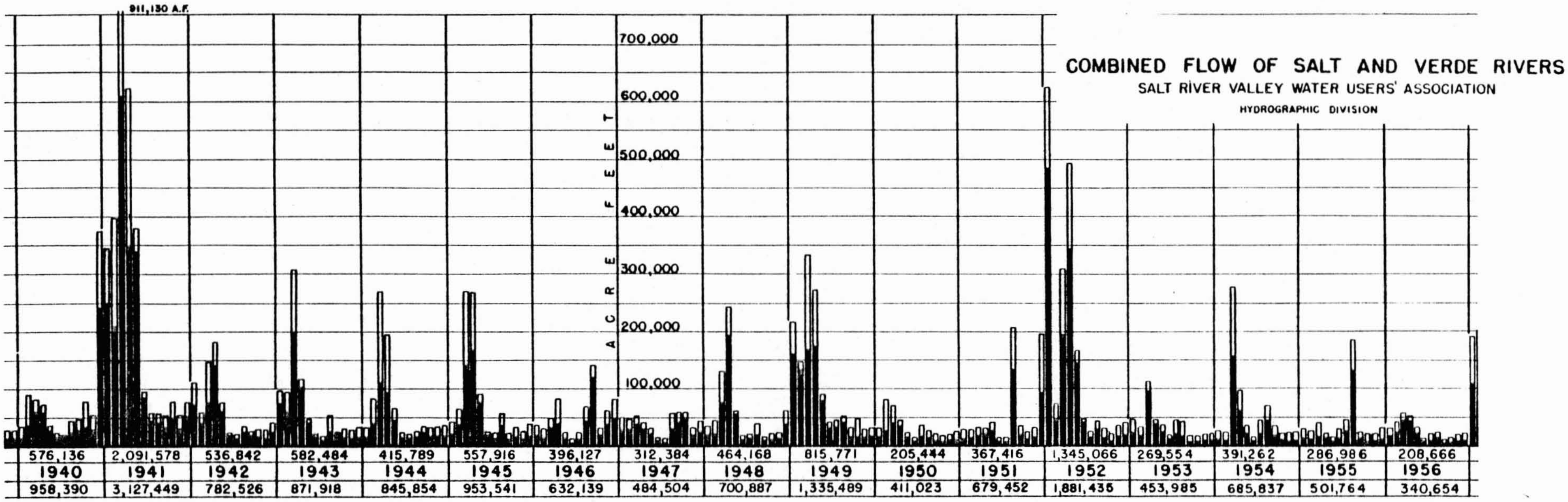


FIGURE 15B


COMBINED FLOW OF SALT AND VERDE RIVERS
SALT RIVER VALLEY WATER USERS' ASSOCIATION
HYDROGRAPHIC DIVISION
911,130 A.F.
ACRE FEET
700,000
600,000
500,000
400,000
300,000
200,000
100,000
576,136 1940 958,390
2,091,578 1941 3,127,449
536,842 1942 782,526
582,484 1943 871,918
415,789 1944 845,854
557,916 1945 953,541
396,127 1946 632,139
312,384 1947 484,504
464,168 1948 700,887
815,771 1949 1,335,489
205,444 1950 411,023
367,416 1951 679,452
1,345,066 1952 1,881,435
269,554 1953 453,985
391,262 1954 685,837
286,986 1955 501,764
208,666 1956 340,654

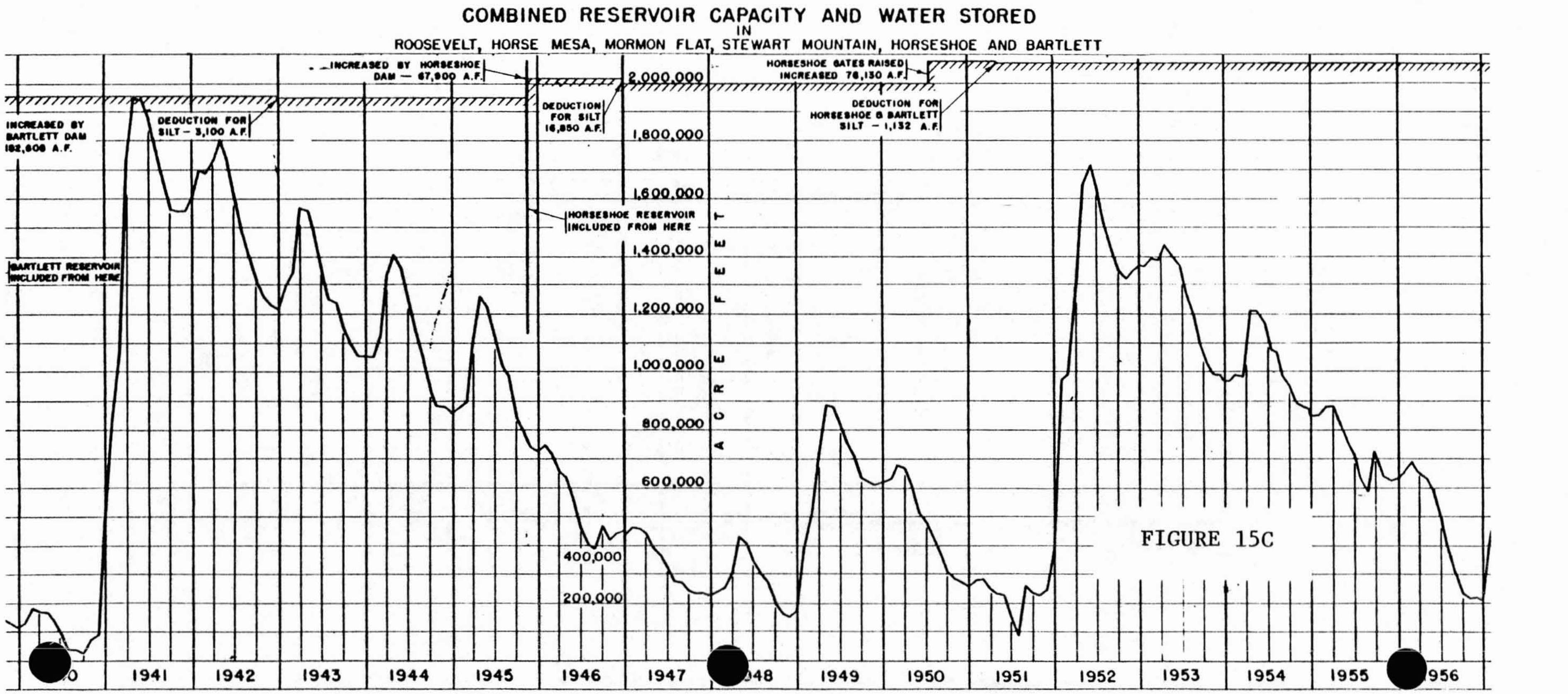

COMBINED RESERVOIR CAPACITY AND WATER STORED IN
ROOSEVELT, HORSE MESA, MORMON FLAT, STEWART MOUNTAIN, HORSESHOE AND BARTLETT
INCREASED BY HORSESHOE DAM — 67,900 A.F.
HORSESHOE GATES RAISED INCREASED 76,130 A.F.
INCREASED BY BARTLETT DAM 182,606 A.F.
DEDUCTION FOR SILT – 3,100 A.F.
DEDUCTION FOR SILT 16,850 A.F.
DEDUCTION FOR HORSESHOE & BARTLETT SILT – 1,132 A.F.
HORSESHOE RESERVOIR INCLUDED FROM HERE
BARTLETT RESERVOIR INCLUDED FROM HERE
ACRE FEET
2,000,000
1,800,000
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
1941
1942
1943
1944
1945
1946
1947
1949
1950
1951
1952
1953
1954
1955

FIGURE 15C

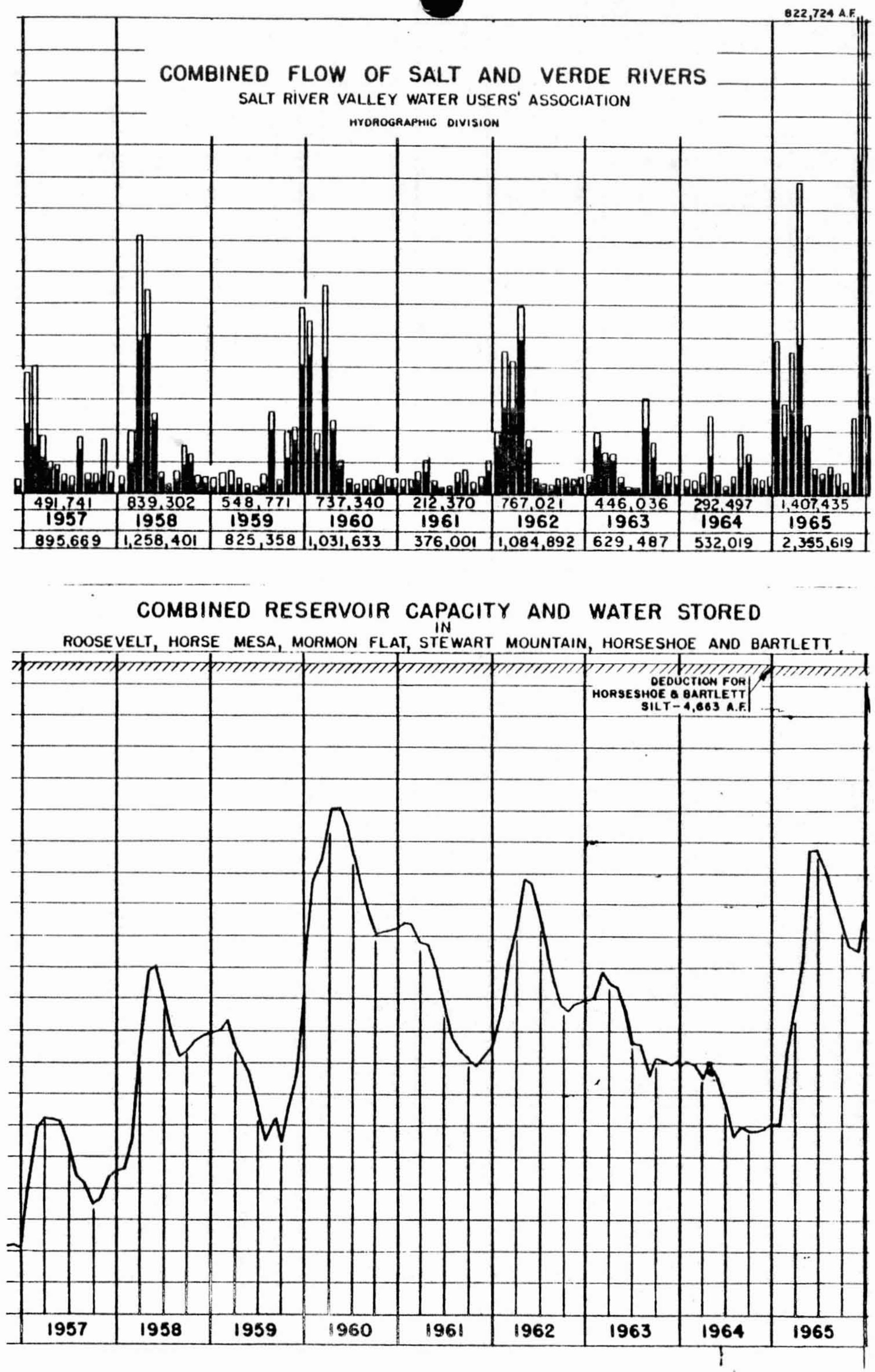

822,724 A.F.
COMBINED FLOW OF SALT AND VERDE RIVERS
SALT RIVER VALLEY WATER USERS' ASSOCIATION
HYDROGRAPHIC DIVISION
491,741
1957
895,669
839,302
1958
1,258,401
548,771
1959
825,358
737,340
1960
1,031,633
212,370
1961
376,001
767,021
1962
1,084,892
446,036
1963
629,487
292,497
1964
532,019
1,407,435
1965
2,355,619
COMBINED RESERVOIR CAPACITY AND WATER STORED
IN
ROOSEVELT, HORSE MESA, MORMON FLAT, STEWART MOUNTAIN, HORSESHOE AND BARTLETT
DEDUCTION FOR HORSESHOE & BARTLETT SILT - 4,663 A.F.
1957
1958
1959
1960
1961
1962
1963
1964
1965

FIGURE 15D

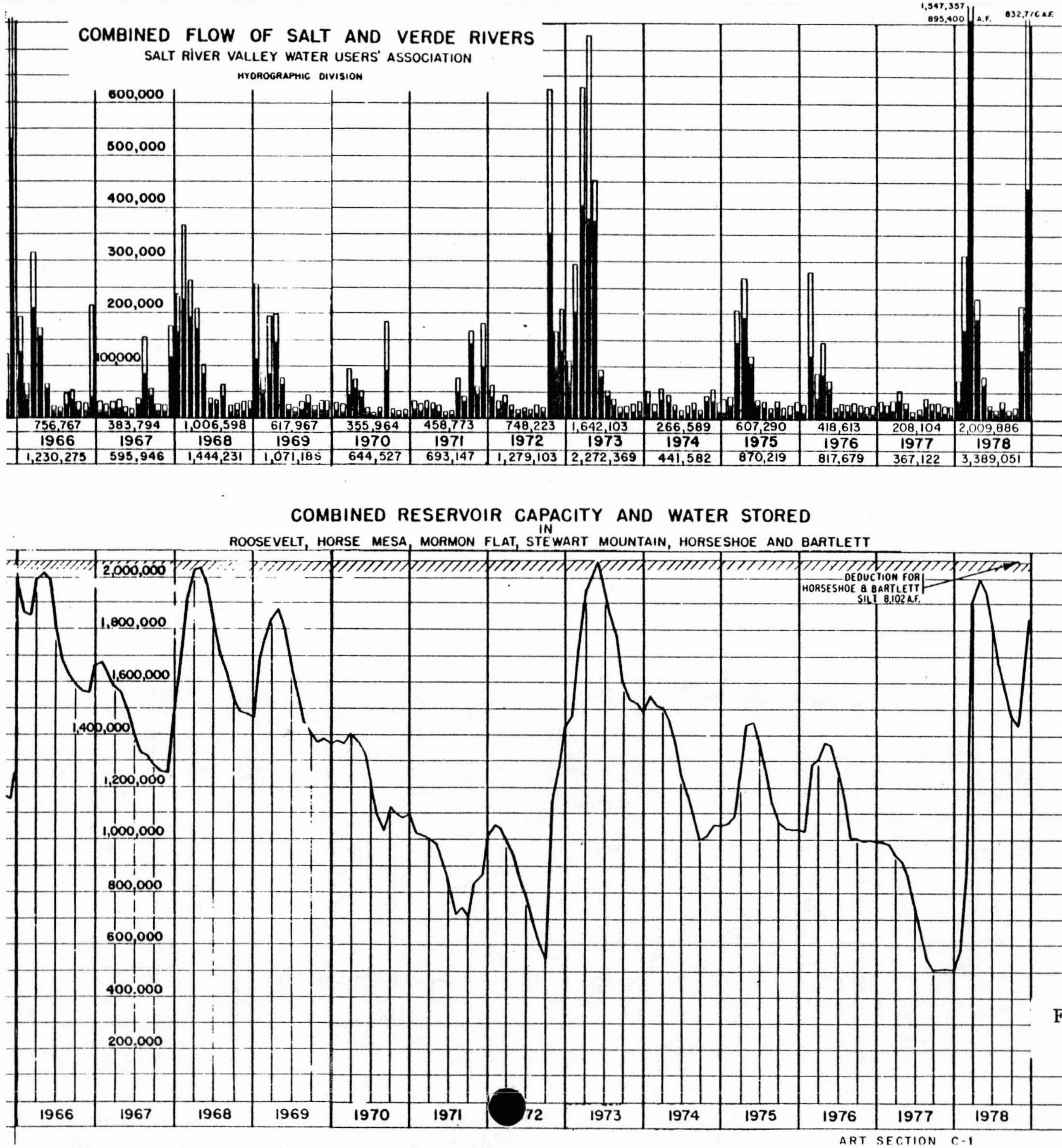

COMBINED FLOW OF SALT AND VERDE RIVERS
SALT RIVER VALLEY WATER USERS' ASSOCIATION
HYDROGRAPHIC DIVISION
600,000
500,000
400,000
300,000
200,000
100000
1,547,357
895,400
A.F.
832,716 A.F.
756,767
1966
1,230,275
383,794
1967
595,946
1,006,598
1968
1,444,231
617,967
1969
1,071,185
355,964
1970
644,527
458,773
1971
693,147
748,223
1972
1,279,103
1,642,103
1973
2,272,369
266,589
1974
441,582
607,290
1975
870,219
418,613
1976
817,679
208,104
1977
367,122
2,009,886
1978
3,389,051
COMBINED RESERVOIR CAPACITY AND WATER STORED
IN
ROOSEVELT, HORSE MESA, MORMON FLAT, STEWART MOUNTAIN, HORSESHOE AND BARTLETT
2,000,000
1,800,000
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
DEDUCTION FOR
HORSESHOE & BARTLETT
SILT 8,102 A.F.
1966
1967
1968
1969
1970
1971
72
1973
1974
1975
1976
1977
1978
ART SECTION C-1

FIGURE 15E

AUTHOR'S BIOGRAPHICAL SKETCH

NAME: Herman Bouwer

EDUCATION: B.S. & M.S. Degrees in Land Reclamation, Drainage and Irrigation from the National Agricultural University at Wageningen, The Netherlands

PhD. Degree in Agricultural Engineering from Cornell University

JOB POSITION: Director of U.S. Water Conservation Laboratory, U.S. Department of Agriculture in Phoenix, Arizona

EXPERIENCE: Research leader in subsurface water management and groundwater recharge with sewage effluent

Teaches groundwater hydrology at Arizona State University

Has authored or co-authroed about 120 publications in drainage, irrigation, seepage, groundwater hydrology and land treatment of wastewater

Published textbook "Groundwater Hydrology" by McGraw-Hill

FLOW PROCESS TO UNDERGROUND FROM SURFACE PONDS

by

HERMAN BOUWER

Introduction

Putting surface water underground for recharge of groundwater involves the following three processes (Figure 1):

1. Getting the water into the ground (infiltration),
2. Getting it down to the groundwater, and
3. Getting it to flow away laterally from the recharge area.

Before infiltration is started, we usually have an unsaturated zone (vadose zone) between the surface and the groundwater zone (aquifer). The top of the groundwater is the water table (Figure 2) and it is the height to which the water will rise in a well penetrating the aquifer. The lower boundary of the aquifer is some kind of impermeable material (clay, bedrock, etc).

When the soil surface is flooded, like in an infiltration basin, water moves into the ground, it wets up the soil, and forms a wetted zone which advances downward (Figure 2). The lower part of the wetted zone is called the wetting front. As infiltration continues, the wetted zone moves down until it reaches the groundwater. When that happens, the water table rises and forms a groundwater mound. This creates a system of lateral flow away from the infiltration area and causes the adjacent water table to rise, thus "storing" the recharge water (Figure 1). Initially, the groundwater mound will rise fast, but with continued recharge it will rise slower and reach a pseudo-equilibrium position.

The above system applies to an unconfined aquifer, which is an aquifer that is "open" at the top to atmospheric conditions and bound by a water table. There are also aquifers that are sandwiched between two slowly permeable layers, like a sand layer between two clay layers. Such aquifers, called confined aquifers, cannot be recharged from the surface, but must be recharged through injection wells. In the Salt River Valley, the upper aquifers generally are unconfined. Deep clay deposits and underlying confined aquifers may also be present.

Water Requirements for Formation of Wetted Zone

The wetted zone functions as a transmission zone, transmitting water from the surface to the groundwater (Figure 1). Water cannot be collected from the transmission zone as such, because the zone is unsaturated and the water is held by capillary forces. Thus, it will not flow into a well. This means that a portion of the recharge water first has to be used to set the soil and create a transmission zone, before the water can reach the groundwater. How much water has to be stored in the transmission zone depends on how dry the soil is before infiltration, and how deep it is to groundwater. If the soil is very dry, the fillable porosity may be around 20 percent, which means that for every 10-ft depth to groundwater a depth of 2 ft. of water must be used to create a transmission zone. If the soil has already been wetted before, like in the Salt River bed or below irrigated fields, the fillable porosity may be on the order of 5 to 10 percent. This means that for every 10-ft. depth to groundwater, 1/2 to 1 ft. of water must be stored in the transmission zone. These figures show that appreciable amounts of water may have to be "invested" in the transmission zone before groundwater recharge begins. Not all the water that is stored in the transmission zone is lost forever, however, because if infiltration is ceased, the transmission zone slowly drains to the groundwater and eventually a significant portion of the water will reach the groundwater.

Infiltration Rates

A very important factor in groundwater recharge is the infiltration rate, which is expressed as a velocity (inches per hour, feet per day, etc.). The infiltration rate can be visualized as the rate of fall of the water surface in an infiltration pond when the inflow of water is stopped. Thus, if the water level then drops 1 inch per hour, the infiltration rate is 1 inch per hour or 2 feet per day. Knowledge of infiltration rates is important because it enables the engineer to predict how much land area would be needed to get a certain volume of water into the ground per year. Also, if only a certain amount of land area is available, it enables one to calculate how many acre-feet of groundwater recharge can be obtained.

Infiltration rates are not constant. They are highest when water is first applied to the basin. This is because the wetting front has not advanced downward very far, and the water pressure due to the water depth in the basin is dissipated over a relatively small distance. After a few hours, however, water mainly moves downward due to the force of gravity, and infiltration rates become essentially constant. The constant or final infiltration rate is about equal to the permeability or hydraulic conductivity of the soil. The coarser the soil, the higher the hydraulic conductivity; and hence, the higher the constant infiltration rate. Orders of magnitude for the hydraulic conductivity and final infiltration rates for soils are:

Clay soils: A few inches per day

Loam soils: A few feet per day

Sands: A few yards per day.

Thus, if we have a loamy sand with a final infiltration rate of 4 feet per day, one acre of infiltration basin can infiltrate 4 acre-feet of water per day.

Clogging Effects

Constant infiltration rates are obtained only if pure water is applied. Unfortunately, water in infiltration basins always contains some suspended particles, such as inorganic sediments like clay, silt, or fine sand, and organic particles like algae. These solids settle out on the bottom of infiltration basins (Figure 2, Right). Also, as water moves into the soil, the particles are physically strained out on the soil surface. When infiltration is just started, very fine particles can actually penetrate into the soil and move down some distance before they are finally trapped in the pores. This trapping causes other particles to become trapped higher up, etc., until the entire surface portion of the soil is clogged by fine particles. Clogging is not only caused by suspended particles in the water, but also by bacterial growth and slime production on the bottom. In addition, algae in the water uses up carbon dioxide during the day, which increases the pH of the water and in turn results in precipitation of calcium carbonate, which accumulates on the bottom. This can actually cause a cementing of soil particles at the surface.

The clogging materials have a much lower permeability than the soil itself, so that infiltration rates gradually decrease to very low values. The clogged layer then becomes the controlling factor or bottleneck in the infiltration process. Eventually, infiltration rates will become so low that the clogged layer has to be removed.

Effects of clogging can be reduced by minimizing the suspended solids content of the water in the infiltration basins. This may require presedimentation of the water in special reservoirs or forebays before it is admitted to the infiltration basins. Some projects use a floating intake facility that skims off surface water for conveyance to the infiltration basins. Other possibilities are coagulation and sedimentation of the water, or filtering it by letting it flow through grassed surfaces to reduce the suspended solids content. Presedimentation basins should not be so large that water stays in them for days or weeks and algae has a chance to develop.

If the infiltration rate in the basin has become unacceptably small, the basin must be dried. When the clogging materials are mostly organic, like algae and bacteria, drying alone may be effective in restoring infiltration rates because the organisms die and decompose, and the clogged layer shrinks and breaks up in curled flakes. If the clogging materials are mostly inorganic, like clay and silt, drying alone will not do the job. It will then be necessary to scrape off the surface layer or otherwise remove the fines that have accumulated on the soil. Infiltration basins for groundwater recharge thus must undergo regular drying and cleaning periods. The "useful" length of flooding periods may vary from several months or more for clean water, to only a few days for very turbid water. Gravel layers, mulches, and other cover layers normally are effective for a limited time in minimizing clogging effects. Eventually, such cover layers also clog up with solids and must be completely removed.

Because of clogging, infiltration rates in the Salt River bed when the river is flowing are much less than the permeability of river-bed material as such. The coarse sands and gravels that prevail in the main channels may have a permeability of about 30 ft per day. Yet, infiltration rates are only on the order of one to several feet per day.

Hydraulic Loading

The depth of water that can be infiltrated over a long period of time with a recharge-basin system is called the hydraulic loading rate or hydraulic capacity of the system. While infiltration rate refers to the actual rate of movement of water into the ground during flooding, hydraulic loading rate includes the time that basins have to be dry for cleaning and infiltration-rate recovery. Thus, if 6-week flooding periods are alternated with 3-week drying periods and the average infiltration rate during flooding is 2 feet/day, the hydraulic loading rate is 485 feet per year. At this rate, 2,060 acres of recharge basin would be required to infiltrate 1 million acre-feet per year.

Effect of Water Depth on Infiltration Rate

If the soil surface is not clogged, the depth of water in the basin does not have a significant effect on infiltration rate, except at the beginning of the infiltration when the wetting front has not yet penetrated very far into the soil. After a few days, however, the pressure due to the water depth is dissipated over a large wetted zone, so that the effect of water depth is small compared to the effect of gravity which then is the main driving force for the downward moving water. However, most infiltration basins will develop a clogged layer at the bottom, in which case the pressure due to the water depth is dissipated over the clogged layer itself. Since this layer is relatively thin (a few inches at the most), water depth then has a significant effect on infiltration. As a matter of fact, the effect is almost linear. Thus, doubling the water depth will essentially double infiltration rates in recharge basins where the infiltration is controlled by a thin, clogged layer at the bottom.

Air-Pressure Build-Up

If the infiltration basin is relatively large, air pressure can build up in the vadose zone underneath the downward moving wetting front. These air pressures could reduce infiltration rates. Air pressures below wetting fronts can be minimized by using relatively narrow infiltration basins, or by installing air-pressure relief pipes.

Effect of Groundwater Depth

The position of the groundwater table has no effect on infiltration rate as long as it is below the bottom of the infiltration basin. This is because there is unsaturated flow in the wetted zone, which is controlled by gravity, and the water in the basin "does not know where the groundwater is." However, if the water table comes within a foot or so of the bottom or even rises above it, it will back up the infiltration process and cause a reduction in infiltration rate. Thus, in designing an infiltration system, one must always make sure that the mound will stay well below the bottom of the basins.

The rise of the groundwater mound depends on how fast the aquifer can transmit the recharge water laterally. The thicker the aquifer and the more permeable the material, the easier it is for the water to flow away laterally, and the lower the mound will be. Where aquifer transmissivity may be insufficient, long, narrow basins rather than round or square basins should be used to minimize mound heights. In the Salt River Valley, aquifers generally are permeable and thick so that excessive build-up of groundwater mounds is not to be expected, at least for normal-sized infiltration basins.

Perching Mounds

Sometimes, there are less-permeable layers in the vadose zone between the basins and the groundwater. Such layers typically occur in alluvial deposits, where clay and silt deposits were formed in stagnant pools or in channels with sluggish flow after floods receded. Where there is an impermeable lens, a perched groundwater mound must build up on the lens before water can move off the edges and percolate downward. If the perching layer is a continuous layer of reduced permeability, a perched mound will build up until enough pressure is created on the perching layer to "push" the water through this layer so that it can flow down to the underlying aquifer.

Sometimes, the restricting layer is the upper confining layer of a confined aquifer. If the confining layer is not completely impermeable (hence, if it is an aquitard and not a aquiclude), recharge water can move into the confined aquifer if the perching mound generates enough pressure on the semi-confining layer. Where the upper confining layer is not sufficiently permeable to transmit water in significant amounts, the underlying confined aquifer can only be recharged by means of wells that penetrate the confined aquifer (well recharge or well injection).

Pre-investigations and Design

The best way to predict infiltration rates and to develop criteria for designing and managing a system of infiltration basins for groundwater recharge is to work with some test basins.

Before that, however, there must be pre-investigations regarding infiltration rates and permeability values of the soils in the vadose zone, for feasibility studies and proper site selection. Also, the transmissivity of the underlying aquifer must be evaluated, so that heights of groundwater mounds can be predicted and optimum shapes and sizes for recharge basins can be selected. The technical knowledge and methodology on these matters has progressed to the point where rational approaches are possible and reliable results can be expected.

REFERENCES

There are numerous articles, reports, etc. on the various aspects of groundwater recharge. For a recent review of this literature (including infiltration, clogging, groundwater mounds, hydraulic-conductivity measurement, etc.), reference is made to the book:

Groundwater Hydrology, Herman Bouwer, McGraw-Hill, New York, 1978 (480 pages).

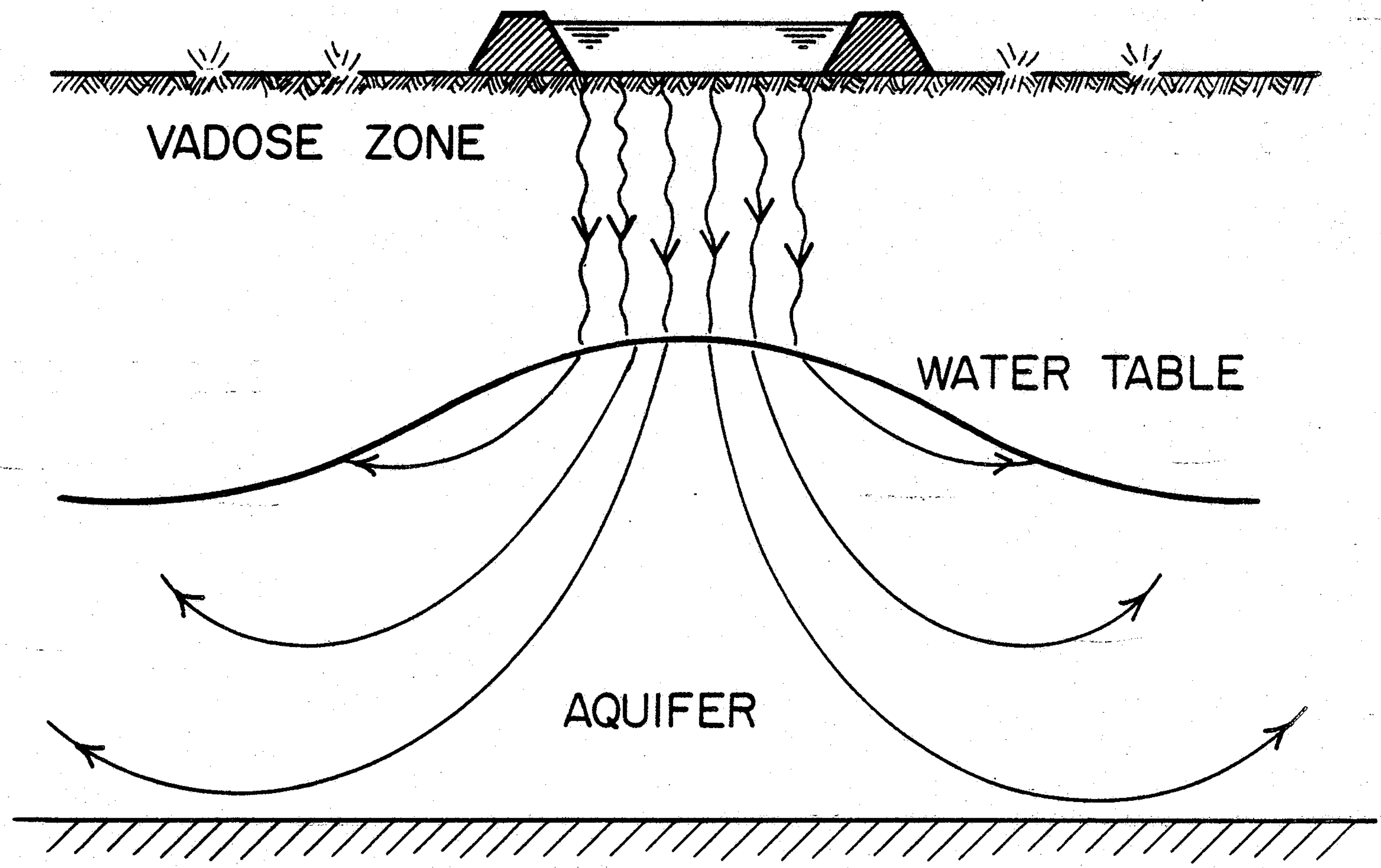


Figure 1. Schematic of groundwater recharge system showing infiltration basin, wetted zone, groundwater mound, and flow lines in aquifer.

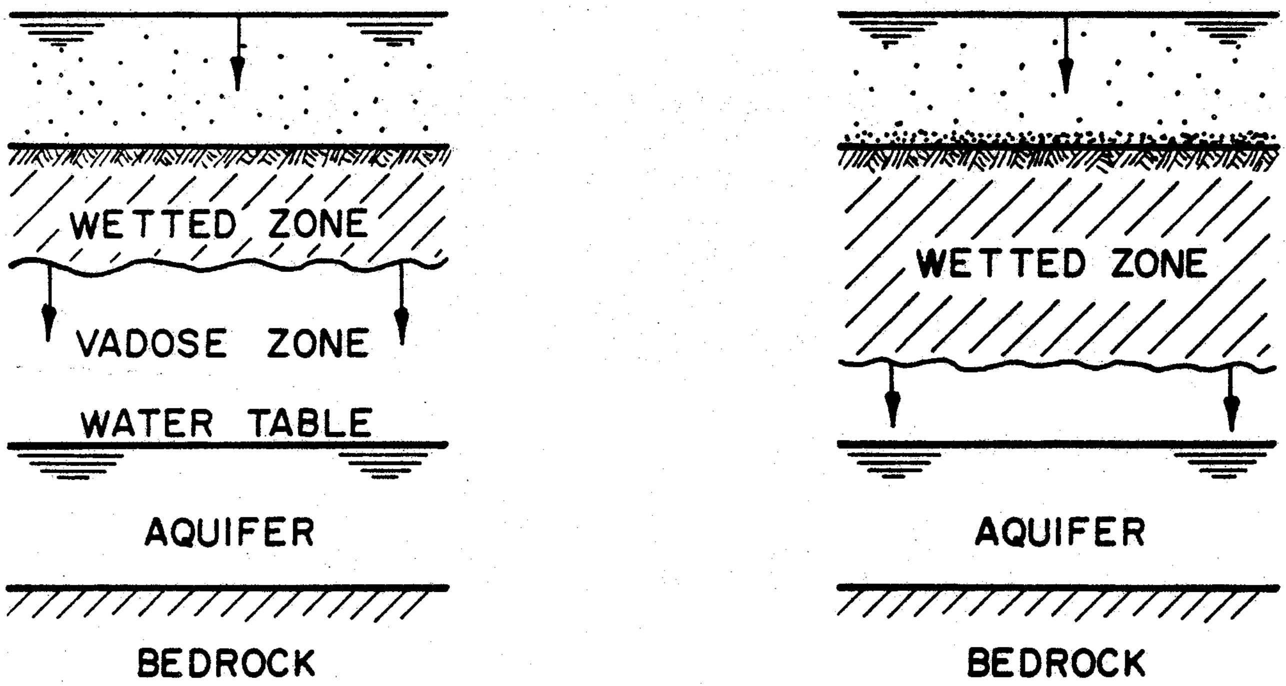


Figure 2. Infiltration system below surface inundation, showing wetted zone shortly after initial infiltration (left) and after it has advanced downward and almost reaches the water table (right). Suspended solids in the surface water are indicated by dots. Sketch on right shows accumulation of suspended particles on the bottom.

AUTHOR'S BIOGRAPHICAL SKETCH

NAME: Ed Weeks

EDUCATION: B.S. Degree in Geological Engineering from the Colorado School of Mines

JOB POSITION: Project Chief of the High Plains Artificial Recharge Research Project for the U.S. Geological Survey in Lubbock, Texas

EXPERIENCE:

Investigated effects of groundwater development for irrigation on streamflow in Wyoming and Wisconsin for the U.S. Geological Survey

Research on field methods to evaluate flow in the unsaturated zone for the U.S. Geological Survey

Staff member of the U.S. Geological Survey Groundwater Branch in Washington, D.C.

Author of several papers on the effects of groundwater development for irrigation on streamflow and on field methods for evaluating aquifer and unsaturated zone hydraulic properties

SOME PRINCIPLES OF FLOW IN THE UNSATURATED ZONE AS RELATED TO ARTIFICIAL RECHARGE

by

E. P. Weeks

This discussion will be geared to emphasize some of the basic principles of flow in the unsaturated zone. An understanding of these principles is important, because many of the familiar concepts of groundwater flow do not apply to the unsaturated zone, and, as a consequence, flow relationships in the unsaturated zone are somewhat nonintuitive. Thus, we need to understand the basic principles of flow in the unsaturated zone so that we aren't mislead by preconceived notions gathered through our work in groundwater.

The first factor that I will discuss is that relating to the pressure head status of water in the unsaturated zone. As you know, head relationships in the saturated zone are determined by measuring water levels in wells. In the unsaturated zone, on the other hand, water is held under negative pressure, and will not enter an open pipe or hole. The cause of this negative pressure may be explained by the theory of capillarity. Effects of capillarity on water in a capillary tube (Stallman, 1964) is shown in Figure 1. Because water has a significant surface tension and tends to cling, or adhere, to the walls of the tube, water rises in the tube. The height of the rise is governed by the contact angle between the water and the tube wall, which is a measure of the adhesive force between the water and the tube material and by the surface tension of the water. These forces, which cause water to rise in the tube, are counterbalanced by the weight of the hanging water body, and the actual height of rise represents that at which the counteracting forces balance. It can be shown that the net effect of the surface-tension force is proportional to the radius of the tube, whereas the weight of the water is proportional to the square of the radius. Hence, the height of capillary rise is inversely proportional to the radius of the capillary, which will thus be greatest in very fine capillaries.

The capillary tube of course shows little resemblance to a porous medium, but the same principles apply. Hence, a capillary water body at the contact between two spheres, also shown in Figure 1, will also be under tension. Such a water body is termed a <u>pendular ring</u>, and the tension within the water body is defined by the radii of curvature r_1 and r_2. Because of this tension, water in the pendular ring will not enter a larger opening, in which the pressure would be higher. The porous medium can be considered to be composed of a great many spheres, with water help by capillarity at each grain contact. This water will not enter an open hole or observation well, just as a fluid moving through a wick will not enter a hole in the wick.

I have belabored this point, but it does represent an important concept, that if unrecognized, could lead to erroneous conclusions. As an example, I was recently at a meeting in which it was argued that no recharge was occurring from a sewage lagoon. The people involved were certain of this because no water entered open holes that they had installed horizontally beneath the lagoon for the purpose of measuring recharge. In fact, however, a water balance of the lagoon suggested that infiltration of several feet a year was occurring. Because the bottom of the lagoon was nearly sealed, water was moving by unsaturated flow through the underlying materials, and could not enter an open hole.

Before progressing further, I should clarify the difference between head and pressure, as water in either the saturated zone or unsaturated zone will move in the direction of decreasing head, rather than decreasing pressure. The difference between head and pressure is shown by examining the relationship between the two in water held behind a dam. In Figure 2, it can be seen that the pressure near the bottom of the reservoir, P_1 is much greater than that near its surface, P_2, yet there is no vertical water movement. Head, on the other hand, is defined by the equation:

$$h = P/\gamma + Z,$$

where P = pressure, in terms of force per unit area;

γ = weight per unit volume of water; and

Z = height above a reference plane, distance.

As we move up from the reservoir floor, the pressure decreases, but Z increases at the same rate, so head is constant. Thus, $h_1 = h_2$, and there is no head gradient in the reservoir.

Pressure Measurement in the Unsaturated Zone

As I mentioned earlier, pressure or head in the unsaturated zone cannot be measured with an observation well. Instead, it must be measured by use of a tensiometer, shown diagrammatically in Figure 3. The tensiometer consists of a cylinder (A), fitted on one end with a fine-grained membrane (B), and on the other by a clear small-diameter tube (C). The tensiometer is filled with water, which forms a continuous water body through the porous membrane with water in the adjoining porous medium, shown by shading in the diagram. Because the water in the unsaturated zone is under tension, it tends to suck water out of the tensiometer. This tendency is counterbalanced by the development of a negative pressure in the tensiometer, and the tensiometer reaches equilibrium when the suction at D equals that at D_1. In the diagram, this suction, in terms of head h is equal to the depression of the meniscus in the tube C below the center line of the tensiometer tube.

Figure 3 is obviously diagrammatic. In actual practice, a tensiometer is generally installed in the bottom of a hole, and tension is read at land surface. Under these conditions water would be drawn out of the tube, C, by capillary suction and gravity. This is overcome by bringing the tube in an inverted U into a mercury reservoir, as shown in Figure 4. Moreover, the tensiometer measures the pressure head at the membrane-soil interface, and total head in the unsaturated zone must be corrected by taking the position of the tensiometer membrane below the reference plane into account.

The above description, although brief, describes the method by which pressure head is measured in the unsaturated zone. Most texts on soil water or unsaturated flow, such as Hillel (1971), and Kirkham and Powers (1971), or Childs (1969), give a more complete account of their operation and use.

Measurement of Moisture Content

Several methods exist for measuring moisture content in the unsaturated zone, but I shall mention only two. One method is based upon core analysis. A core of material from the unsaturated zone, taken, say, by drive-coring to avoid disruption of its moisture content, would be weighed and its volume measured. It would then be dried in an oven and weighed again. The weight loss, in grams, represents moisture content in cubic centimeters, which, when divided by the volume of the core, represents the volumetric moisture content as a dimensionless fraction.

A second method for measuring moisture content is by neutron logging (Stallman, 1967). Use of this method requires a neutron moisture meter or logger and an access tube for lowering the neutron probe through the soil. Essentially, the neutron probe consists of a source of fast neutrons and a detector for measuring slow neutrons. The fast neutrons, commonly generated by an americiam-beryllium source, will pass through steel or aluminum, because the particles are without charge. When a fast neutron does strike the nucleus of a large molecule, such as that of iron or silica, it will rebound elastically with little loss of energy. However, when a fast neutron strikes a hydrogen nucleus, an elastic collision occurs that accelerates the hydrogen nucleus but slows the neutron, much as a cue ball is slowed upon striking an object ball in a pool game. Measurement of the flux density of the slow neutrons gives a measure of the volumetric moisture content in the unsaturated zone.

The neutron log measurements will vary with access hole construction and other factors. However, the neutron logs can be calibrated against volumetric samples, as described above. Once calibrated, the neutron moisture meter or logger provides a convenient and accurate method for making repeated nondestructive measurements of moisture change at a site.

Relationship Between Moisture Content and Moisture Tension

Moisture content and tension, the measurement of which were just described, are related. I am going to use a capillary tube model to illustrate this relationship. Now, all of you who have ever looked at a handful of dirt know that a capillary tube doesn't look anything like a porous medium. Surprisingly, however, the capillary tube model provides an effective tool for understanding flow in the unsaturated zone.

A curve of moisture content versus height above the water table, which would be equivalent to tension in this example, is shown in the bar graph in Figure 5. The two smallest capillaries combined will produce the moisture content shown by bar A, the medium capillary are shown by bar B, and the effects of a large capillary are shown by bar C. If however, instead of only four capillaries, we had a large number, their cumulative effect would be to produce a smooth curve of moisture content versus height above the water table, as shown by the curve in figure 5. Thus, the relationship between moisture content and tension is defined by pore size distribution. The curve describing this relationship is frequently called the moisture characteristic curve.

The capillary tube model also may be used to explain the concept of air entry pressure. Assume that the large capillary C (Figure 5) represents the largest capillary in the porous medium. Note that it contains water held by capillarity under a certain negative pressure, and that the pressure immediately above the capillary interface is atmospheric. An additional pressure equal to the height of capillary rise in the capillary will be necessary to push the water out of the capillary, and once that has occurred, air could move through the capillary. Hence, the air entry pressure can be considered to be that required to evacuate the largest pore in the medium.

Relationship Between Moisture Content and Hydraulic Conductivity

The rate of flow of a fluid in a porous medium resulting from head gradient, for either saturated or unsaturated flow, is given by Darcy's Law. For saturated flow this relationship is quite simple:

$$q=K \frac{dh}{dl}$$

where q = flow rate (specific discharge), L/T;
K = hydraulic conductivity, L/T; and
dh/dl = head gradient, or decline in head per unit length, dimensionless.

For saturated flow, K is a constant that depends on the properties of the medium and upon the viscosity and density of the fluid, but is independent of head.

Darcy's Law for the unsaturated zone, however, is more complicated. Again referring to the capillary tube model in Figure 5, water can only move in the capillaries filled with water, so, at high tensions (or low heads), only the fine capillaries can conduct water, as the large capillaries will be filled with air and thus impermeable to water. Consequently, in the unsaturated zone, hydraulic conductivity is a function of moisture content, as well as of the properties of the medium and fluid. Moreover, since moisture content is a function of tension or head, unsaturated hydraulic conductivity is also a function of head.

The fact that hydraulic conductivity is a function of head causes flow in the unsaturated zone to behave in a manner contrary to our intuition. As an example, a clay will contain many fine pores, but few coarse ones, while a sand will contain mainly coarse or large pores. Hence, at higher tensions the clay will have many more pores than the sand that can transmit water, and it will actually have a higher hydraulic conductivity at that tension than the sand. Thus, a vertical sand stringer in the soil would not necessarily be a preferred conduit for unsaturated flow, but might instead be a barrier to such flow.

Another example of nonintuitive flow behavior in the unsaturated zone is that occurring when a clay overlies a sand, as shown in Figure 6. In this case, the effect is the same as having a fine capillary overlying a coarse one. A positive pressure will be needed to move water from the fine pore to the large one. Hence, during recharge or downward percolation, water will accumulate in the clay until the clay is saturated and has a positive head before percolation occurs into the sand. As a result, the sand will act as a temporary barrier to downward unsaturated flow.

Review

As a matter of review to this point, water occurs in the unsaturated zone under negative pressure. Hence, head or tension cannot be measured by an observation well, but must be measured using a tensiometer. In addition, moisture content can be measured by sampling and by neutron logging. The relationship between moisture tension and moisture content can be explained on the basis of a capillary tube model, and is governed by the pore size distribution. Moreover, hydraulic conductivity in the unsaturated zone is also a function of moisture content and tension. This results in fine grained material sometimes having a greater hydraulic conductivity than coarse grained materials.

Some Applications of Unsaturated Zone Flow Theory to Artificial Recharge

The theory of flow in the unsaturated zone is complicated, and generally requires elaborate computer models that frequently work only under certain conditions. However, there are a number of simple applications of unsaturated zone flow theory that can be used to explain the behavior of recharge from a spreading basin.

Figure 7 is a generalized diagram of infiltration rate versus time for a spreading basin. Scales are not shown, because the infiltration rate and its duration vary greatly from place to place. For example, on Long Island, the maximum infiltration rate might be 30 feet per day; in areas underlain by some tight soils in the Panhandle of Texas, it might be 0.3 feet per day; and in other areas of the Southern High Plains of Texas, it might be 3 feet per day. However, although the maximum recharge rate varies by a factor of 100 among these areas, the general shape of the curve is similar to those shown in Figure 7. As shown by the figure, the infiltration rate generally declines at the start of recharge. After leveling off, the recharge rate increases either to a new maximum or submaximum and then again declines. Let's look at how some aspects of unsaturated flow theory may be used to explain this general S-shaped curve.

The initial decline in infiltration rate may be explained by the theory of Green and Ampt (1911), already mentioned by Dr. Bouwer. This theory is illustrated by Figure 8, which shows water moving into a homogeneous medium until a wetting front has been developed down to a certain depth. The theory of Green and Ampt states that the flow rate is given by the equation:

$$q=K\ (h\ -\ h\ +\ L)/L,$$

where q = infiltration rate per unit area, L/T;

K = saturated hydraulic conductivity, L/T;

h = ponded head, or depth of water above basin floor, L;

h = pressure head at wetting front, L;

and L = distance from floor of basin to wetting front, L.

Based on the above equation, the infiltration rate will be relatively large when the depth of the wetting front is small, but will decrease as the wetting front advances and the flow rate increases. Basically, the ponded head and the wetting front head remain constant, but the flow path length increases, resulting in a declining infiltration rate. This phenomenon explains the initial decline in infiltration rate shown in Figure 7.

The increase in flow rate illustrated by the rising limb of the curve in Figure 7 is due to an entirely different phenomenon, the dissolution of trapped air. As water begins moving down from land surface, it traps air as isolated bubbles in some of the pores, shown diagrammatically in Figure 9. The small circle in Figure 9 represents a bubble trapped between three spheres. The air bubble, which is impermeable to water, is relatively stable both because of a near balance of forces acting on it, and because of capillarity. In regard to the status of forces acting on the air bubble, they include an upward-directed buoyance force on the air bubble, they include an upward-directed buoyance force arising from the difference in density between the air bubble and water, and a downward-directed viscous drag exerted by the water as it flows around the air bubble. These forces tend to counterbalance each other so that there is little net force on the air bubble. Moreover, the surface tension of the water acts to keep the surface of the air bubble as small as possible. Thus, the air bubble tends to remain spherical in shape. If the air bubble began to move into either neck of the pore shown in Figure 8, it would deform and obtain a greater surface area. Thus surface tension also tends to keep the air bubble in place. Hence, the air bubble essentially has to dissolve out. The dissolution of entrapped air explains the long climbing limb of the infiltration rate curve. Dissolution of the air may take weeks or months, but often results in an increase in the infiltration rate by a factor of two to four.

The last part of the curve in Figure 7 shows a decline in infiltration rate. This is due to clogging by sediment and by various biological effects.

Effects of Low Permeability Layers

The performance of a spreading basin may be governed by low-permeability layers either at the surface or at depth. The effect of the limiting layer at land surface is shown in Figure 10. The clogging layer is shown by hachures in the left hand diagram and pressure head is shown on the right. Note that the pressure head at land surface is just equal to the pond depth.

At the clogged layer-aquifer interface, on the other hand, the pressure head, h , is negative and the flux is given by the equation:

$$q=K_C(h_p - h_i + L_C)/LC$$

where q = infiltration rate, L/T;

K_c = hydraulic conductivity of clogged layer, L/T;

h_p = ponded head, L;

h_i = head at clogged layer-aquifer interface, L;

and L_c = thickness of clogged layer, L.

The head at the interface h_i, is determined by the relationship between unsaturated hydraulic conductivity and pressure head for the aquifer material, and is the tension at which the unsaturated hydraulic conductivity equals the infiltration rate. An increase in pond height will increase the head on top of the clog layer, and will increase infiltration rate to some extent. However, the head at the interface, h_i, will become less negative, so that the head gradient will increase by less than the increase in pond depth. As an example, assume that the clay layer is one meter thick, pond depth is one meter, the hydraulic conductivity of the clay layer is .01 meter/day, and the tension in the underlying aquifer material is one meter. Then the infiltration rate, q, is determined as follows:

$$q = .01(1-(-1)+1)/1 = .03 \text{ m/day}.$$

Next, assume that the pond depth is increased to two meters, but the tension beneath the clay layer is reduced to 0.5 meters.

Then the infiltration rate is increased to:

$$q = .01(2-(-.5)+1)/1 = .035 \text{ m/day}.$$

Thus, doubling of the pond height only increases the infiltration rate by about 20% for these assumed conditions. Changes in infiltration rates for an actual spreading basin will of course depend on conditions prevailing at the site, but the relatively small impact of pond height on infiltration rate has often been observed in artificial recharge studies.

The layer limiting infiltration may occur at depth, rather than at land surface, as shown in Figure 11. The limiting layer in this case results in the development of a perched mound that might extend to land surface. Should this happen, the hydraulic gradient at the base of the pond, and consequently the infiltration rate, would be greatly reduced.

We have been working on a method for measuring the hydraulic conductivity of such limiting layers at depth. The method relies upon the measurement of air pressure changes at depth as the atmospheric pressure changes at land surface. As the atmospheric pressure changes, air must move into or from the unsaturated zone to balance the change. However, such movement is impeded by the inverse of the permeability of the material to air, or by its pneumatic resistance, and by the change in soil-gas storage resulting from its compressibility as the pressure changes.

In order to determine the permeability of materials in different layers in the unsaturated zone, screens are placed within the bottom layer and at each layer boundary, as shown in Figure 12. Thus, we end up with a nest of piezometers that are open to the soil-gas atmosphere and measure soil-gas head rather than water head. These piezometers may be connected through a manifold to an inclined manometer, which is a very sensitive differential pressure measuring device shown diagrammatically in Figure 13. Note that when the valve to piezometer 1 is open, the downhole pressure for the screen is transmitted to the manometer reservoir, whereas the meniscus in the manometer tube is at atmospheric pressure. The manometer fluid will migrate up or down the tube until the weight of the fluid counterbalances the difference in pressure between the piezometer and atmosphere.

Periodic measurement of atmospheric pressure changes and of downhole pressure difference result in curves of soil-gas and atmospheric pressure versus time for each piezometer, as shown by Figure 14. These data may be analyzed by trial-and-error variation of permeability in a simulation model, as described by Weeks (1978). Once simulated heads are matched to measured heads by such manipulation, the permeability to air of each layer will have been determined.

The relationship between air permeability and hydraulic conductivity is not always clear cut. The permeability of the materials may be altered by the effects of wetting on the structure of the medium. Moreover, the medium contains residual moisture that reduces the permeability to air. Finally, if the materials are fine-grained, the permeability of the medium to air will be greater than that to water because of the Klinkenberg effect. Nontheless, in an experiment near Lubbock, Texas, the method gave reasonable estimates of hydraulic conductivity for several layers at depth, but not for the surface layer.

The method, despite its problems, may be the only one feasible for certain problems. For example, in the Southern High Plains of Texas, a fossil caliche layer is reputedly a restricting layer that prevents recharge, based on laboratory analyses of cores of the caliche. The cores are indeed impermeable, but the air-permeability method has shown that the caliche beds have significant permeability to air, apparently because of solution openings and fractures. Various ponded infiltration experiments have born out that the caliche is indeed permeable. Thus, from materials in which fluid movement is mainly through secondary permeability features, the air permeability method gives an index of the permeability of that zone that cannot be obtained in any other simple way.

In summary, we have covered several aspects of flow in the unsaturated zone, including measurement of moisture tension and moisture content, the relationship among moisture content, moisture tension, and unsaturated hydraulic conductivity, an explanation of typical curves of infiltration rate versus time, and a method for measuring the permeability of limiting layers at depth. This is a great deal of material to simulate in a short period of time, but hopefully illustrates some of the effects of unsaturated zone flow behavior on infiltration during an artificial recharge operation.

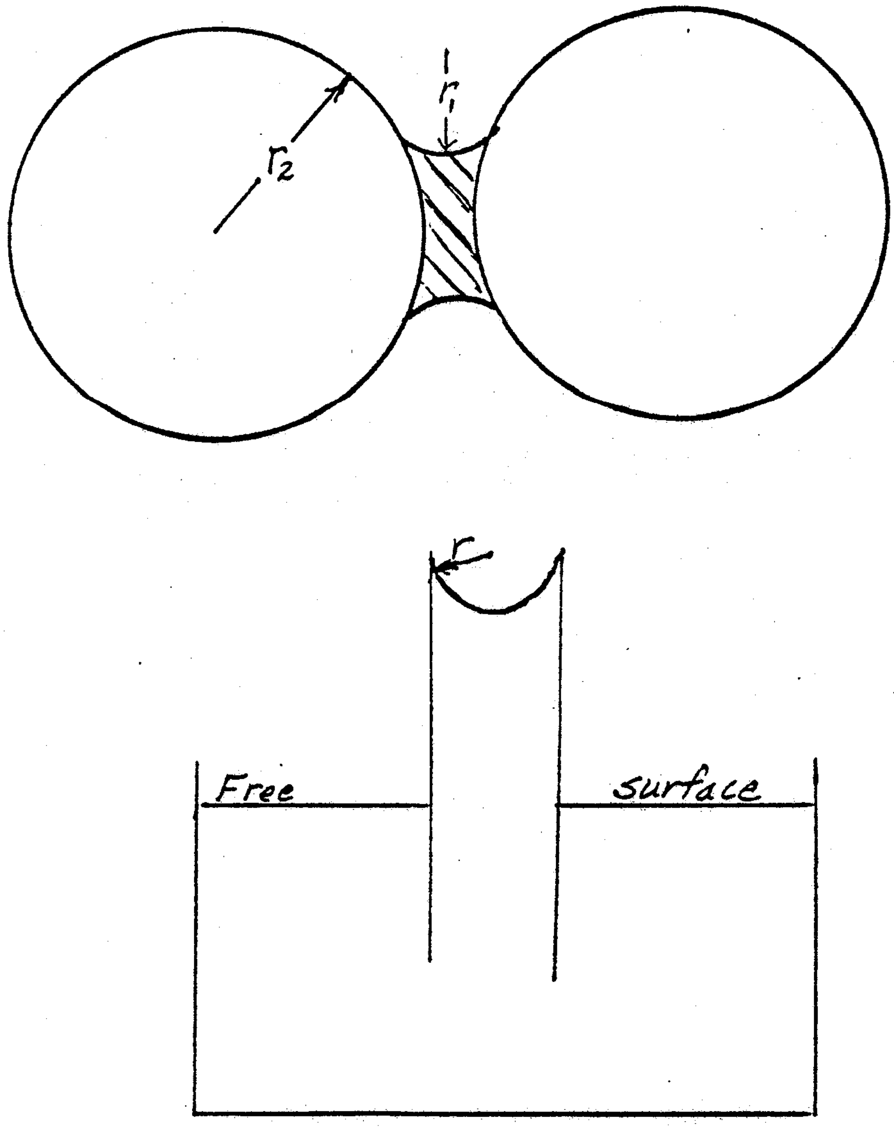


Figure 1.

Capillary forces in a capillary tube and in a pendular ring between two spheres.

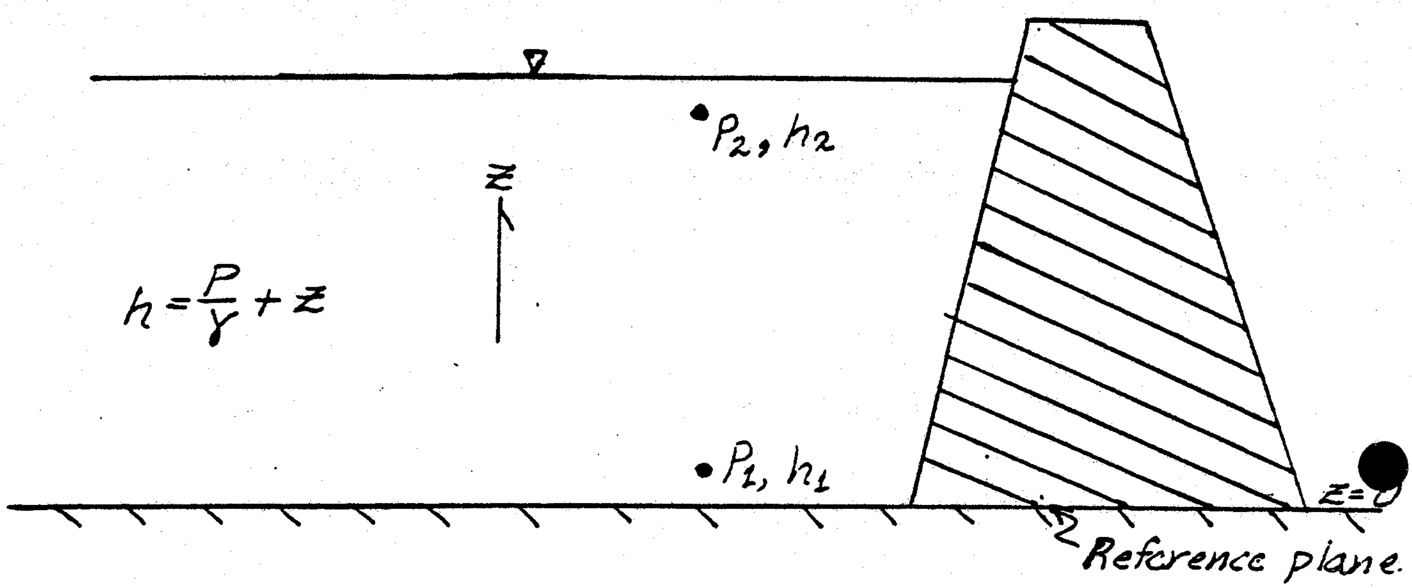


Figure 2. Diagram showing the realtionship between head and pressure for water held behind a dam.

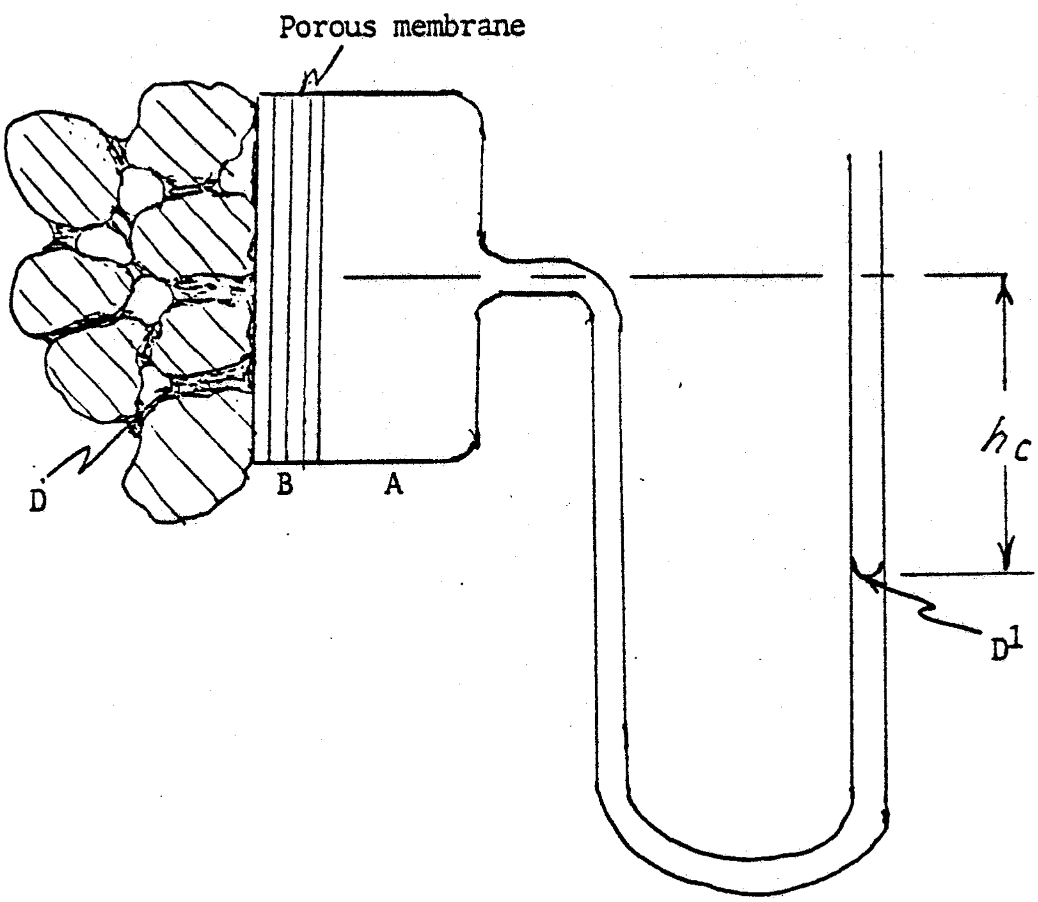


Figure 3.

Measurement of hydraulic head or tension in the unsaturated zone.

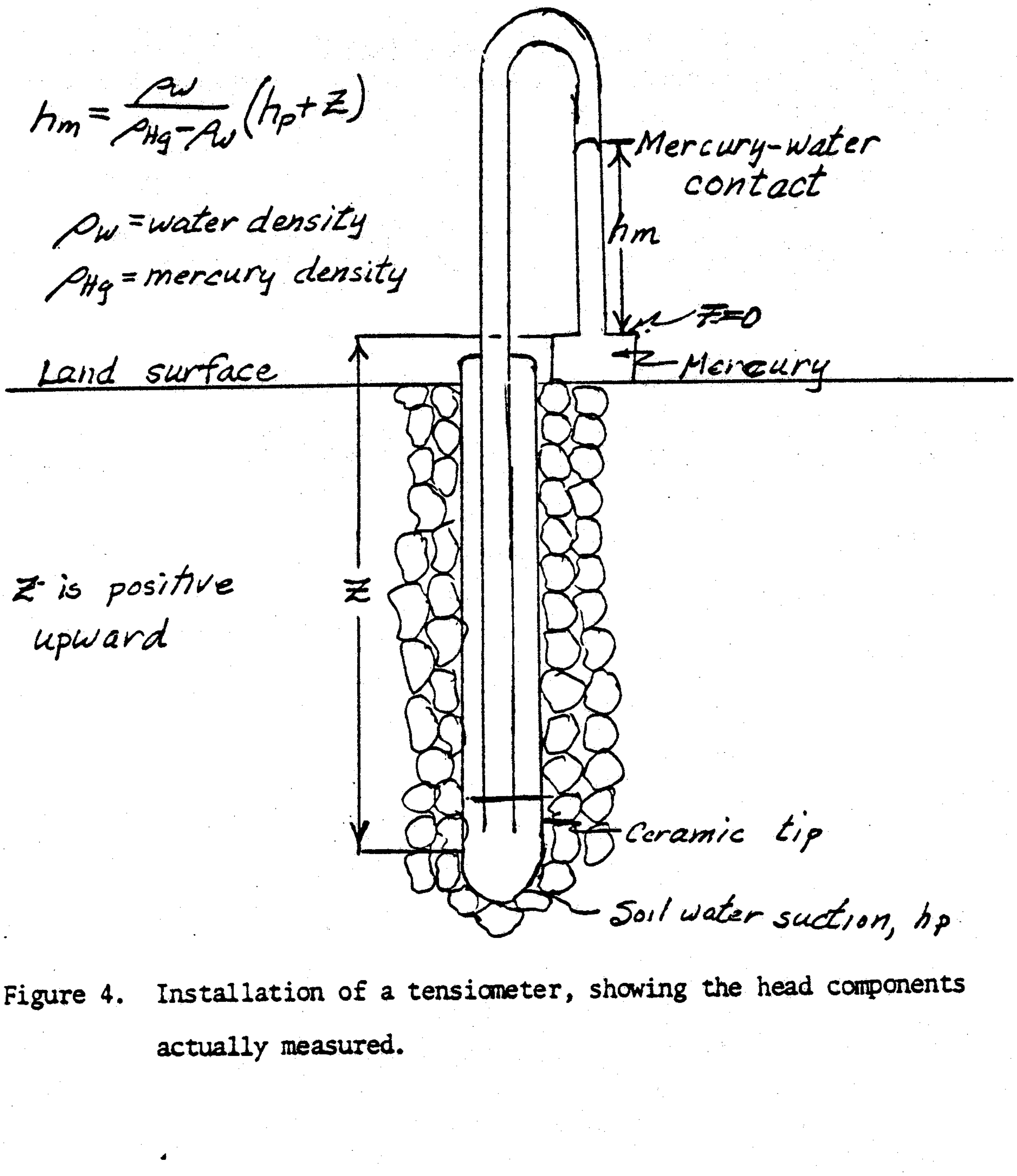


Figure 4. Installation of a tensiometer, showing the head components actually measured.

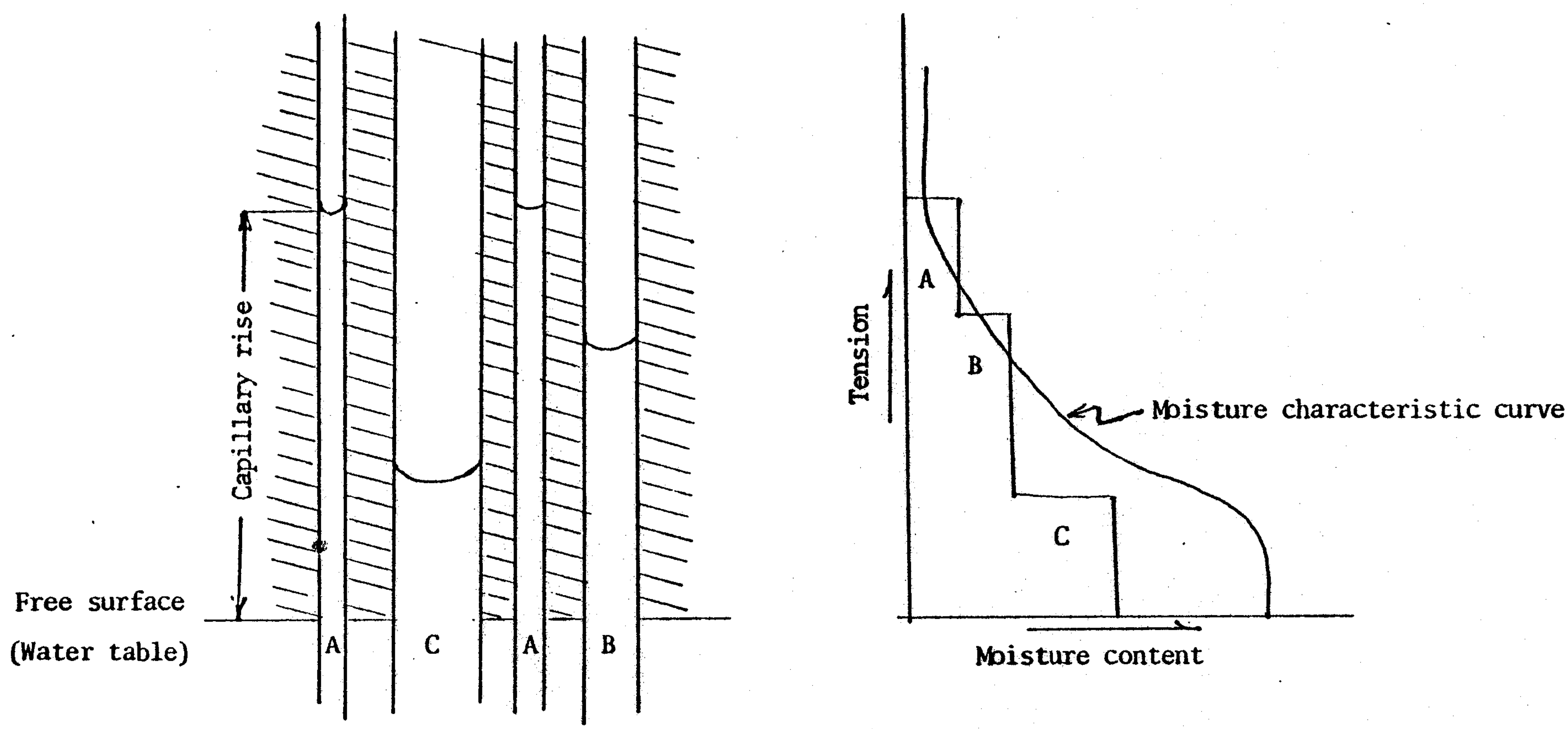
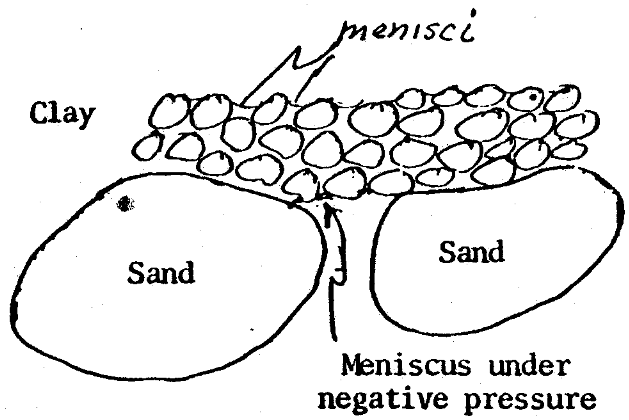
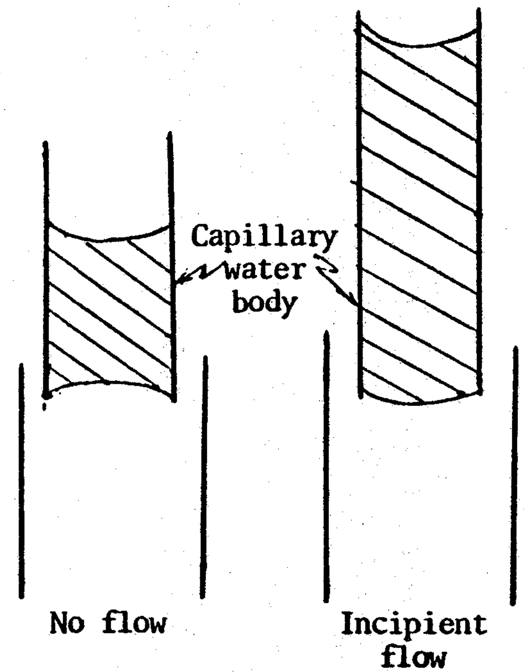


Figure 5. Pore size distribution governs the amount of water retained at a given suction.



Water in small capillaries in clay will not move into large one between sand grains.



Small capillary overlying a large one.

Figure 6. Effect of fine grained material overlying coarse-grained material on infiltration.

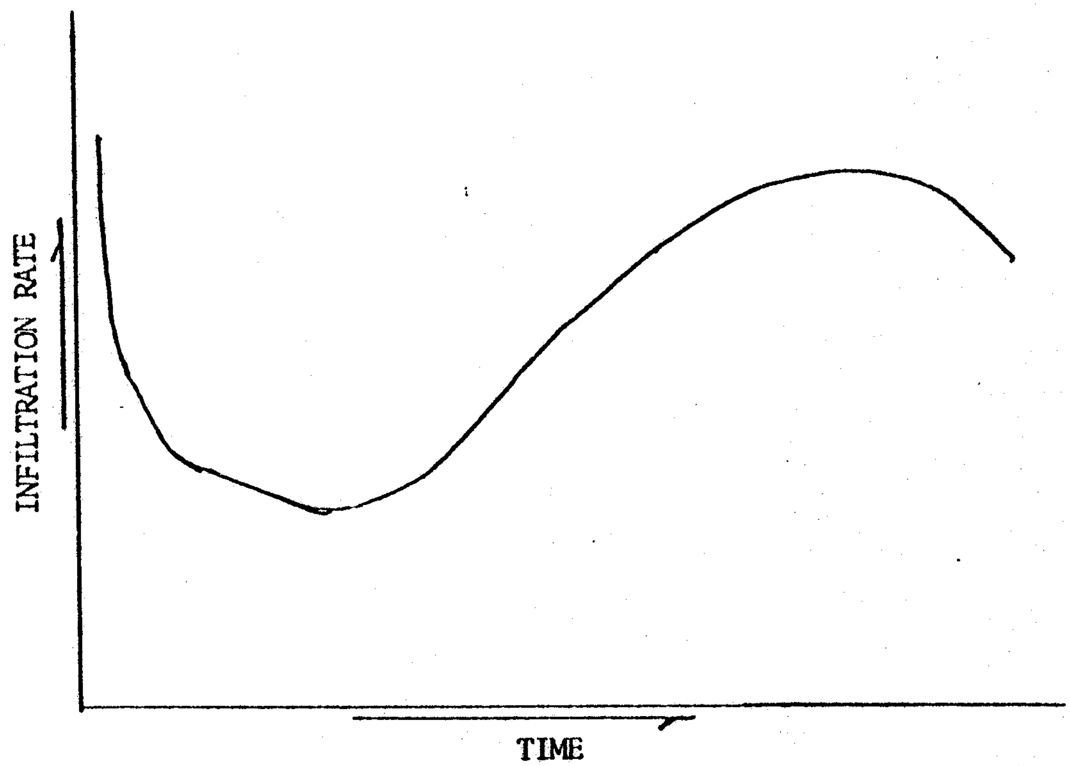
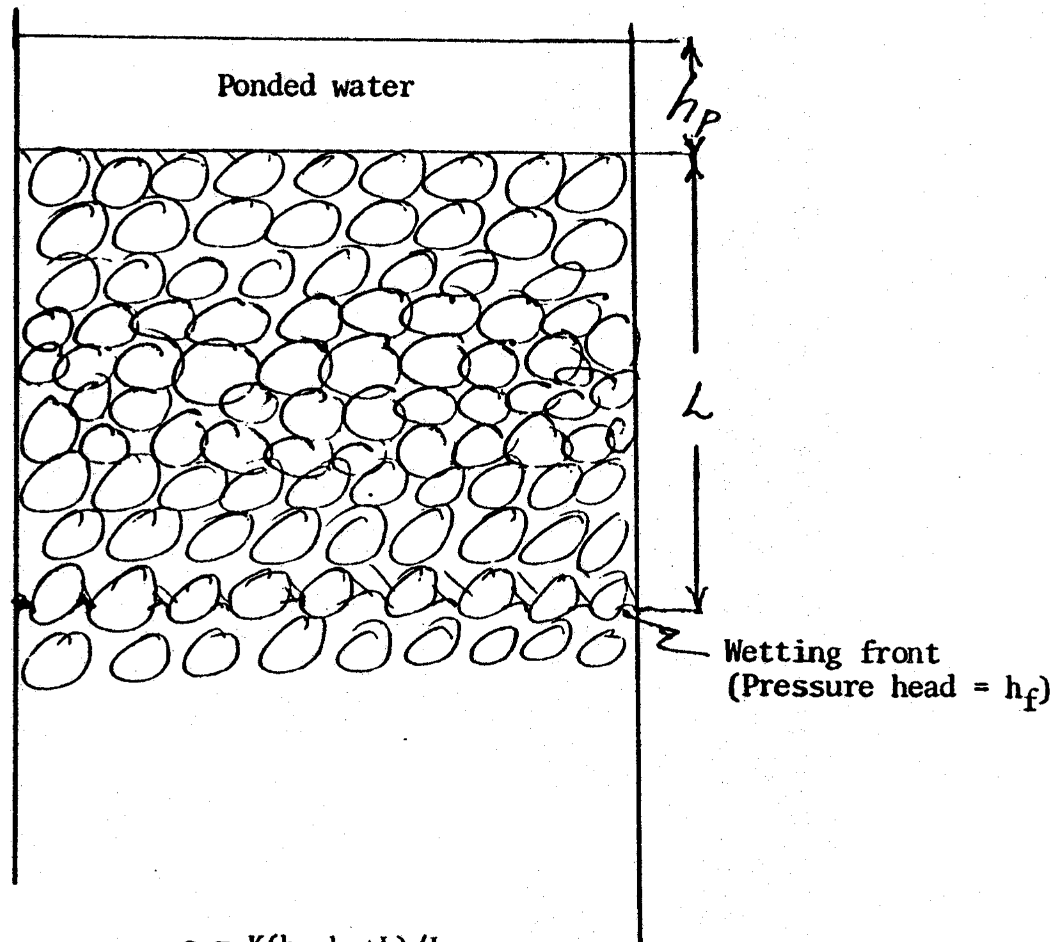


Figure 7. Generalized graph of the variation of infiltration rate with time during spreading-basin recharge.



$$q = K(h_p - h_f + L)/L$$

Figure 8. Infiltration rate (q) as given by method of Green and Ampt.

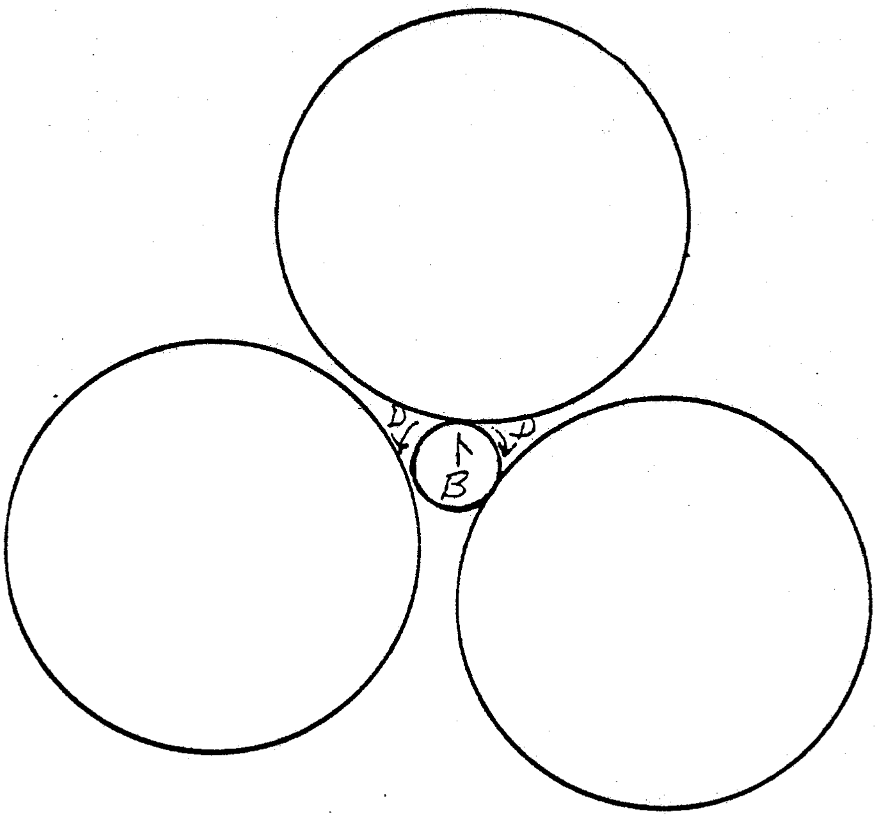


Figure 9.

Forces acting on a trapped air bubble during downward infiltration.

B = buoyancy; D = viscous drag.

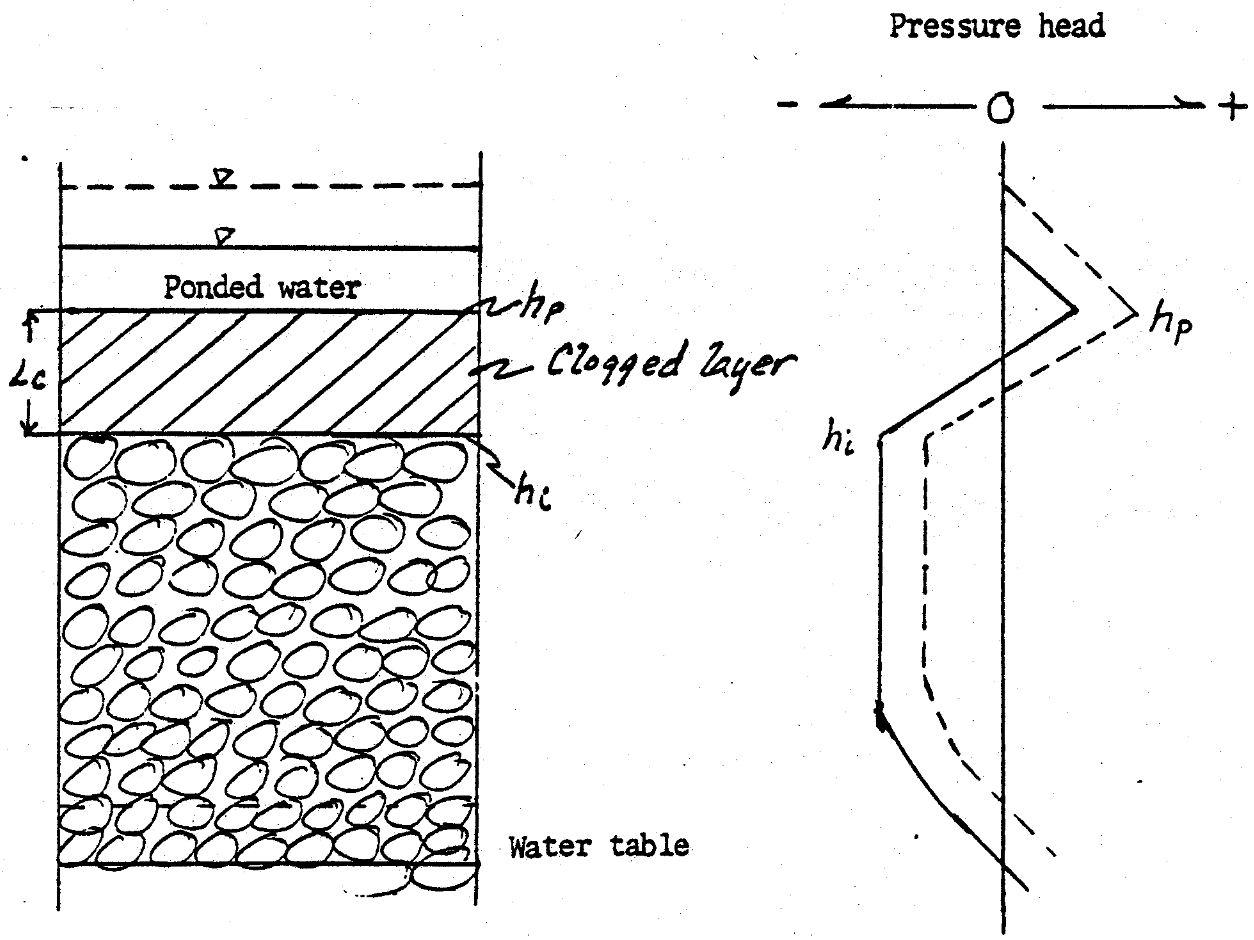


Figure 10.

Sketch showing effect of increased ponding depth on pressure head during infiltration through a clogged surface layer.

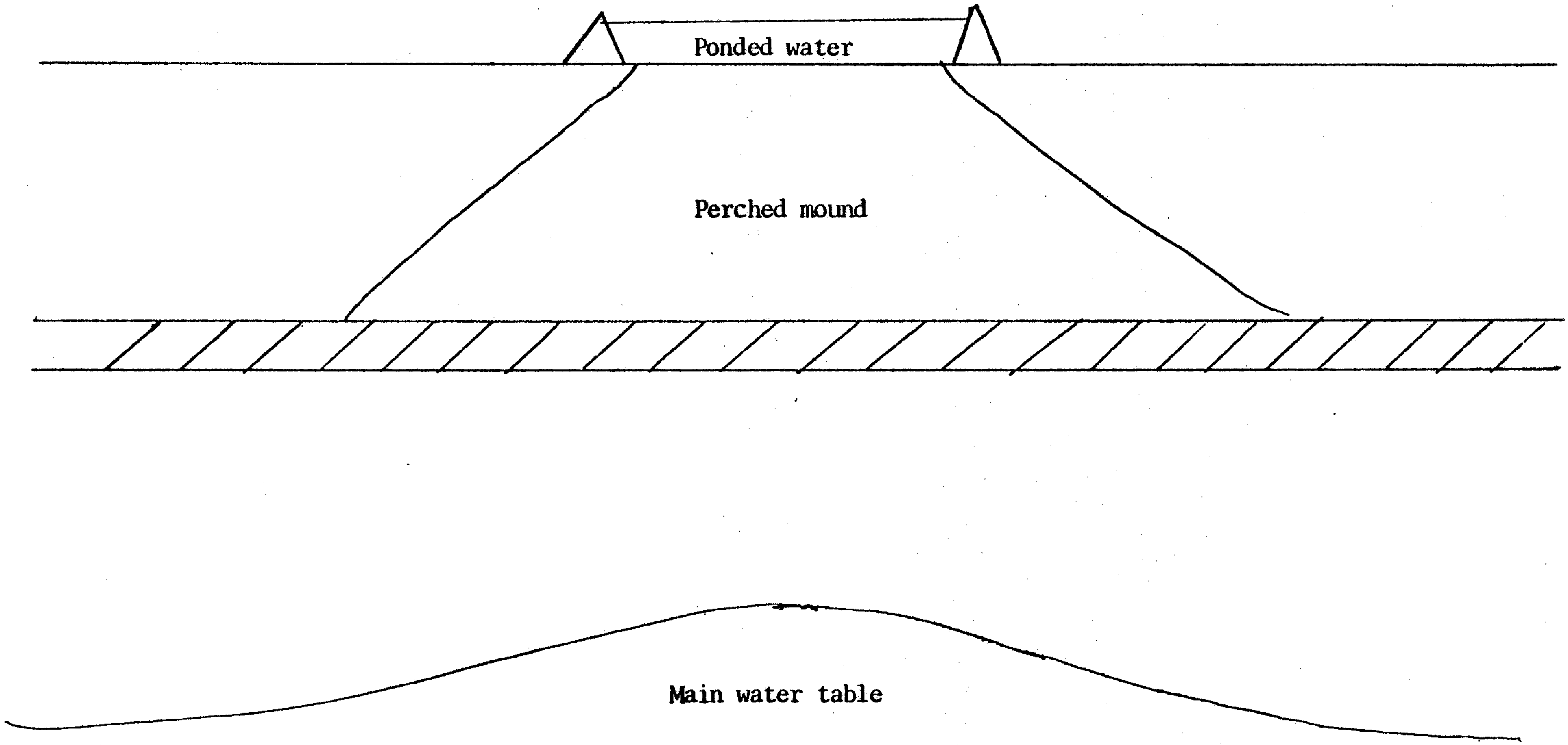


Figure 11. Sketch showing effect of a low-permeability layer at depth on spreading-basin recharge.

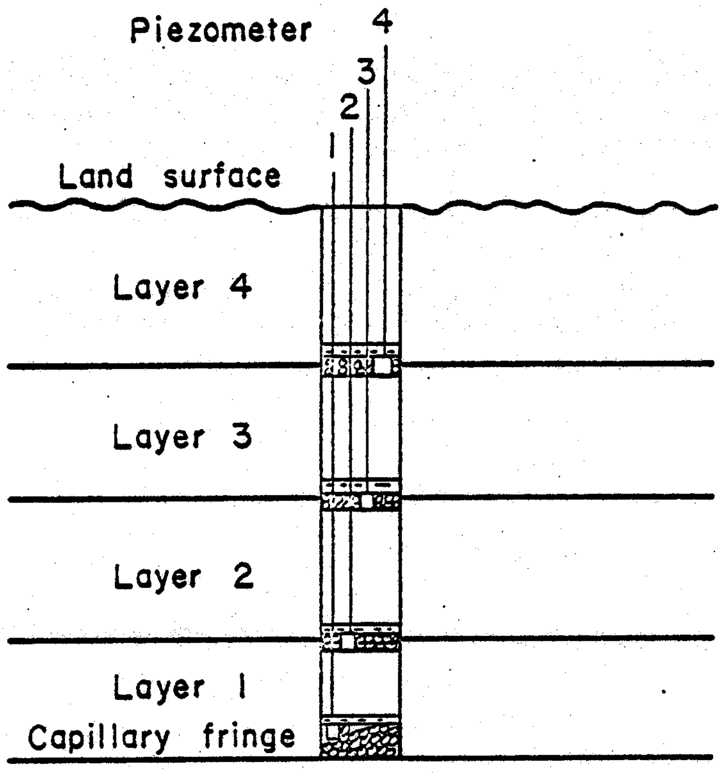


Figure 12. Typical piezometer nest used to determine pneumatic heads at selected depths in the unsaturated zone.

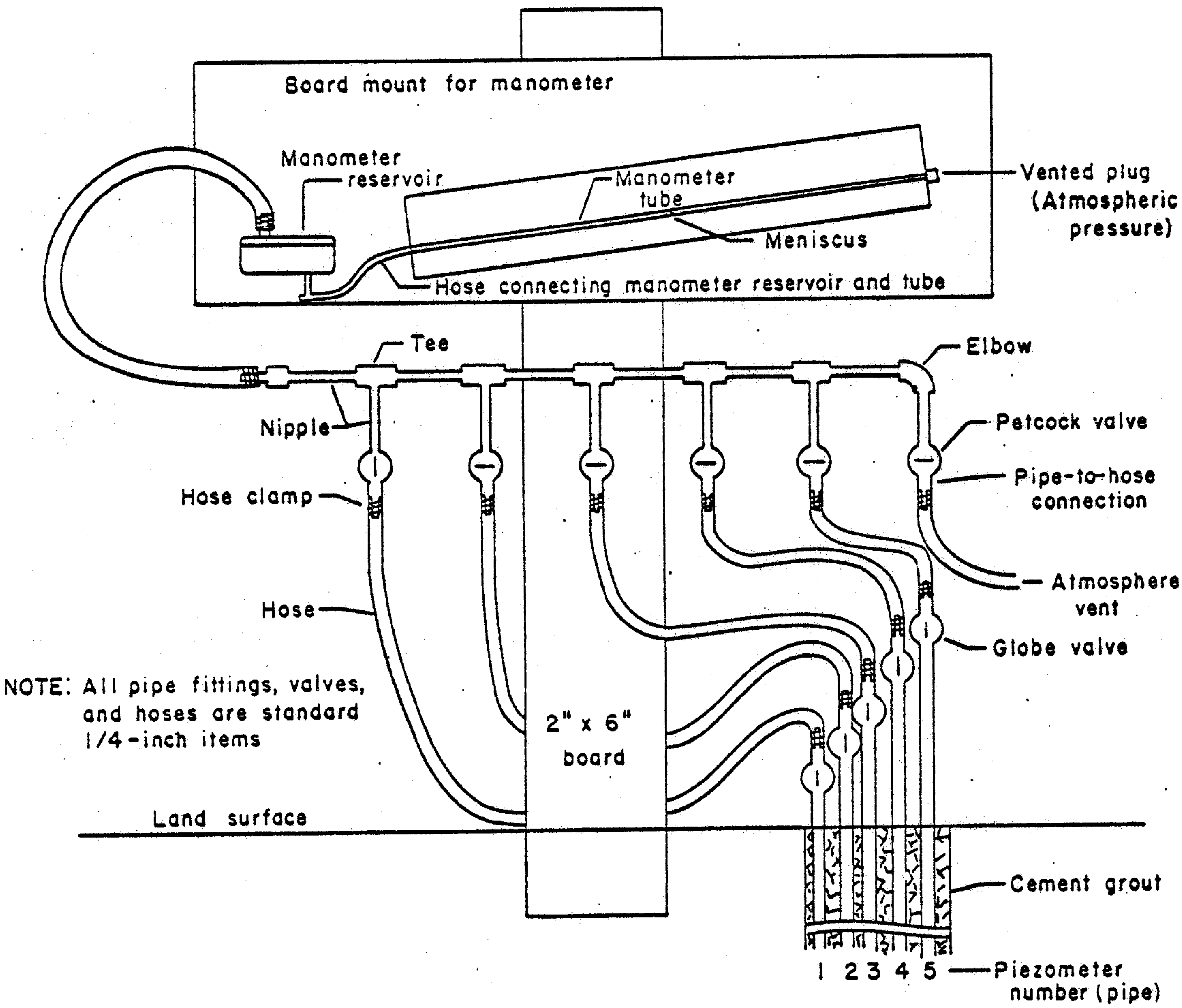


Figure 13. Diagram showing an inclined manometer connected through a manifold to a piezometer nest.

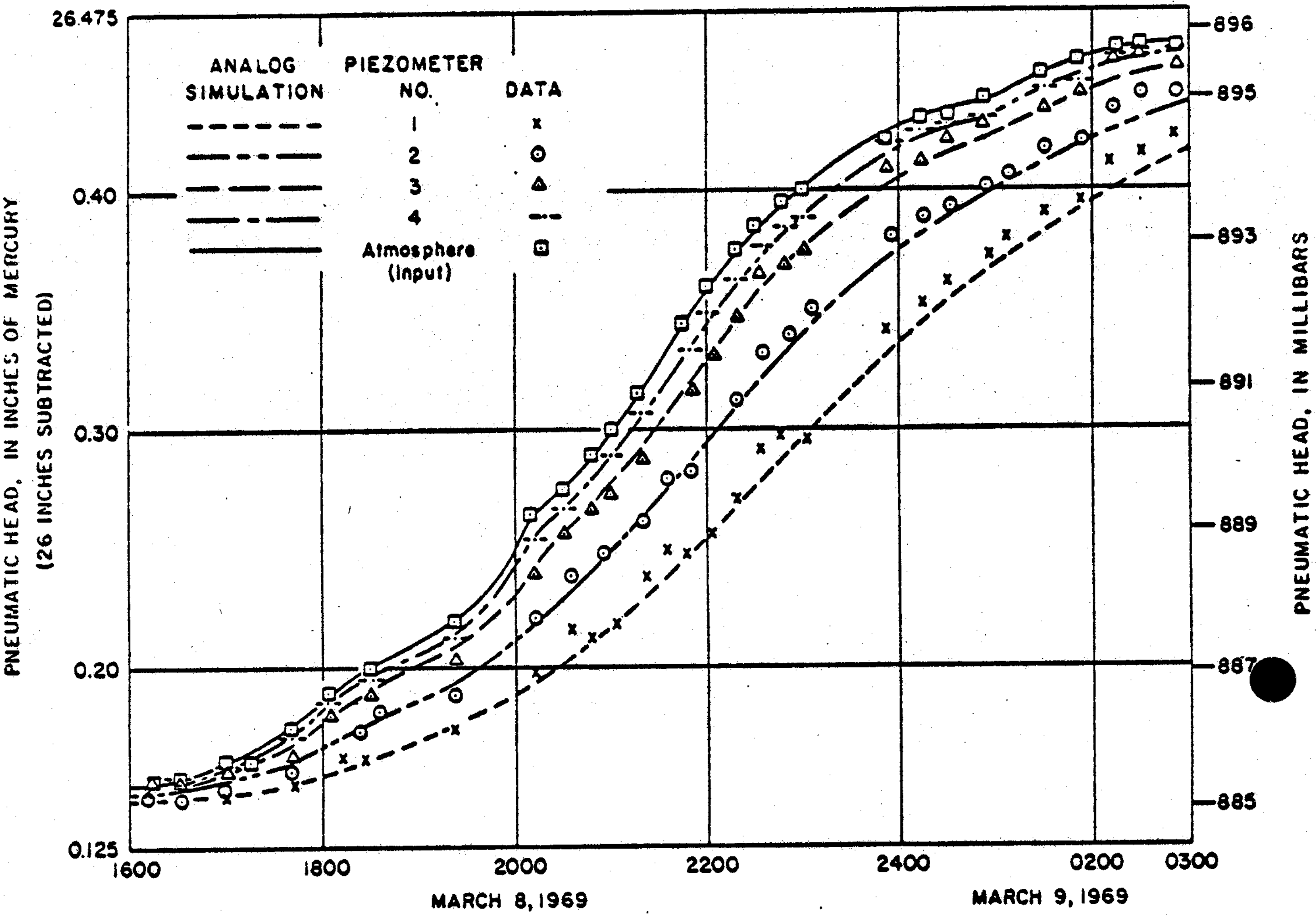


Figure 14. Comparison of measured pneumatic heads at several depths to the best-fitting numerical simulation.

AUTHOR'S BIOGRAPHICAL SKETCH

NAME: Herbert E. Skibitzke

EDUCATION:

JOB POSITION: Hydrologist and Mathematician for Hydro Data Corporation in Tempe, Arizona

EXPERIENCE:

Internationally recognized authority in the field of hydrology, retired from the U.S. Geological Survey in July 1976 after 30 years of service. Was the U.S. Geological Survey's leading authority for mathematical theory describing groundwater motion

Aerial surveying of the 1964 Alaskan earthquake damage plus hydrologic and environmental considerations

Remote sensing by means of sidelooking airborne radar (SLAR), thermal infrared imagery, and photography of the Trans-Alaska Pipeline System

Consultant to the National Aeronautics & Space Administration on remote sensing

A member of President Kennedy's commission to study water salinity in West Pakistan

Author of numerous professional and scientific publications

A DISCUSSION ON AQUIFER RECHARGE FROM INJECTION WELLS

BY

HERBERT E. SKIBITZKE

The problems encountered in aquifer recharge from injection wells is the subject for this session. We have already heard some discussion about the problems of introducing water into the aquifer from pits located above the aquifer. Wells have now entered into the considerations of recharge because the geologic nature of sediments is such that the horizontal permeability is much greater than the vertical permeability. Hence, it is easier to inject water laterally than vertically. In certain parts of the world, and particularly in the western United States, stratification has made vertical injection very difficult. In most of the experiments that have been undertaken, wells have been used. In other parts of the world such as in Holland where recharge from pits has been very successful, both the vertical and the horizontal material is of uniform permeability, allowing the water to flow into the ground quickly.

The central Arizona flood of March 1978 presented an interesting study of the recharge process. It has been reported that 526,000 acre feet of water was released at Granite Reef Dam on March 3. Between March 3 and March 13, 385,000 acre feet of water arrived at the Painted Rock Reservoir near Gila Bend. The difference, about 141,000 acre feet, was lost in the channel (although some of that probably arrived at the reservoir after March 13). Most of the missing 141,000 acre feet was absorbed into a very dry channel. The water was largely taken up by capillarity, and has been or will be released by evaporation in subsequent months. Therefore, there are approximately 385,000 acre feet of water to observe in the Painted Rock Reservoir.

Since March, the rate of decline in the reservoir has been about 10,000 acre feet of water a month, with a head loss of 9 feet in the five-month period following. The rate of seepage from the bottom of the reservoir is probably about 0.4 foot per month. The water level has been lowered 0.6 foot per month during the same period, and evaporation losses account for some of the decline. Therefore, the rate of water going into the ground is quite slow, even though 109,000 acre feet of water has entered the groundwater system from the Painted Rock Reservoir since March.

A lake covering 16,500 acres of land has been required to introduce 109,000 acre feet of water into the groundwater system. If reservoirs are to be built to provide similar amounts of water for recharge in the upper part of the basin near Phoenix or near Mesa, where it is needed badly, between 10,000 and 20,000 acres of land must be set aside for each reservoir site to store the water while it seeps into the ground. As an alternative, it has been proposed that injection wells be used in conjunction with existing reservoirs to supplement the seepage losses from the reservoirs. Roughly, about a third or a little more of the water in the reservoir is lost to evaporation and this will always be a problem. Thus, some of the water in the reservoir is lost by evaporation, and some is lost by seepage; now, we propose to investigate the possibility of pumping some of the water from the reservoir into wells for recharge into the ground. It might be well to look into the physics of the problem.

According to Mr. Bauman, from the Los Angeles Water District, who wrote a number of papers on the problem of injection wells in the 1950's and 1960's, the problem of injecting water into the ground through a well is not exactly the reverse of pumping the water from the well. As a matter of fact, there is a great difference, and the different factors must be considered carefully before injection commences.

An important consideration, and one that is frequently misinterpreted in reporting on occurrences such as floods in the river channel, is the concept of movement of water versus the concept of pressure changes. I would like to draw an analogy to illustrate the lack of understanding of these phenomena. Let us suppose for a moment that the water supply system for the City of Phoenix -- all its piping, all its duct work, all its storage facilities -- were drained. Then, let us suppose that after the system was dry, water was reintroduced into the system from the Squaw Peak station and the pipes began to fill throughout the system. Early in the filling process, we would find some water at the lower end and we would also find that there was pressure in the taps. As the water filled the pipe system, increasing numbers of residents would find water pressure at their taps. Finally, after the entire system was filled, we would have pressure in all the taps and, of course, the greatest pressure, if no water were being drawn, would be at the lower end. Now an interesting thing would take place. If suddenly very high pressure were exerted on the upper end of the system, say at the Squaw Peak Station, we would find that the pressure would respond in the lower part of the system almost simultaneously. That does not mean that water has been moved from the upper end down to the lower end. It simply means that pressure has been transferred from the upper end to the lower end. A similar situation applies in groundwater systems.

Considering the case of transferring pressure in a groundwater system without moving water, consider, for example, that at the junction of the Salt and Gila Rivers where the pore spaces of the soil are virtually filled with water, the river begins to flow in flood stage. Three or four miles away, the pressure in the wells begins to rise, not because the water has moved from the river channel to the wells several miles north of the river, but because the pressure waves have moved. The process is very similar to the pressure change in the upper end of the city water system and the simultaneous response at the lower end of the system. To say that the water in the flood channel has moved great distances because of the rapid response from pressure changes in areas where the pore spaces in the aquifer system and above the water table are full, is to misinterpret the occurrence. So, care must be taken in interpreting the meaning of the rapid changes that are occurring.

As a matter of fact, in the case of the March flood, only 114,000 acre feet of water was lost from the channel by evaporation, capillarity, seepage, or whatever means, and did not arrive downstream at the Painted Rock Reservoir. Let us keep in mind that we are dealing with two different phenomena -- a pressure wave which manifests a rapid transfer in any groundwater system, and water movement, which is very slow by comparison. Actually, the rate of groundwater movement in Arizona amounts to only a very few feet per year. It takes hundreds of years for groundwater to move a mile in the natural state. The only way we can speed the process is to increase hydraulic gradient steeply by drilling wells into the ground and pumping rapidly. In the days before irrigation was so extensive in the Salt River Valley, tens of thousands of years would have been required for the movement of groundwater from Apache Junction to a point just below Phoenix. The pressure changes, however, could occur considerably faster.

Let us consider some of the problems that occur when groundwater injection is initiated. Figure 1A depicts the problem that exists in Salt River Valley. Water is seeping from a pit, attempting to work its way to the groundwater table. However, the material between the pit and the hard rock at the bottom of the aquifer, is composed of lenticular layers of gravels and sands. After the water leaves the pit it must move in devious channels and, in some cases, must flow through the lenses of large continuity to reach the aquifer. Just so, the rate of vertical recharge at Painted Rock Reservoir is slow.

Conversely, on the right side of Figure 1A, the water being discharged laterally from the wells, is moving between the lenses and quickly filling in the pore spaces. The result is more rapid recharge to the aquifer than if the pit drainage were the only resource. However, the recharge process is not as rapid as it appears in the diagram, as a quantitative analysis will show in a later paragraph.

If the lenticular systems that were described above, were down near the original water level, as shown in Figure 1B, the water table would be virtually confined. If water were injected from a well below the confining clay layer the water would fill the spaces below the confining layer and the water resource would not be increased in this particular area at all; rather, the water pressure would be increased.

If the water pressure were raised to the level indicated as the piezometric surface, water would be found in the observation well that is shown to the left of the injection well, because the observation well is below the piezometric surface. The problem in getting the water from the groundwater system to move up and fill the zone above the water table is quite often the same problem as that encountered in getting the water from the pit at the surface of the ground to move down to the water table; only the directions are reversed. Probably by far the best way to get water into the groundwater system in this region would be to perforate both above and below the confining clay layer, allowing the water to move laterally along the clay layers filling in the entire region to the ground surface.

Figure 2 is a set of tables for the transmissivity and permeability relationships that are found in normal materials in the Salt River Valley and throughout central Arizona. The permeability in almost every unit runs from 10^{3} feet squared per minute for clean sands down to 10^{4} feet squared per minute for the clay layers. The variation, then, is 10^{7}, one million times the change in permeability of the normal rock materials in which wells are being drilled in central Arizona. One million times is a huge factor and since the preferred stratification is lateral, it means that the chances of getting water in vertically are severely limited, considering the large extents of very low permeable zones that must be traversed.

The diagrams of Figure 3 illustrate the problem encountered in injecting water into the ground. In Diagram A, two solid lines appear to be a section through a cone of impression around the wells. If a single well were injecting water into an aquifer that had no confining zone, the condition might be as shown by the solid line in Diagram B, indicating a single cone of impression building up over the water table as water is injected into the system. However, returning to Diagram A, there are two cones; each intruding upon the other's space. The dotted line shows that the two cones have joined and a water surface is forming above the original water table in the pattern that is shown more simply in Diagram C. After the wells have joined, the water table begins to build and injection from each well interferes with the injection rate of the other. The quantity that might be injected from a single well will be considerably greater than the quantity injected from each well when two wells are placed side by side.

As for trying to build an injection field by placing numerous wells in close proximity, the cones begin to join as shown in Diagram D, resulting in the formation of a mound. The wells in the center of the mound can take in very little water because the adjoining wells severely interfere with the hydraulic gradient. The result is that instead of the single cone pattern of a single injection well like the one in Diagram B, a pattern is formed of a series of these cones joined together. As the multicone pattern is built up the water level will rise more rapidly in the center of the cone than at its outer perimeter.

Placement of 36 wells in a rectangular pattern in one valley location is being considered, as shown in the upper right corner of Figure 4. Thirty six wells! Observe the rise in water level in those wells, and also the build-up of the water level two miles away. In the center of the well field, the water table building toward the surface of the ground limits injection. Once the water table rises to the surface of the ground or to any interfering body, no more water can enter the system. For example, if the water table were at a depth of 100 feet, no more water could enter the system after the water table had been built up 100 feet.

The computations of Figure 4 show that the wells would be limited to an average intake of 1,289 gallons per minute. In a 36-well field such as this, a total intake of 46,415 gallons a minute would be possible. This would represent, in a year's time, 75,000 acre feet of water that could enter such a well system. At a distance of two miles away, however, the water table would rise only 2.63 feet after one year. The spread would continue with time until about 254 days after injection ceased, when the water table in the cone of impression would have declined to about half its value.

Again, a large well field such as this could handle 75,000 acre feet of water per year. Economically, the cost of the well field is probably less than the cost of a reservoir to store 75,000 acre feet of water for input to the well field at the rate of about 1,285 gallons per minute per well. The 75,000 acre feet of water will have to be stored for about a year. The acreage required for the reservoir would depend on the depth of water required to store the 75,000 acre feet. For example, if ten feet were the depth of water that could be stored in the reservoir, 7,500 acres of land would be required. Thus, the greatest cost in well injection is not in drilling the wells but in providing the reservoir for the distribution of water to the injection site.

The size of the well field is limited. In the field under discussion, with the 36 wells spaced at intervals of 1,500 feet, there is sufficient mutual interference to cause diminished efficiency of the injection scheme. If the well field were doubled in size the amount of water injected would not be doubled; rather, the proportion of increase would be much smaller. The percentage of increase falls off rapidly as the field size is increased. If fewer wells were spaced at greater intervals, the water would then necessarily be distributed in channels or in pipelines over a much wider area. Remember, also, that when water is injected at a given location, the water level at a remote site is not affected by the injection. In the case considered, even at a distance of two miles away, the water level had increased only 2.63 feet at the end of a year. Therefore, the injection sites must be located where the water is required. That means that the water must be transported from whatever reservoir is used to the injection site.

The problem now is largely one of economics. Could we pay for the reservoir? Could we pay for wells to furnish, as in this case, 75,000 acre feet of water for the year that injection might be possible? Also, consider that in the case of Painted Rock Reservoir, probably as much as a third of the water is being lost by evaporation, so the reservoir must have the capacity to store the additional one-third that will be lost by evaporation in addition to the amount that will be lost by seepage. Of course, seepage losses would amount to an additional source of water to the ground water system -- if it were in the area where water is needed. Otherwise, any advantage from seepage might be in terms of budget, only, and not in terms of water available for use in a given locality. That is very important because groundwater moves slowly; therefore, the injected recharge must be furnished in the areas of intended use.

Now, comes the task of actually getting the water into the wells. Three of the most severe problems are illustrated in the rather simple diagram of Figure 5. The upper part of the diagram depicts the No. 1 problem: Air bubbles from the water are filling the pore spaces in the porous material surrounding the slotted steel casing (left) and are held there by capillarity. Neither the pump nor the injection system is powerful enough to move these air bubbles; and as air entrapped in the water rapidly seals the well, injection ceases completely. Because of this formidable problem, there can be no air in the water that is being injected. At the bottom of the diagram, we see that small particles entrained in the water also fill the pore spaces and seal the well. Therefore, all the sediment carried in the water must be removed. Air bubbles and sediment create more difficulty in the injection well than in the pit, because the cross-sectional area of the well is so small; and because the water that is entering through the few existing openings in the casing is so concentrated, whatever sediments are contained in the water are going to be trapped in the porous material and thus force the incoming water to back up. The third problem shown in the diagram occurs because the interval between floods may be long and the availability of water for injection may be nil over long periods of time. Biological changes may occur in the pore spaces, which will also effectively seal the well, precluding further injection. Thus, the injection system that was considered adequate is suddenly backing up.

To circumvent the problems that have just been described, many alternatives have been proposed. As an example, Reider, in his experiments in New Mexico, advocates injecting the water through four-inch pipes so that the loss of pressure in the pipe does not allow any air into the system. Then a series of four-inch pipes would be required to bring the water that is to be injected down to the level of the water table, to prevent air from entering the system. However, some air is bound to enter.

The severity of the biological problem, as well as the sediment problem, depends upon the area and the content of the water. In some parts of the country, injection water must be treated just as the drinking water is treated. A high chlorine content is necessary. All the small particles, as well as the air, must be removed. Therefore, the water handling process, from the reservoir on, is expensive.

In the eastern United States, the Ranney Collector System Figure 6A, has been utilized for water injection. The Ranney Collector System is quite a large installation. Pipes extend horizontally from the base of a large shallow well. The reason that this method of injection has been used in eastern U. S. is that back pressure can be applied to remove the sedimentation and the entrapped air. The procedure is to use one set of collectors for injection while using another set to pump water back out, thus removing some of the extraneous material. These systems, useful at rather shallow depths, are very expensive. In Arizona, injection can be accomplished at shallow depths more effectively than at greater depths, so that criterion is appropriate, but otherwise, the extent to which the Ranney Collectors could be used here is questionable. At any rate, the Ranney Collector System is one way of handling the entrapment problem.

Diagram 6B shows the flow system out of a vertical well that is above the water table. Diagram 6C is from a Russian publication showing a system of injection from above the water table, creating flow lines and pressure pattern extending from the injection point down to the water table. This is another method that has not been tried in Arizona where a considerable amount of stratification of clays and sands and gravels exists; rather, it was tried in an area where uniform sands prevailed. The Arizona problem is illustrated in Figure 7.

If the well was not drilled all the way to the original water table and water was injected through screened slots in the pipe above the water table, the area above the original water level would be filled rapidly. That essentially would be premature filling of the pore spaces that we are attempting to recharge. This would be interesting: In the one case, discussed earlier, in a well injecting below the confining layer, only a very small quantity of water would be entering the aquifer, but huge changes in pressure would occur; and in this case, a large quantity of water is entering with no pressure change in the early stages at all. The pore spaces are just being filled and at some later date, the water table will begin to rise abruptly. In a single well system, the latter would probably be the much more efficient method. If a Ranney Collector System were used, injection would be done at a shallow depth. It would not be necessary to reach the water table. The trouble in Arizona is that in some areas the soil is very dry, and it would have to be recharged. The clays would have to be filled in a non-reversible process. The water used to wet the clays could never be retrieved for irrigation.

In Arizona, where air is continually allowed to circulate in aquifers, dessication, or drying processes, occur. When recharge commences and the clay layers are wetted, a problem that already exists is accentuated; that is, the land either subsides or rises as a result of recharging or discharging of the groundwater system.

In conclusion, most of the problems with injection wells are economic. The entire matter of economics of recharge by injection wells -- not just the cost of wells, but also the cost of reservoirs and the distribution systems -- should be analyzed. The reality of the situation should be investigated before speculation on research activities along these lines is even considered. Sufficient information is probably available to determine the feasibility of using injection systems.

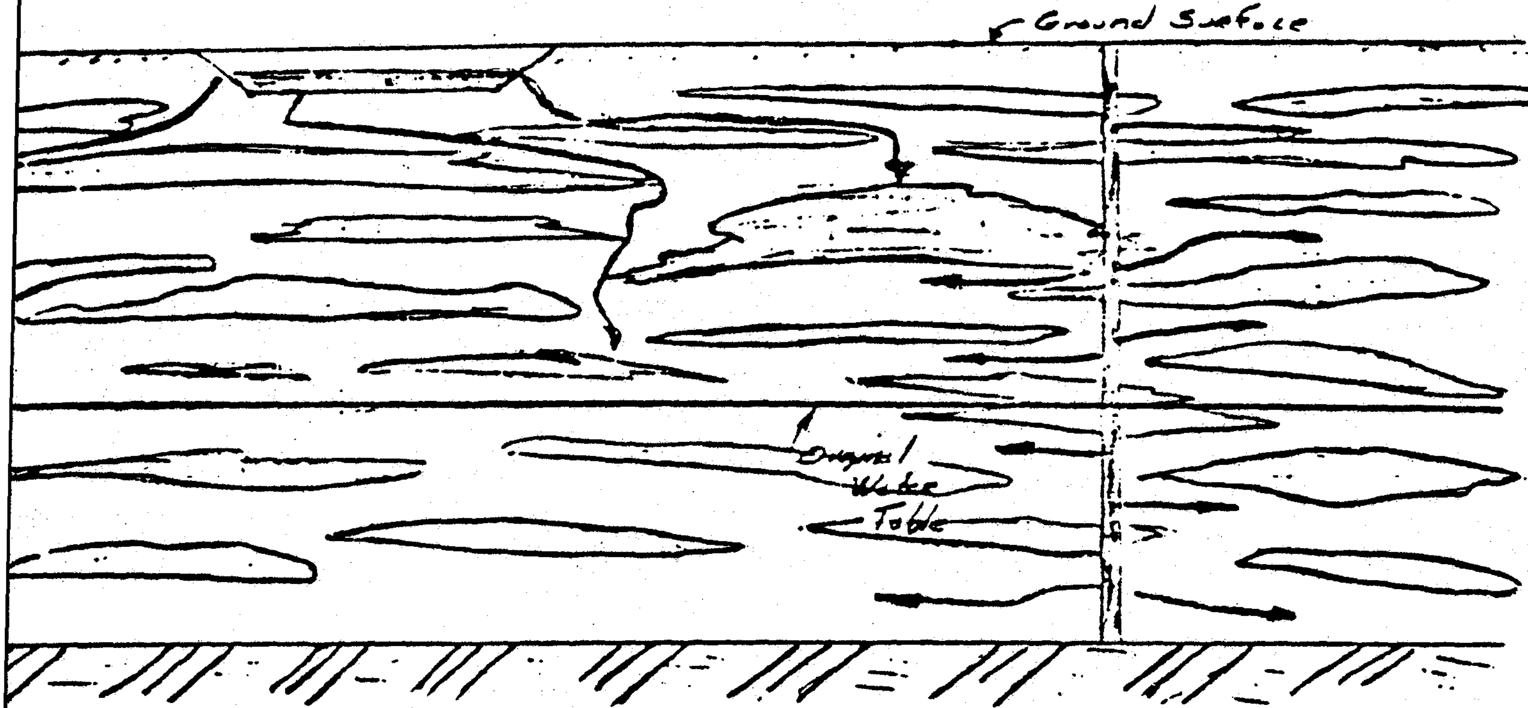


FIGURE 1A

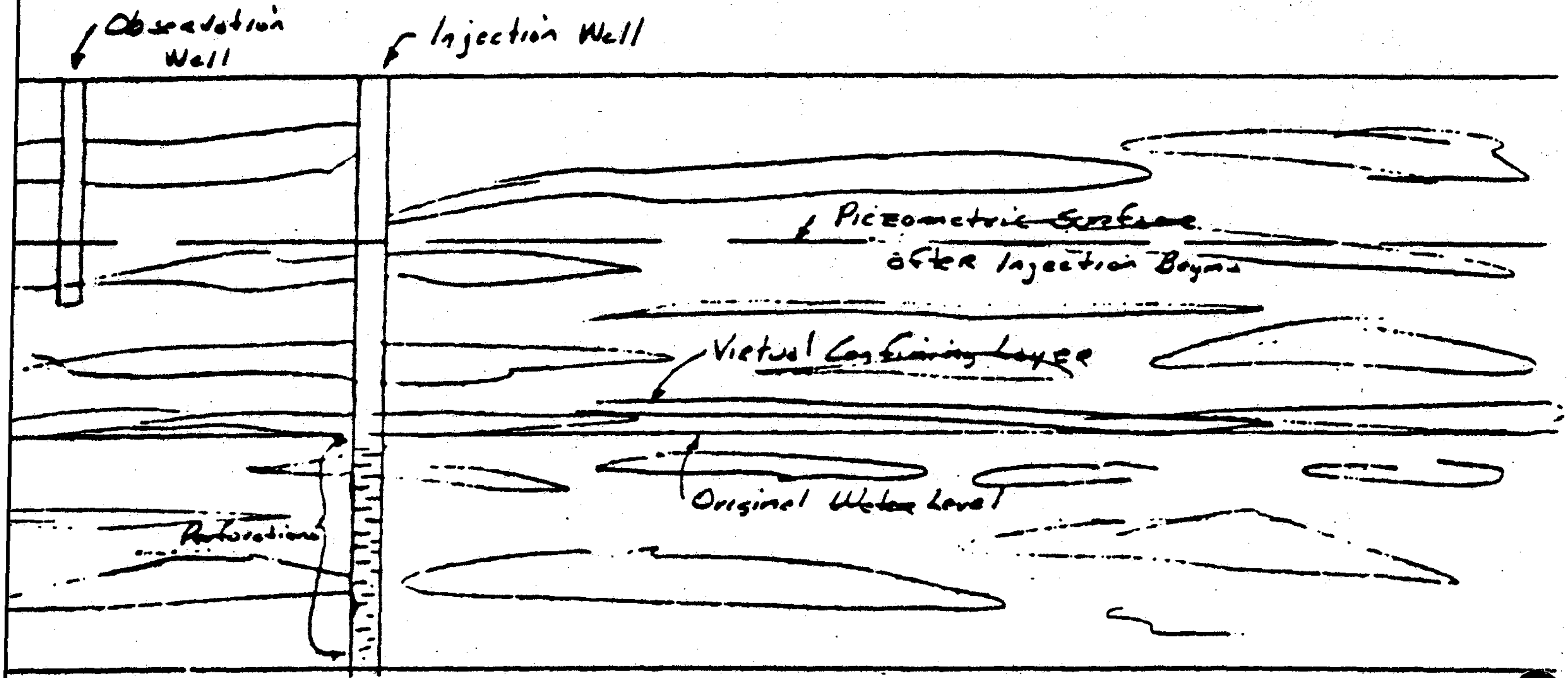
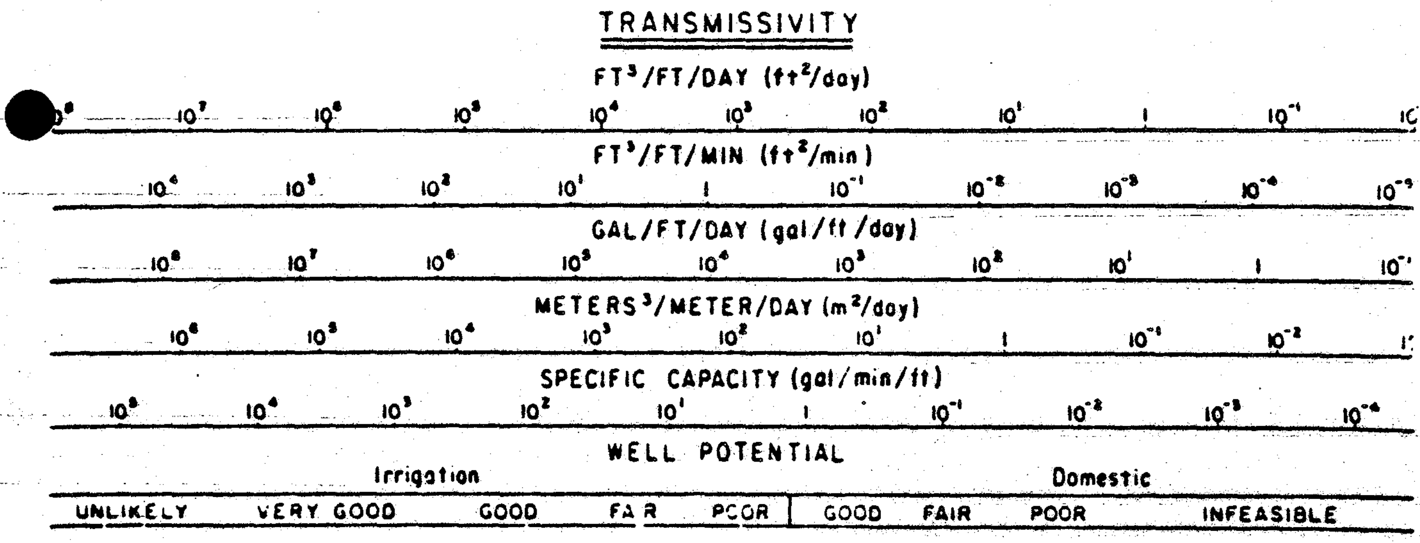


FIGURE 1B



NOTES: Transmissivity (T) = KM where
K = Permeability
M = Saturated thickness of the aquifer
Specific capacity values based on pumping period of approximately 8-hours but are otherwise generalized.

FIGURE 2-4.—Comparison of transmissivity, specific capacity, and well potential. 103-D-1406.

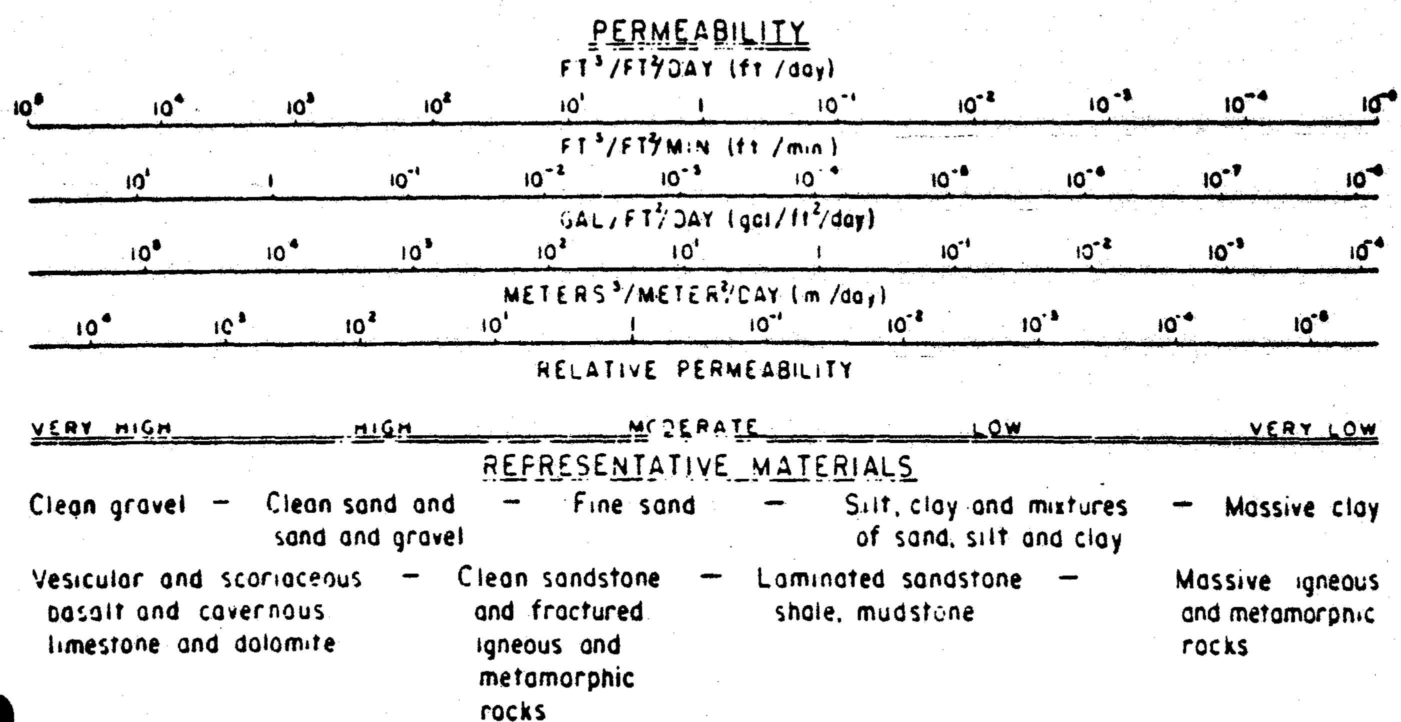


FIGURE 2-5.—Comparison of permeability and representative aquifer materials. 103-D-1407.

FIGURE 2

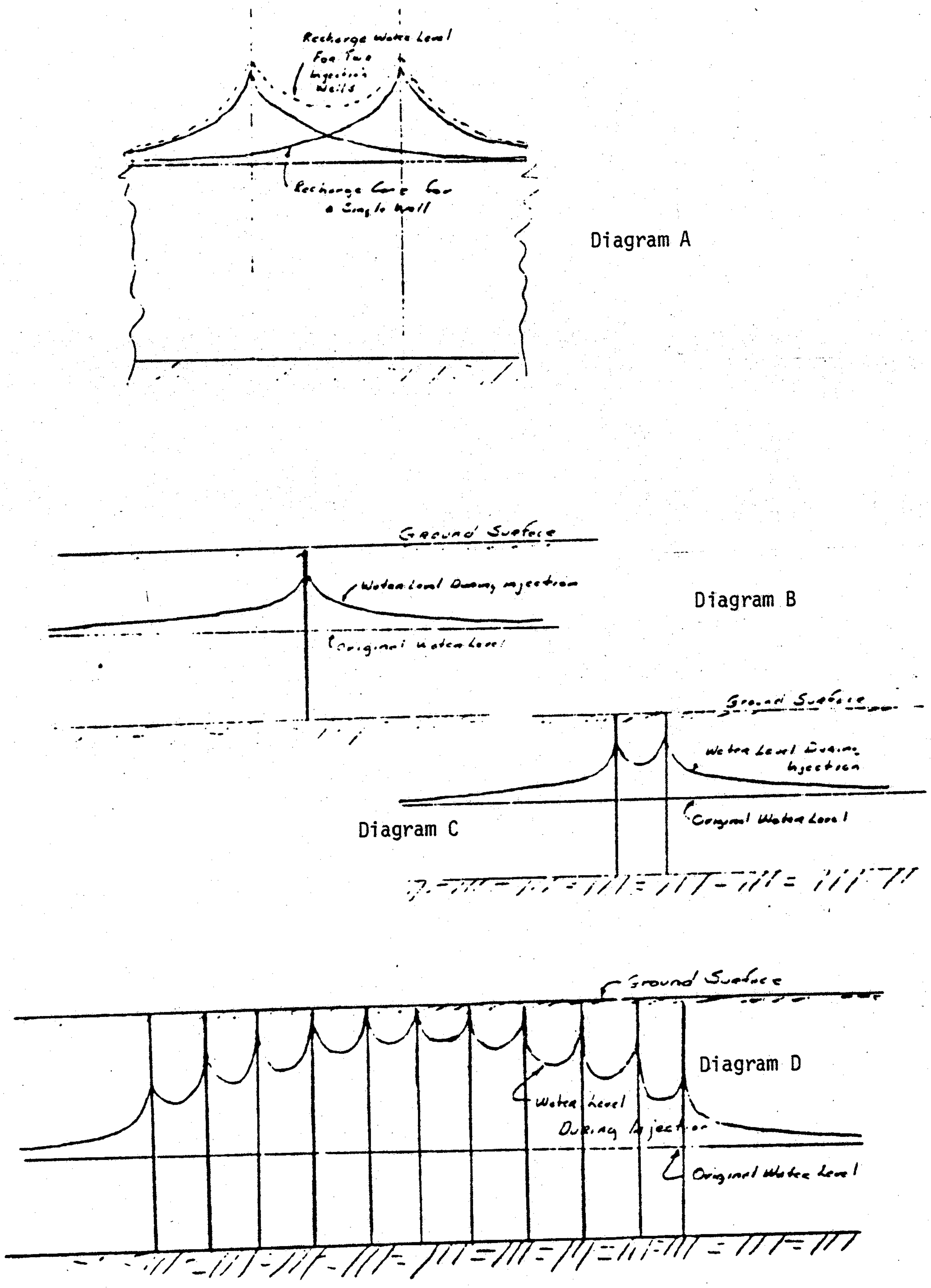
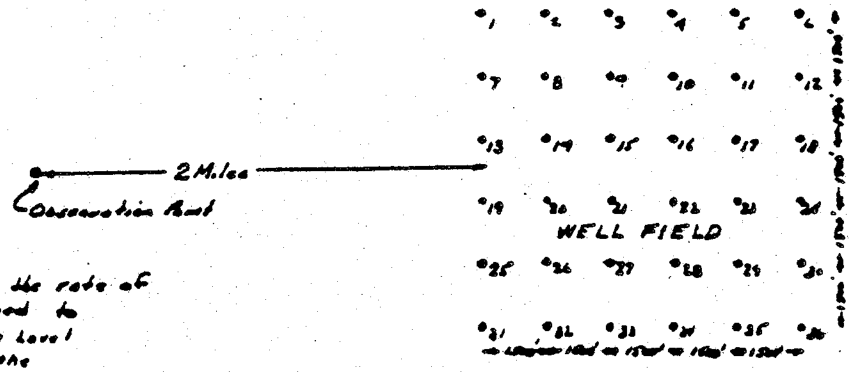

Recharge Water Level For Two Injection Wells
Recharge Cone for a Single Well
Diagram A
Ground Surface
Water Level During Injection
Original Water Level
Diagram B
Ground Surface
Water Level During Injection
Original Water Level
Diagram C
Ground Surface
Water Level During Injection
Original Water Level
Diagram D

FIGURE 3



Determination of the rate of injection required to Raise the water Level 100' under the Well Field

$$S = \frac{114.6\,Q}{T}\left(W(u_1) + W(u_2) + W(u_3) + \cdots + W(u_{36})\right)$$

From Computation Table 1

$$\left(W(u_1) + W(u_2) + W(u_3) + \cdots + W(u_{36})\right) = 67.68$$

$$\frac{1}{Q} = \frac{114.6}{100 \times 100\,000}(67.68)$$

$$1/Q = 7.756 \times 10^{-4}$$

$$Q = 1289 \text{ GPM}$$

$$\sum Q = 46{,}415 \text{ GPM in all wells}$$

The wells receive 75,000 AF in the Years they operate

Q = Injection rate/well

T = Transmissivity = 100,000 GPD/FT

S = Storage Coefficient = 0.20

$$U = \frac{1.87\,S}{T\,t}R^2$$

Decay of Recharge Mound 50'

Approx.

$$\frac{h_0}{H} = 1 - e^{-\frac{a^2}{4\alpha t}}$$

h_0 = Height of Mound after time t

H = Original Height

a = Radius (approx) of Well Field

$\alpha = T/S = \frac{100{,}000}{.2}$

t = time of decay

$$.5 = 1 - e^{-\frac{(4500)^2}{4 \times 6 \times 10^5 \times t}}$$

t = 254 Days

Determination of drawdown at the observation point 2 miles away.

$$S = \frac{114.6\,Q}{T}\left(W(u_1) + W(u_2) + W(u_3) + \cdots + W(u_{36})\right)$$

From Computation Table 2

$$\left(W(u_1) + W(u_2) + W(u_3) + \cdots + W(u_{36})\right) = .178$$

$$S = \frac{114.6 \times 1289}{100{,}000}(.89) = 2.63' \text{ Increase in Water levels}$$

Computation Table 1

	R	1.025×10^{-8}	U	$W(U_i)$
1	5300		.29	.93
2	4400		.20	1.22
3	3800		.15	1.46
4		by		
5		Symmetry		
6				
7	4400		.20	1.22
8	3200		.10	1.82
9	2500		.06	2.30
10		by		
11		Symmetry		
12				
13	3800		.15	1.46
14	2250		.05	2.47
15	1050		.01	4.04
16		by		
17		Symmetry		
18				

Other Half by Symmetry

Computation Table 2

	R	1.025×10^{-8}	U	W(u)
1	11700		1.4	.116
2	13200		1.72	.070
3	14650		2.20	.037
4	16000		2.60	.022
5	17500		3.14	.011
6	18000		3.31	.009
7	11300		1.31	.130
8	12800		1.68	.076
9	14300		2.10	.043
10	15800		2.56	.025
11	17300		3.07	.011
12	18[illegible]0		3.54	.006
13	11000		1.24	.170
14	12600		1.63	.0[illegible]0
15	14100		2.04	.0[illegible]6
16	15500		2.49	.025
17	17100		3.[illegible]	.013
18	18600		3.54	.006

Other Half by Symmetry

FIGURE 4

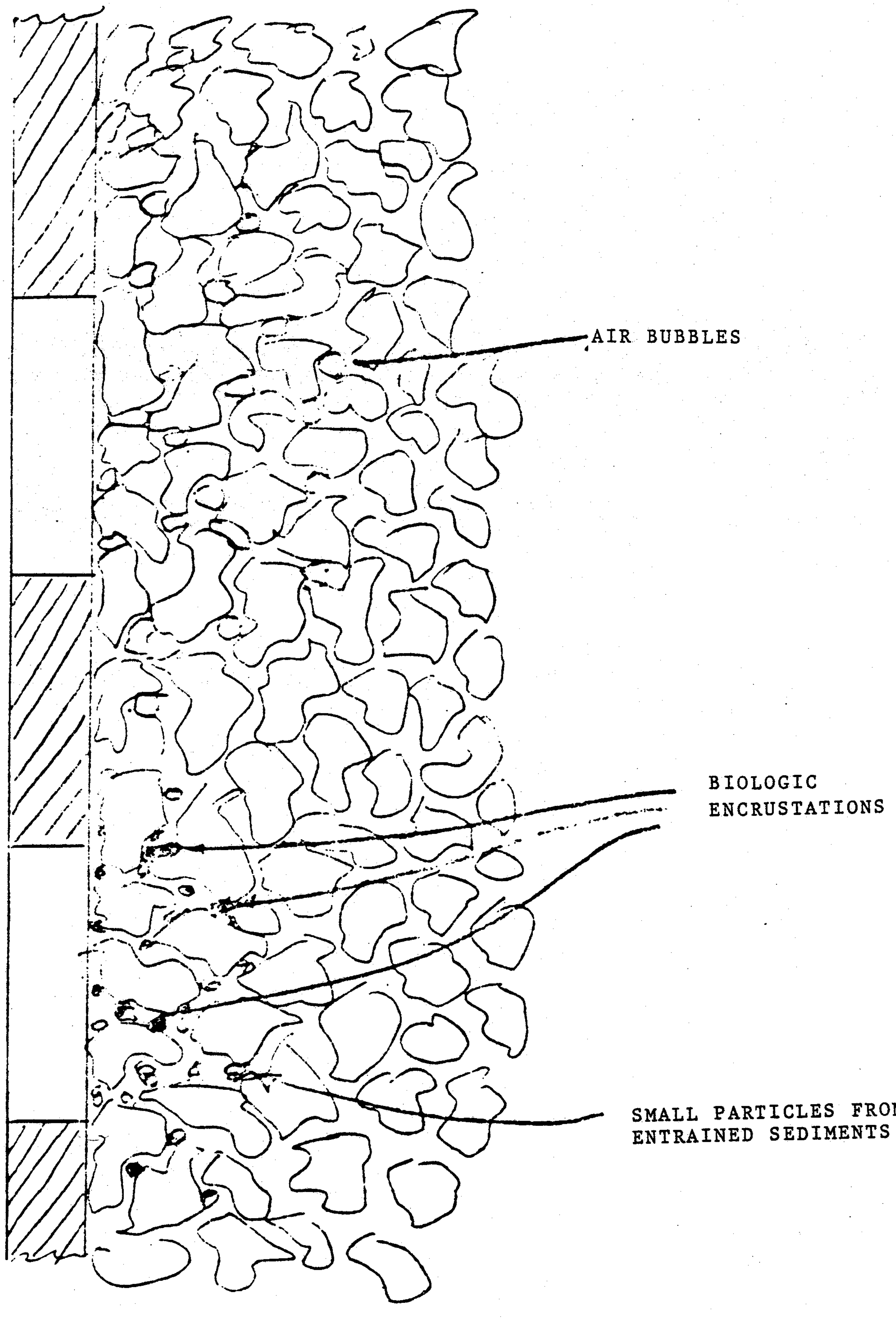

AIR BUBBLES
BIOLOGIC ENCRUSTATIONS
SMALL PARTICLES FROM ENTRAINED SEDIMENTS

FIGURE 5

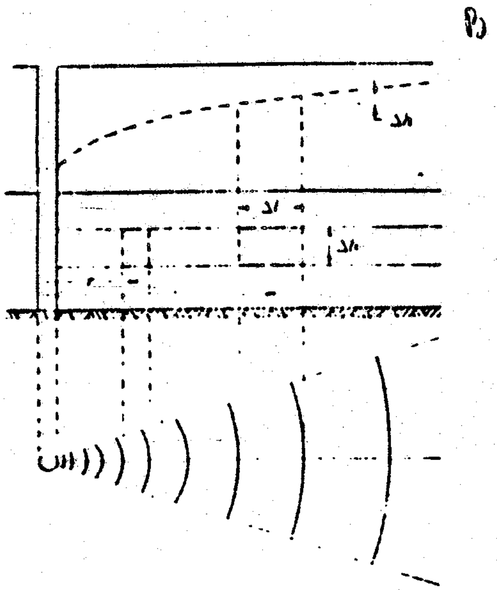
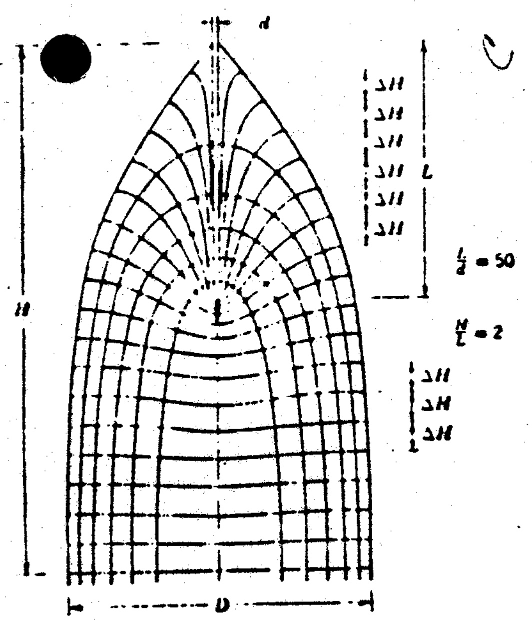
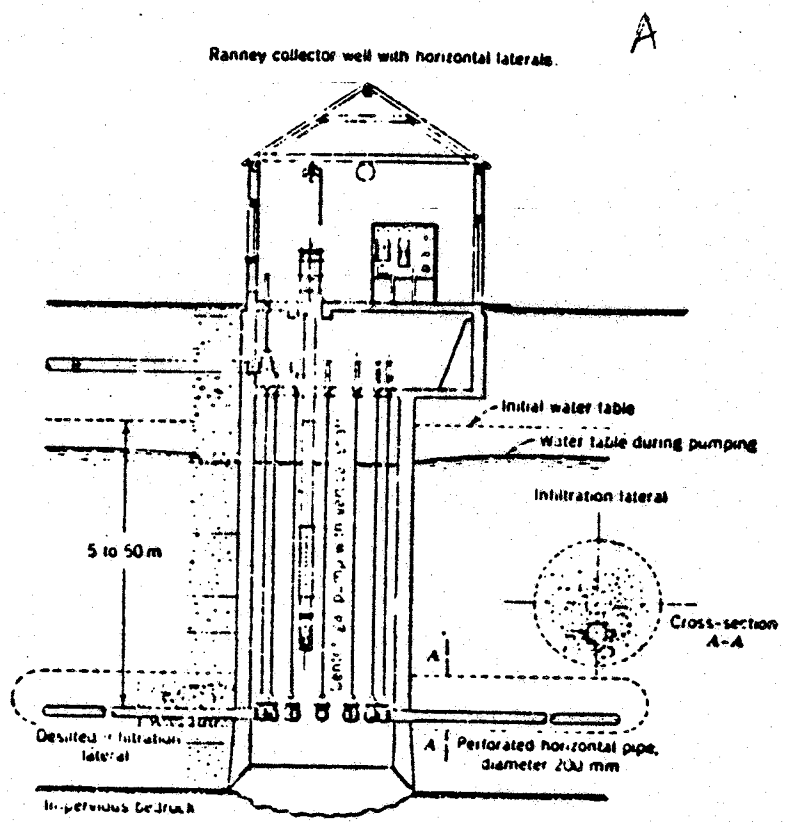


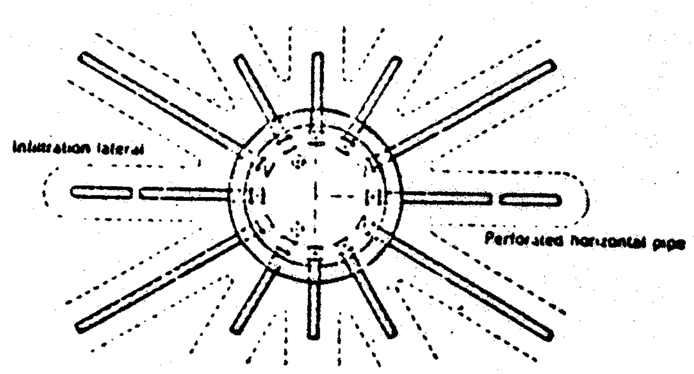
Fig. 5-21 Radial horizontal flow.



Steady well recharge. (After Polubarinova.)

Ranney collector well with horizontal laterals.





Sketch of Ranney collector wells.

FIGURE 6

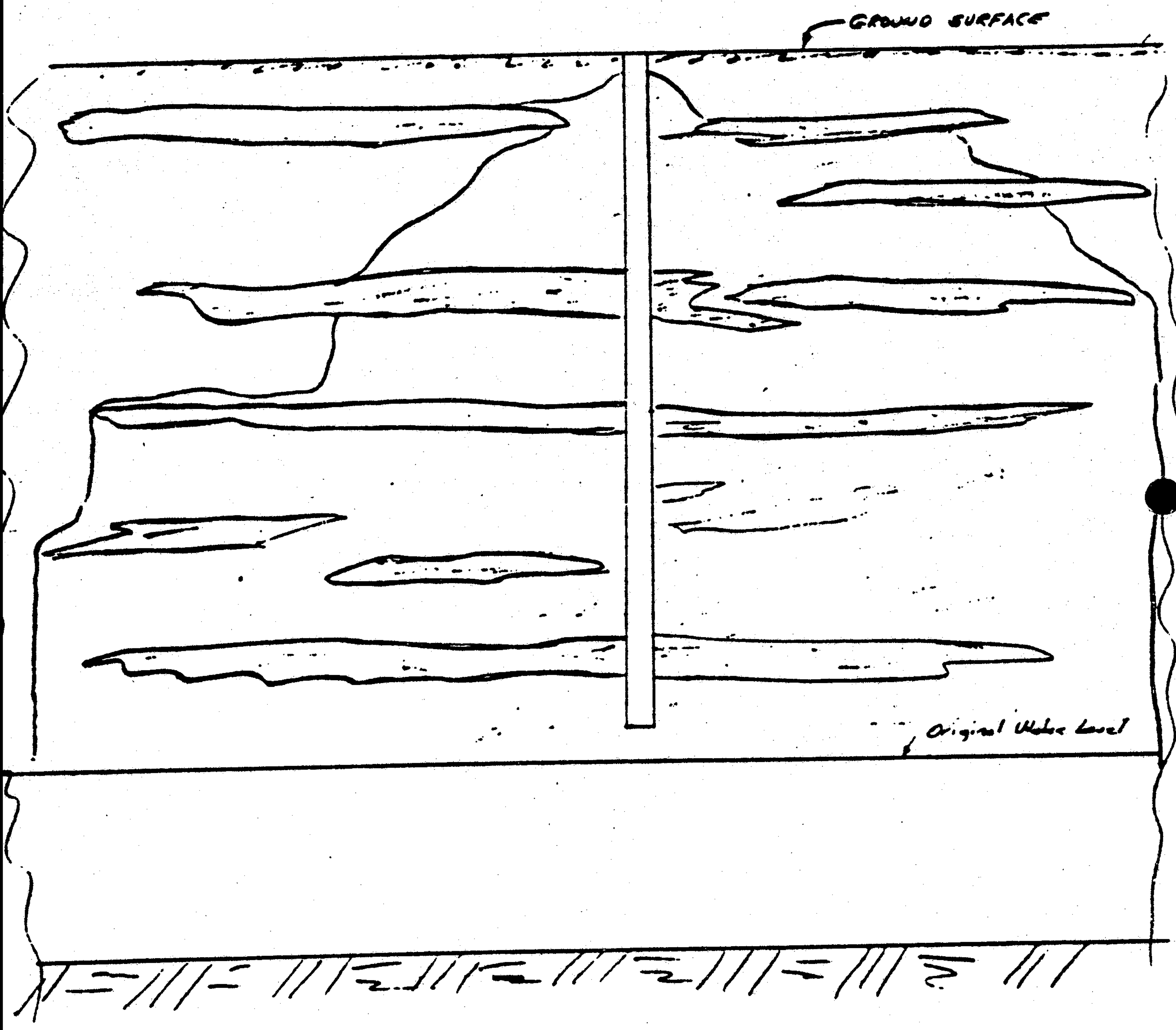


FIGURE 7

AUTHOR'S BIOGRAPHICAL SKETCH

NAME: Harrison C. Dunning

EDUCATION: A.B. Degree <u>summa cum laude</u> from Dartmouth College

LL.B. Degree <u>cum laude</u> from Harvard University

JOB POSITION: Staff Director of the Governor's Commission to review California Water Rights Law, Sacramento, California

EXPERIENCE: Taught law in Ethiopia

Professor of Law at University of California at Davis, specializing in property law, water law and environmental law

LEGAL CONSIDERATIONS OF GROUNDWATER RECHARGE

by

HARRISON DUNNING

We heard this morning a good deal about the technical and physical considerations involved in groundwater recharge. I think those are matters that are universal. You don't have to worry too much about political boundaries when you're talking about experience gained on those technical questions. I'm not sure it's the same with the law. The law is very particular and peculiar to given jurisdictions and perhaps doesn't travel the way some of the technical items do. In any event, I think insofar as California is concerned, the news is good in that recharge has been carried out rather extensively and, as far as I can see, the law has not been a barrier. The law developed in the California courts has been very accommodating to the objectives of those involved in recharge programs, and although there are many parts of California groundwater law which, in my opinion, are not today satisfactory, the law on recharge is not one of those areas.

Before I talk about the specifics of the legal considerations involved in recharge of groundwater basins, I'd like to put the matter in context a little bit by talking about groundwater rights in general.

All but one jurisdiction in the United States took, at the beginning, the common law of England as the basic foundation.

The common law of England provided with regard to water that for surface water, riparian rights would be recognized. This is the right of the land owner adjacent to a stream to have some share in that water course available for the land owner's use.

With regard to groundwater, the English rule was the rule of Acton vs. Blundell developed in 1843, a rule sometimes referred to as the Rule of Absolute Ownership. This meant that the owner of the surface was absolutely entitled to full utilization of any water that could be pumped up from the subsurface. Of course that rule was developed in the 1840's at a time when groundwater hydrology was an infant science, if indeed it existed at all, and when judges certainly knew nothing about the ways in which groundwater travels beneath the surface. I suppose it seemed, in that kind of circumstance, we don't really have any legal regime for the groundwater, and we just say whoever pumps it up gets to keep it. In fact, although that rule is often referred to as a Rule of Absolute Ownership, really it was just a rule of capture. You captured and could hold whatever you brought to the surface, but you had absolutely no protection against your neighbors and what your neighbors might capture through their wells. In any event, the English Common Law on water rights has been largely rejected in the western United States.

With regard to surface waters, of course, many states have followed the so-called Colorado Doctrine. This doctrine rejects out-of-hand the riparian right and says the principal water right for surface waters is the appropriative right, the right of the appropriator of water to put that water to beneficial use. Not all western states have done that. California and a few others have recognized riparian rights as well as appropriative rights, although California is the only one today that really gives riparian rights any great significance.

With regard to groundwater, Acton vs. Blundell was based on the old concept that a landowner owns up to the heavens and down to the bowels of the earth, including the resources to be found in those two areas. That concept, obviously, is a difficult one to live with once you have airplanes, for example, and some of the other things of modern life. It's been rejected with regard to the area above the surface many times in all jurisdictions. Landowners, for example, cannot charge for aircraft passing across "their" air space.

Similarly, this concept has by and large been rejected with regard to the space below the landowner's parcel. There apparently are some remnants of the Acton vs. Blundell approach in Texas. But most of the western states in the United States have abandoned this notion of absolute ownership of groundwater in the landowners and instead have developed some variation of a reasonable use theory. Landowners are regarded as entitled to reasonable use of the groundwater resource, but that's tempered by the needs of their neighbors and, in some jurisdictions, by the needs of society in general. California distinguishes between those landowners who overlie the basin and those who do not and provides a preference for the overliers, but also provides very clearly that non-overliers or overliers who wish to use the groundwater for non-overlying purposes may appropriate surplus water.

Like most of the other western states, California has decided as a policy matter that the water ought to be movable. It ought to be available to go to the place of beneficial use. Surplus groundwaters like surplus surface waters are subject to appropriation and movement to other areas. California, like most of the western states, has nothing like the appurtenancy doctrine which seems to be unique to Arizona and which ties the water to the land parcel for which it originally was appropriated.

All right, that's a little bit of background on groundwater rights generally. Turning to recharge problems, I will distinguish three stages involved in recharging. First of all, is the spreading or infiltration stage; secondly, maintenance of recharge water in the basin; and, thirdly, recapture of the recharge water for beneficial use.

With regard to the spreading, the first obvious question is, "Where do you get the water?" This morning most of the emphasis seemed to be on floodwater: the capture of floodwater in certain years and use of that floodwater for recharge purposes. This is done rather extensively in California. The Los Angeles County Flood Control District, for example, has an elaborate system for flood control and recharge of groundwaters. Usually the legal questions, if they arise, are liability questions, and by conserving the floodwater and using it for recharge purposes, one decreases the possibility for damage and, consequently, the exposure to liability. However, there are other sources of water for recharge purposes in addition to conservation of peak flood flows.

One source which has been used extensively in California is simply to purchase water for recharge purposes from whoever has water to sell. The major projects, the Federal and State projects in California, have been important suppliers of water, some of which is used for recharge. For example, the Metropolitan Water District of Southern California, operating throughout the metropolitan Los Angeles and San Diego areas, buys Colorado River water, some of which ultimately is used for recharge purposes. I would assume as the negotiations develop and the contracts are executed for the Central Arizona Project that some consideration may perhaps be given to use of Central Arizona Project waters as a source of water to purchase and use for recharge operations.

There's one legal consideration which is worth mentioning in this connection and that's the excess land law. Section 5 of the 1902 Reclamation Act and Section 46 of the 1926 legislation limit federally subsidized water to certain amounts of land. As I understand it, however, the Bureau of Reclamation has taken the position that the excess land limit does not apply to situations where the benefits conferred on landowners are involuntary. You have such a situation with groundwater replenishment, I suppose, where project water is purchased and used for a recharge operation. This would have the general effect of raising a water table and there would be some benefit to landowners. As I understand the Bureau's position, that would be an involuntary benefit not subject to the excess land limit.

Another source of water, one of increasing importance in California, is the waste water treatment plant. The State of California has set a goal of tripling the amount of sewage effluent to be reused by the year 1982, and there are some legal questions about that. Industry practice, in general, in California at least, is to treat the waste water treatment plant operator as the owner of the treated effluent for purposes of subsequent resale. Now, there is some question under our existing law in the state as to whether in fact the treatment plant operators are the owners. There may be an argument that the suppliers of the effluent, the ones who provided the water in the first place to the treatment plant, do have a claim in that water and can follow through and perhaps claim some of the proceeds of the sale. The question really has not arisen yet as a practical matter, because the water is not being sold for a price high enough to make anybody really care about it. But, in fact, if the utilization of treated waste water greatly increases and if the values go up in future years, we are concerned that these ownership questions will be raised. The Governor's Commission to Review California Water Rights Law in its draft report has recommended that California enact legislation which would specify that ownership of the treated effluent is concentrated in the treatment plant operator and that there is no valid claim on the part of the supplier. I hasten to add this would affect only the relationship between the supplier of the effluent and the treatment plant. It would say nothing at all about the relationship between the treatment plant and anybody downstream who had a vested property right in the return water from the plant.

A second question with regard to the spreading phase of the operation is finance. Assuming that there is a source of water, either floodwaters or treated effluent or water purchased from a project or whatever, the question arises how to finance the acquisition. In California, a common practice has been to use the replenishment assessment, or as it's commonly called, the pump tax - in effect, to use everybody's money from the particular area as a source for paying for the recharge water.

The Orange County Water District has been a pioneer in this area. They had very serious sea water intrusion problems at one point in Orange County. In 1953, the Water District acquired the power to levy a replenishment assessment on the various pumpers. That was tested in court in 1956. The California Court of Appeal held that the exercise of the pump tax power was constitutional.

The Orange County Water District has developed quite a sophisticated system of fiscal control of groundwater pumping. The pump taxes themselves are levied only when an overdraft exists, although that's been the case since the district began. Even today there technically is an accumulated overdraft still in existence in Orange County. Proceeds of the pump tax are used for the acquisition of recharge water and to build the necessary associated facilities. As I understand it, currently the pump tax may not exceed $5.50 per acre foot, although an additional assessment is possible on water pumped for non-irrigation purposes.

Also worth mentioning in connection with the Orange County Water District is another fiscal control, one known there as a basin equity assessment. This is a way of adjusting the relative amounts of groundwater and surface water that are used. Every year, the Orange County Water District Board sets a production maximum for the groundwater basin and also a basin production percentage for each pumper. If the pumper pumps more than the allowed percentage, then payment is made to the District. If a pumper pumps less, then that pumper receives from the Basin Equity Fund an amount to compensate for that difference. The net effect of this fiscal control through the basin equity assessment is to equalize the cost of water to all pumpers within the District. They pay the same whether they're pumping groundwater or relying on the more expensive supplemental surface supply.

It's not just in Orange County that fiscal controls like this are used. They've been used increasingly in other parts of Southern California, and in the Santa Clara Valley area in Northern California. I might point out that even in basins which have been through the long, elaborate and complicated process of court adjudication, such as the basins in the coastal area of Los Angeles County, there also are fiscal controls being used.

A third question with regard to the initial stage of the operation, the spreading or infiltration stage, is this. Assuming that there is a source of water which can be acquired and assuming that some method of financing that acquisition has been developed, where should the water be put? Is there storage space available? What about the recharge facilities themselves, the spreading ponds, the injection wells, whatever might be used?

As far as the spreading ponds are concerned and the injection wells, that's really a matter of land law, not water law. The recharger has to buy land or acquire an easement or do something of that sort to have access to the recharge area. But then there's an interesting question about finding storage space. In many areas so far, this question really has not arisen because you've got badly depleted groundwater basins and there's been a lot of space available. Districts acting under district laws have taken advantage of that storage space, or in some instances, project operators by agreement have arranged to use space. For example, we had the same storms in March 1978 that hit in Arizona, and one of the interesting developments was flooding on the Kern River and the Southern San Joaquin Valley. The State's Department of Water Resources as operator of the State Water Project was able to take a certain quantity of the floodwater, some 22,000 acre feet, and move it to Southern California. It was stored by agreement in the Mojave area and by agreement it was decided that this water would subsequently be withdrawn by the Mojave Water Agency in lieu of the deliveries from the State Water Project which that agency otherwise would have received. This is a rather complicated arrangement and involves the State Department of Water Resources, the Mojave Water Agency and also the San Bernardino Valley Municipal Water District. But it showed that in a short period of time, by agreement, these water entities could take advantage of sudden availability of floodwaters, instead of having those floodwaters either run to the ocean or, worse, flood agricultural land. Temporarily they could be diverted and put underground and in effect banked for use later on.

The second stage, assuming that the water has been acquired, it's been financed, spreading facilities have been obtained, storage space has been found and somehow the water is underground, a second stage is simply to maintain the water there - to prevent interference by other individuals. We had a rather dramatic case a few years ago in California where the Alameda County Water District in the San Francisco Bay Area was conducting a replenishment program. They were systematically putting water underground. In that case, they were doing it to prevent salinity intrusion and the ruination of the basin from ocean waters. At the same time they were doing this, there was a sand and gravel operator in the area who, pursuant to its sand and gravel operation, was pumping water out. So you had a situation where the Alameda County Water District had a replenishment program putting water underground, and the sand and gravel company at the same time was pumping water out of the underground into San Francisco Bay to get rid of it so it could continue with its quarrying operation. The two entities were operating at direct cross-purposes.

This situation resulted in controversy and litigation. The Water District sued to prevent continued pumping by the sand and gravel company. The Water District was successful. The

California Court of Appeal concluded that landowners, including the sand and gravel company, are subject to a public servitude which permits replenishment of the water table up to the historic level, which prevents owners of the surface from interfering with that replenishment and incidentally which makes clear that such landowners are not entitled to any compensation for the use of the aquifer. Some lawyers in California read that case more narrowly and believe it turns simply on the fact that the sand and gravel company was wasting the water by putting it out in the Bay. They weren't putting it to beneficial use themselves. Most others, however, read it more broadly and there certainly is language in the opinion which supports the broader reading that this is a general limit on the right of overlying landowners subject to this public servitude.

A third kind of stage is reached when the water is underground, the attacks of third parties like sand and gravel companies have been repelled, and it's a question of recapturing the stored groundwater. Some of our storers, of course, don't wish to do that. Los Angeles County Flood Control District, Alameda County Water District and so forth are simply putting water beneath the surface for the general benefit of the community and are not seeking to establish ownership to that water or to recapture it themselves. Others, however, operate differently.

One major controversy we have had has been with regard to the San Fernando Basin in the Los Angeles area. For many years the Los Angeles Department of Water and Power has been bringing water from the Owens Valley on the Eastern slope of the Sierra Nevada Mountains to Los Angeles. Owens Valley water constitutes about 80% of the municipal water supply of the City of Los Angeles. Some of this is spread directly to recharge the groundwater basin. Some is served to customers in the San Fernando Valley, and then after the customers have used the water, a certain portion of it ultimately reaches the groundwater basin. For many years, there was competition over that groundwater in the basin. The City of Los Angeles was claiming it, but also some of the San Fernando Valley cities other than Los Angeles were claiming it. Burbank, Glendale, San Fernando argued they were entitled to groundwater from the basin. The matter has taken many, many years to resolve.

There is one lawsuit, the Glendale suit, which was decided by the Supreme Court of California in 1943 but proved not to be a final resolution of the matter. There was another suit filed in 1955. It took 20 years and many hundreds of thousands of dollars for that lawsuit to get to the California Supreme Court in 1975. In fact the suit still isn't over, because after the Supreme Court finished with it, they sent it back to the trial court and it still is in the trial court in California. So the litigation has been going on for 23-24 years now.

In any event, with regard to the conjunctive use portion of that decision, the California Supreme Court decided very clearly that importers of water who store that water, either directly through a spreading operation or indirectly through delivery to customers, do have first claim to the water when it's underground. They have a right to recapture. This meant in that particular litigation, Los Angeles was successful.

There were other issues in the case besides the conjunctive use point. Los Angeles also was asserting its pueblo right from Mexican law to the native water of the San Fernando Basin, which the court concluded they had. The other cities were found to have acted wrongfully in most of their groundwater pumping and apparently six million dollars ultimately is to be paid by Burbank, Glendale and San Fernando to Los Angeles. I've given you some of the detail on that litigation simply to stress that it's been a long, complicated and expensive process in California to reach the conclusion that the importer of water who stores it in a groundwater basin is entitled to recapture that water.

As has been mentioned, California water rights law is now being reviewed. A Governor's Commission to Review California Water Rights Law was appointed in 1977. It's chaired by the retired Chief Justice and is advisory to the Governor. In August 1978, a draft report was issued. Nearly half of that report deals with groundwater. The emphasis in the report is very much upon developing a better system for groundwater management. Unlike many other western states, California never put groundwater appropriations under the control of the State Engineer. Nor did the state enact any critical basin legislation. So consequently, groundwater pumping is almost entirely unregulated except in the few areas where there are comprehensive water district programs or an adjudication. Farmers and cities, or whoever, are quite free to put in wells whenever they want, wherever they want and take out any amount of groundwater.

The Commission has recommended that this situation be ended and that there be groundwater management through designated groundwater management authorities. With regard to recharge, which is your interest here today, the Commission has concluded that because of the Niles decision which is the one involving the public servitude and the sand and gravel company and because of the Los Angeles vs. San Fernando decision, the law is in a relatively good state. In fact the only major thing the Commission is recommending, aside from codification of those principles, is that with regard to storage space in groundwater basins, the designated groundwater management authority have control of that storage space. In the future, storage would take place only pursuant to agreement with the local designated groundwater management authority, with a preference given to local users.

I know that you have a Groundwater Management Study Commission which is reviewing the law here. I would think that in conjunction with that review, there would be an opportunity to study the existing Arizona law on conjunctive use, including recharge of groundwater basins. I would think the California experience would suggest that it is much less costly and much more direct to legislate beneficial principles, such as the public servitude principle and the principle that those who store the water have the first claim to recapture it, than to spend the time and the money, hundreds of thousands if not millions of dollars, necessary to go through the courts. We have used judicial processes in California and the results from the point of view, at least of those who wish to have successful recharge programs, have been good, but it has been a long, difficult and costly route.

AUTHOR'S BIOGRAPHICAL SKETCH

NAME: Irv Sherman

EDUCATION: B.S. Degree in Soil Service from the University of California, Berkeley

M.S. Degree in Engineering from the University of California, Los Angeles

JOB POSITION: Division Engineer for the Water Conservation Division of Los Angeles County Flood Control District, Los Angeles, California

EXPERIENCE: Division Engineer responsible for groundwater recharge, sea-water intrusion control and water quality monitoring for the Los Angeles County Flood Control District

Worked for the following Federal agencies: Soil Conservation Service, Corps of Engineers, Geological Survey and the Forest Service

ECONOMICS OF GROUNDWATER RECHARGE

by

IRV SHERMAN

What do we mean when we talk about the economics of groundwater recharge? To put it very simply, I think what we're really looking at are costs and benefits, trying to put as much as possible in terms of dollars to decide whether it's worthwhile and if so, how worthwhile. I understand that I was invited to talk to this symposium because of the experience of the Los Angeles County Flood Control District in this field. We have been in the groundwater recharge business now for about 45 years. In that time, we have recharged over five million acre feet of water by surface spreading. That includes storm runoff, imported water and reclaimed water. We also have barrier projects to control sea water intrusion, and in those projects, we've recharged over six hundred thousand acre feet of water.

The cost situation is particularly pertinent at the moment. Particularly because of Proposition 13, we have been forced to take a very close look at our costs, partly because we are dickering with various water agencies hoping that they will reimburse us so we can continue our recharge operations if we can't finance them any other way. Naturally, those agencies are interested in the question of what does it cost and why. Now, of course, the cost figures that I'll be able to present later will not necessarily represent what anybody else's cost figures would be. But, the principles are generally the same and many of the cost elements are the same. So what I'd like to try to do is to first list some of the cost elements that anybody interested in groundwater recharge should consider, talk about evaluating benefits, present some of the cost data that I happen to have available, talk about some of the benefits in Southern California from groundwater recharge and finally, I'd like to show some figures.

In talking about costs, first of all there is the basic decision of the choice of type of facility. We've heard about spreading versus injection wells. Obviously, surface spreading is far less expensive if the situation is right. In surface spreading there is also the choice as to whether to try to perform your recharge operation within the existing stream channel or perhaps a modified stream channel or whether to construct an off-channel spreading basin operated with a diversion works. The on-stream facility is generally much less expensive but it may not be as effective. And then, of course, there are the economics of scale. In general, one large facility will be more economical to operate in terms of dollars per acre foot than a number of smaller facilities with the same total capacity.

Generally, in chronological order, the first set of costs to be considered are the capital outlay costs as the accountants would call them. I include in that the cost for the various studies that are necessary before you can build anything: engineering, geology, hydrology, what have you, the costs of preparing designs, plans, specifications and in these days don't forget the cost of preparing an environmental impact report. One very important cost, perhaps the most important in some cases, is the cost of the land. In this respect, I suggest that the original cost of the land is not the only cost of the land to be considered. That's the cost, of course, that the accounting system will show. But, five years down the road after you've bought the land or ten years or at some later point, you should be asking yourself what is the present value of the land, what could we sell it for, what impact would this have on the overall situation? Because if you don't ask yourself this question, somebody else will ask it of you and then you may have to respond in a rather awkward way. I'm not suggesting that necessarily you should give up a groundwater recharge facility because the value of the land has gone up. But you should ask yourself the question. There are the costs of all the various structures that you need. There are the costs of treatment works. It may be necessary to add a flocculant to remove sediment. Perhaps you have to filter the water. There is a cost for measurement: staff gauges, recorders, observation wells, conductivity meters, whatever. If your recharge system involves the use of dams and reservoirs to store storm waters during periods of peak flow, then naturally there is at least a portion of the cost of the dam and reservoir that has to be figured in as part of the recharge cost. If it's a multiple purpose reservoir, then you have the interesting question of how to allocate cost between groundwater recharge and say flood control or power generation. There are conveyance systems: canals, pipelines, siphons. If your environmental impact report says that there are adverse impacts, you may find yourself with a cost for mitigation measures. And, of course, if you have injection wells, those are very expensive.

Operations costs primarily, of course, but not entirely, are for manpower. Don't include just the cost of basic salaries. Remember the fringe benefits. Remember overtime pay: it always seems to rain at night or on weekends. There are the costs of supervising the people who actually spread the water and don't overlook the cost of overhead. Operations involve equipment: vehicles, electrical generators, aerators, bulldozers, maybe you have two-way radios, sampling equipment, office furniture, and typewriters. There will be various materials and supplies: fuel, flocculants, recorder graphs, data sheets, rubber boots, flashlight batteries, whatever. You'll have utilities: telephone, water, electricity, and possibly fossil fuels for heating.

One very pronounced influence on the cost of operation is the type of operation that you have. If you can operate totally on post-storm spreading of controlled releases from reservoirs, you can perform the spreading operation with far less manpower than you need if you spread the water of an uncontrolled flow during storms. During storms the uncontrolled flow varies very widely in quantity, and you have to have a larger staff in order to be able to handle the peaks.

Let's talk about the cost of maintenance. We've heard already today about the cost of removal of sediment. There will be costs for weed control. We've had costs for gopher control. You need to allow for the repair and replacement of structures, for the maintenance of access roads and levees and if you do much spreading, particularly in warm weather, you may have costs for control of vectors or insects. If you operate injection wells, you'll have costs for redeveloping or cleaning those wells from time to time.

You can't operate a recharge system in a vacuum. You need information and the information costs money. You need to know how much water you're recharging. You need information on water quality: the quality of the water being spread, the quality of the water underground in the first place, how the water being spread interacts with the soil and changes in quality, and how the various waters interact with each other. It's somewhat ironic that any organization that is cost conscious incurs an additional cost in finding out how much it's costing them. The accountants don't work for nothing. Then, of course, when you get all through, it's necessary to evaluate your overall process and how you're doing and that costs money. Don't forget the cost of evaluating not only the intended results, but also the unintended results.

There are liability costs. You may find yourself deciding to pay insurance premiums instead of being self-insured. You'll have legal fees of one kind or another. You will very likely have claims as does anyone that owns land. You may have litigation and even if you win in court, you'll have the cost of defending yourself. If you decide to try to reduce your liability by keeping the public out of your facilities, then you'll have the costs for fences, gates, locks and all those good things. So much for a quick look at costs.

In evaluating benefits, you have to decide what kind of benefits you're after. If you're putting water underground only for the purpose of augmenting the supply, that's one thing. It's also possible to recharge groundwater in order to provide protection. The sea water barrier projects of the Los Angeles County Flood Control District fall in that category. If it's a matter of supply, then to evaluate the benefits, what you usually do is compare the costs of what you propose to do with the cost of an alternative supply, if there is an alternative supply. If there is none, then you ask what is the cost of creating one. I've heard figures in California that if we have to expand the California Aqueduct to bring more water to Southern California via that route, we may be talking about an incremental cost of $200 or $300 per acre foot.

In looking at alternative supplies, you also must consider what the quality of that supply will be and you also must try to evaluate what inflation will do to future costs and benefits. Again, in the case of the California Aqueduct, we believe the costs will go up much more sharply than the benefits because we expect very sharp increases in the price of electrical power needed to pump water through the Aqueduct beginning in about 1983. Then, of course, you want to ask whether the alternative supply may be more likely to be interrupted by a natural catastrophe such as an earthquake and how much is the value of non-interruptibility.

One of the interesting things we've discovered is that we can use groundwater systems not only for storage, but also for conveyance. By recharging in a forebay area, we can supply users closer to the coast and avoid a significant cost for surface piping systems. Of course, once you've put the water underground, the question is what is the value of that water in the ground. And, of course, you have to allow for the various costs: production, treatment and conveyance. I might mention that there is an interesting tax situation in this respect. In the Southern California adjudicated basins, not only is there the replenishment assessment to which Professor Dunning referred, but in Los Angeles County, the Assessor has decided that water rights are property because they are indeed bought and sold and therefore they are taxable. He does indeed assess them and the owners pay property taxes on water rights. On the other hand, groundwater generally does not have to be filtered, and so there is a cost avoidance feature as compared with most surface supplies.

In the groundwater recharge business as in all others, it is necessary to predict the future. How can things change? I think Murphy's Law probably applies in this case. In addition to inflation, you must consider the change in infiltration rates due to sedimentation. There are some interesting political constraints. We've discovered that when we have a reservoir that we try to operate for groundwater recharge purposes, there are enormous political pressures to construct a park or other recreation facility next to the lake. When it rains and we're trying to impound the water so that we can release it later, we're getting phone calls saying, "Get rid of the water; you're flooding our park." There may be legal rights in California now whereby sand and gravel operators are not supposed to interfere with groundwater recharge, but in 1969 the gravel pit operators persuaded the Corps of Engineers to release the water from Santa Fe Dam because the infiltration through the reservoir bottom behind the dam was raising groundwater levels and adding to their flooding problems. We estimate that there was at least a million dollars worth of water lost to the ocean on that account. There may be changes in water quality due to recharge and of course, there may be a need to buy more land than you had figured on if you have to provide a rotation system for your basins in order to control insects. We find it necessary in long term spreading to keep the basins dry two-thirds of the time.

Now for some specific cost data, if I may. First, on our barrier projects. We have three such projects. We have 180 injection wells at 150 sites and four extraction wells. The capital cost of the facilities themselves is estimated at $16,700,000. It costs us roughly $1,300,000 a year for operation and maintenance. We inject about 45,000 acre feet per year on the average, and that works out to an operation and maintenance cost of about $27 per acre foot. We also extract about 1,360 acre feet of saline water, and that costs about nearly $62 per acre foot for extraction. That's not counting the cost of the water. We don't buy the water. That's supplied to us by the Central and West Basin Water Replenishment District. But right now, they're buying that water from Metropolitan Water District at $69 an acre foot. So all told, they're spending over $3,000,000 a year for the water. You put it all together and the total program is costing about $4,400,000 per year, including the cost of the water, but not including the amortized costs of the facilities or engineering for additions to the projects.

Our surface spreading operations involve some 29 spreading grounds and basins and about 20 dams, most of which we own but some of which the Corps of Engineers operates in cooperation with us. We have a total wetted area of over 1500 acres. The capital cost of the spreading facilities is about $9,150,000.

Let me give you cost data on two interesting recent years, firstly 1976-77 which was a drought year and then 1977-78 which was the wettest year since the turn of the century. In 1976-77, we spread about 117,400 acre feet from all sources: local water, reclaimed, and imported water. The operation and maintenance cost was roughly one and a half million dollars. That works out at about $12.75 per acre foot. In addition, the Replenishment District bought reclaimed water at $7 an acre foot and various agencies bought imported water from Metropolitan Water District at $36 an acre foot. You put it all together and you have nearly three and a half million dollars which works out to a little bit less than $30 per acre foot all told, including the cost of the purchased water. Now, that was the dry year. In 1977-78, we recharged 492,000 acre feet. The amount of local water that was spread was nearly ten times as much as in the dry year. The total cost went up but not all that much: two million dollars as compared with one and a half million. When you add in the cost of the purchased water, the total was $4,923,000 for an overall total cost of about $10 per acre foot. Now that doesn't include reservoir cleanouts. In 1970 we had a reservoir cleanout at the Whittier Narrows Reservoir. In a very favorable situation, it only cost us $1,000 per acre foot of storage capacity for that cleanout. We have a contract now underway at our Big Tujunga Reservoir that's in a much less favorable situation; and, of course, inflation has occurred since 1970. The cost at Big Tujunga is about $5,500 per acre foot of capacity restored. Now most of those costs for reservoir cleanouts might be attributable to flood control but you have to look at each situation individually.

Let's look at benefits. The benefits in Southern California, particularly from recharge of local water, are the avoidance of the costs of purchasing imported water from Metropolitan Water District. If you buy Metropolitan Water District water now for municipal and industrial use, their wholesale charge is $95 per acre foot. On the first of January, that goes up to $100 per acre foot. After 1983, that might be $200, maybe $250; we don't know.

I might talk a little bit about some of the benefits from the barriers. You cannot justify the cost of our barrier projects just on the basis of putting water in storage. But you buy protection. We're protecting some 22 million acre feet of potable water in storage with an estimated value perhaps of a billion dollars. In addition, by having the barrier projects in operation, the coastal groundwater basins can be operated with a much steeper gradient than would be possible otherwise. The amount of recharge that's possible in the forebay is perhaps ten times as great as what it used to be naturally. The basin serves as a conveyance system, and all this is taken into account in the adjudication that governs the operation of the basin.

Figure 1 is a profile along the San Gabriel River that shows our very favorable groundwater recharge situation. The mountains are the watershed. Downstream of the mountains we have some very fine groundwater basins. We have a series of dams to control the water. In the groundwater basin that's shown farthest to the left, that's our coastal plain and you can effectively spread water there on the surface only at the upstream part of it. When you get farther downstream, you have the intervening clay layers that we heard about this morning that make surface spreading ineffective. Figure 2 is San Gabriel Dam with a conservation release going on this last January. You can see the water coming out of the discharge valve. The dam itself doesn't look like too much; most earth-fill dams do not. Figure 3 is a combination situation. In the background you have Hansen Dam owned and operated by the Corps of Engineers, and in the foreground Hansen Spreading Grounds owned and operated by the County Flood Control District. This is a very favorable situation from the standpoint of spreading because we have only controlled releases. The Corps is incurring a cost as they accumulate sediment in their reservoir. Figure 4 is San Gabriel Spreading Grounds in the Coastal Plain; the San Gabriel River is on the right. Normally, we have finger levees, as we call them, built in the river itself and use the river itself as a spreading area. Those levees are always washed out by high flows. The basins in the lower right-hand corner of the figure are the desilting basins. The water is routed through them so as much as possible of the sediment drops out before getting into the spreading basins. Figure 5 is Peck Road Water Conservation Park, which is on stream; it is not operated by diversion works. Sawpit Wash and San Anita Wash come into it; there's no control over what happens. We've lost much of the recharge capacity in this basin. It's so deep that it's never totally dewatered, and we have no way of cleaning the sediment out economically. This Figure 6 is the Santa Fe Reservoir Spreading Grounds, our most effective and most economical facility. It's most economical partly because we didn't have to pay for the land; we're there operating under permit from the Corps of Engineers, but it is also extremely effective. Figure 7 is the San Gabriel River looking downstream from Santa Fe Reservoir. You'll notice the drop structures in the river. This is a case where we were able to convince the Corps of Engineers to build a soft bottom channel so that recharge could continue to occur within the river and not to build another concrete channel which foreclosed the possibility of infiltration. Figure 8 is the Eaton Spreading Basin in the San Gabriel Valley. This is a mined-out gravel pit, off-stream, and controlled by a diversion. If you go the injection well route in a residential neighborhood in Los Angeles County, Figure 9 is what it looks like on the surface. There is a recharge well, vault and all, underneath that manhole. That's the kind of expense we have to go to in order to live with the neighbors. For imported water, here Figure 10 is a photograph of one of the connections to the Metropolitan Water District's supply system. This is on San Dimas Wash in the Northeast corner of the San Gabriel Valley. The water travels many miles through the flood control system of channels down to the forebay area of the coastal plain to be spread. The water is purchased by the Central and West Basin Water Replenishment District. It takes approximately 16 hours for the water to travel from this outlet down to the point where it is spread, but it's much less expensive to run the water that way down the flood control channels than to get it there by pipeline. Figure 11 is the headworks at San Gabriel Spreading Grounds. You saw the aerial photograph before. The diversion works here includes a pair of inflatable rubber dams. The dam on the lefthand side of the photo is down and water is going over it into the river. The dam on the righthand side is up and you can't see the water behind it. Figure 12 shows some diversion and control structures within San Gabriel Spreading Grounds. We used to build them with creosoted timbers but the kids set fire to them - don't forget the cost of vandalism - so now we build of concrete. Figure 13 is the headworks at Hansen Spreading Grounds. There is a radial gate lowered within the concrete channel to create a forebay, and in the channel wall at the right are slide gates to allow the water to be diverted into the spreading grounds. Figure 14 is a sump diversion at Forbes Spreading Basin. We used a sump diversion here so as not to have any obstruction within the channel at any time. It works pretty well most of the time but it is not self-cleaning. We have to pay the cost of cleaning debris out of the sump every so often. Figure 15 is the flocculation facility at Hansen Spreading Grounds. The drums in the foreground contain the flocculant material. The material has to be mixed with water and put into the water in the forebay and then you use one or two basins in the spreading grounds for desilting. Here bulldozers are at work building levees in the San Gabriel River in order to increase the travel time, and with this process we can spread up to 100 cubic feet per second in the lower San Gabriel River (Figure 16). Here is an electrical generator (Figure 17). You sometimes need standby power for whatever purpose. Your measurement facility may consist of something as simple and inexpensive as a gauge board Figure 18 or maybe you'll have a recorder in a recorder house Figure 19. Figure 20 is our key well installation in the San Gabriel Valley. We have an observation well here and a weather station including an evaporation pan. Figure 21 illustrates the effect of sedimentation on the infiltration capacity at Eaton Spreading Basin. Notice the starting curve over on the right and now the successive curves went further and further over to the left as the infiltration rates declined until we got to 1969-70. Then between then and 1973, we had a contractor who wanted earth material, so he enlarged the basin and in so doing removed some of the sediment accumulation. This increased the infiltration capacity somewhat so the curve for 1973 shifted further over to the right.

Let me just summarize by saying that if you have the right conditions, groundwater recharge can be a very economical way of augmenting the natural water supply. But it can be very expensive under adverse conditions. There is just no substitute for a thorough analysis on a case-by-case basis.

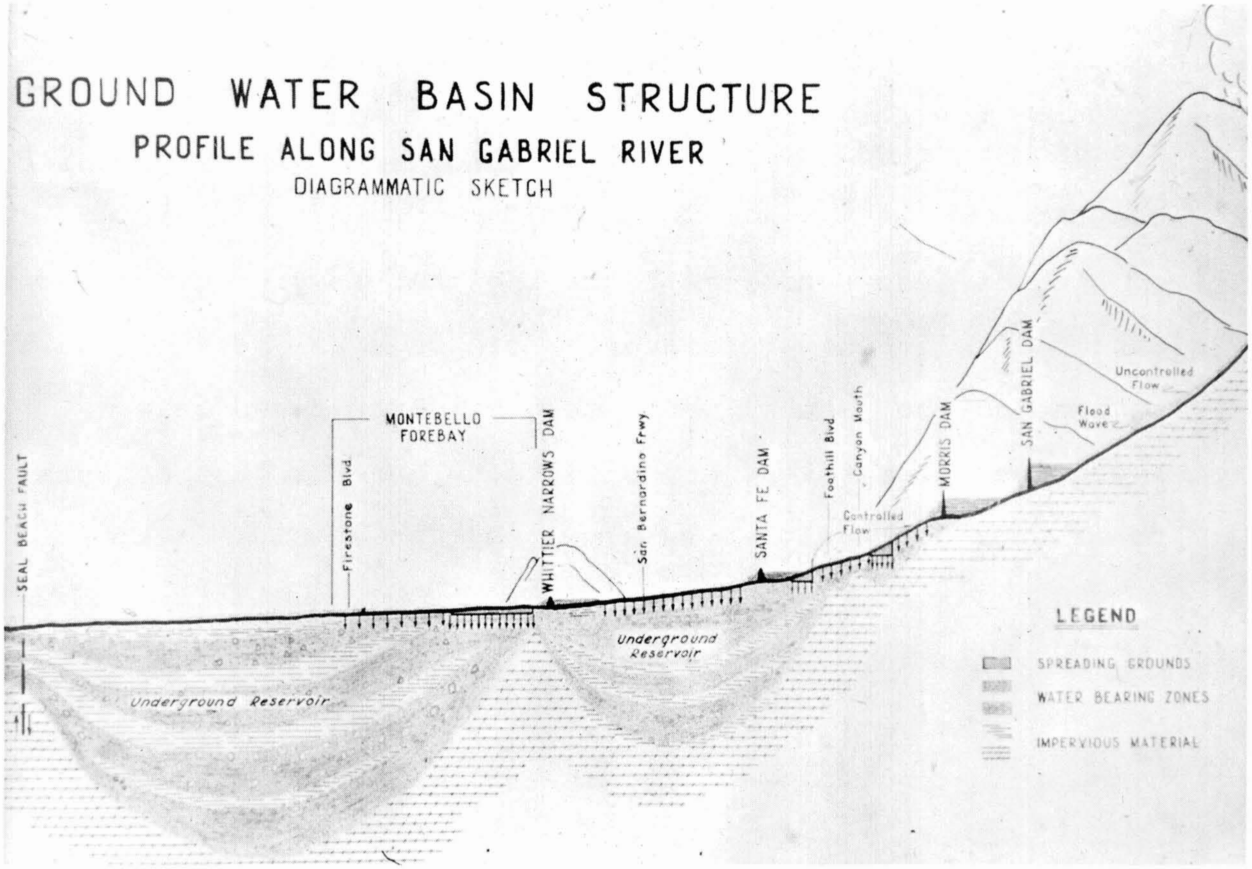


FIGURE 1 - PROFILE ALONG SAN GABRIEL RIVER

FIGURE 2 - SAN GABRIEL DAM

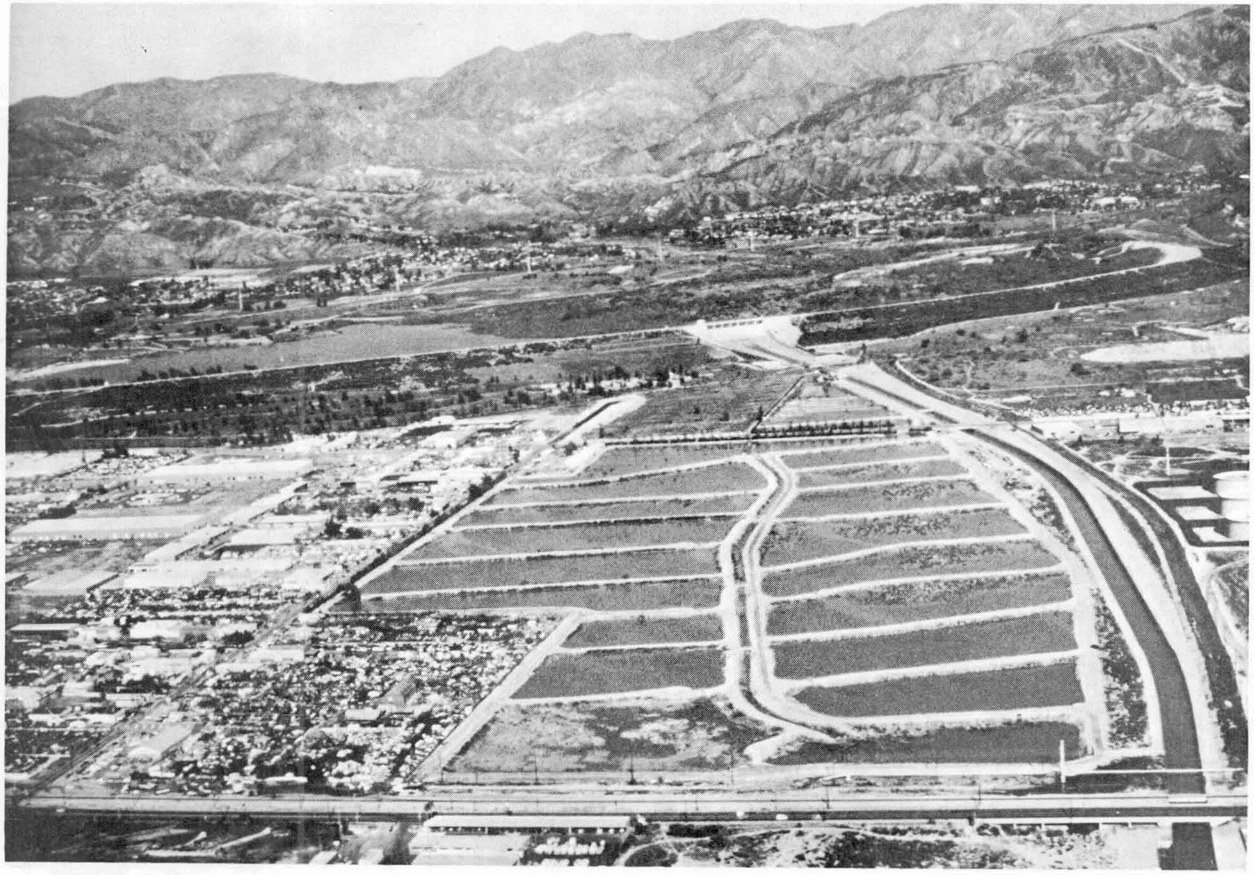


FIGURE 3 - HANSEN DAM AND SPREADING GROUNDS

FIGURE 4 - SAN GABRIEL SPREADING GROUNDS (SHALLOW, OFF-STREAM)

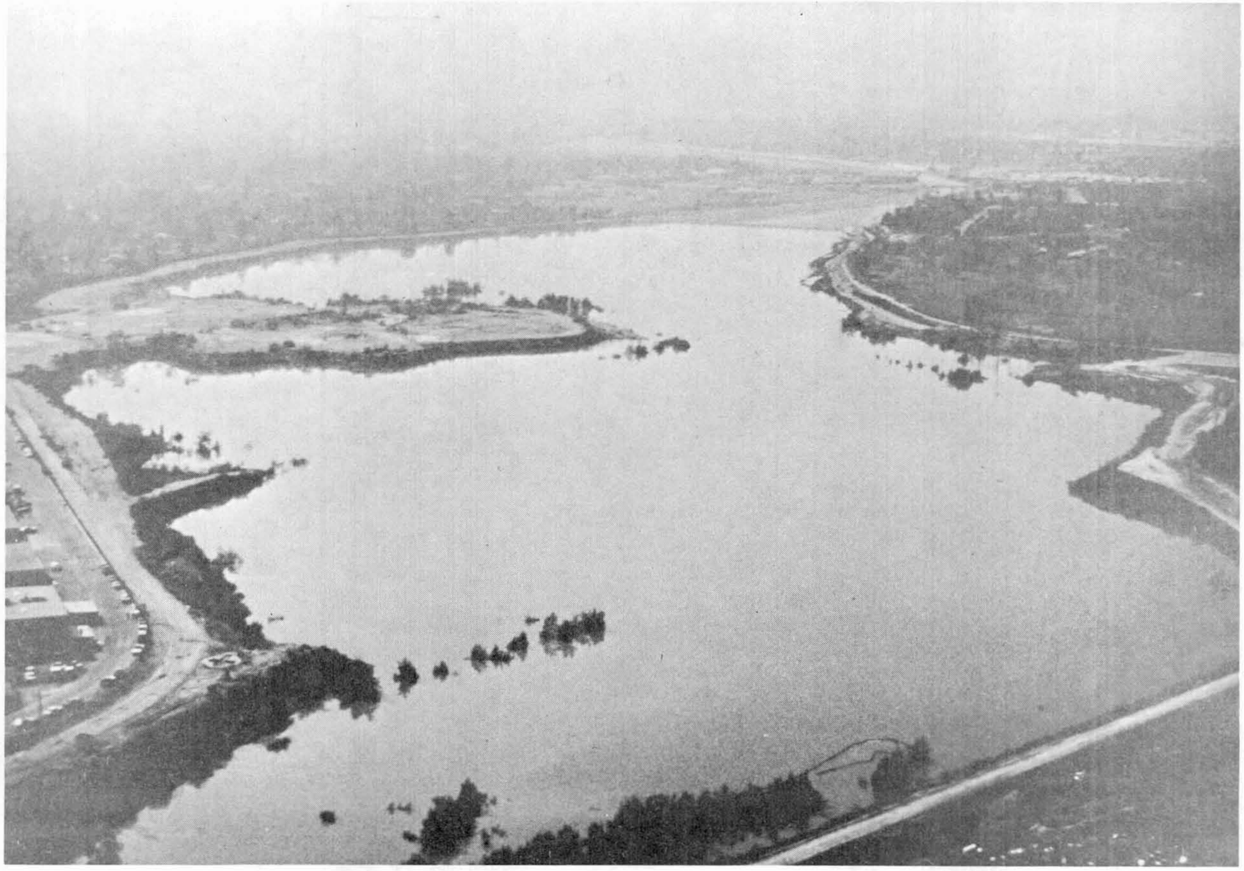


FIGURE 5 - PECK ROAD WATER CONSERVATION PARK (DEEP. ON-STREAM)

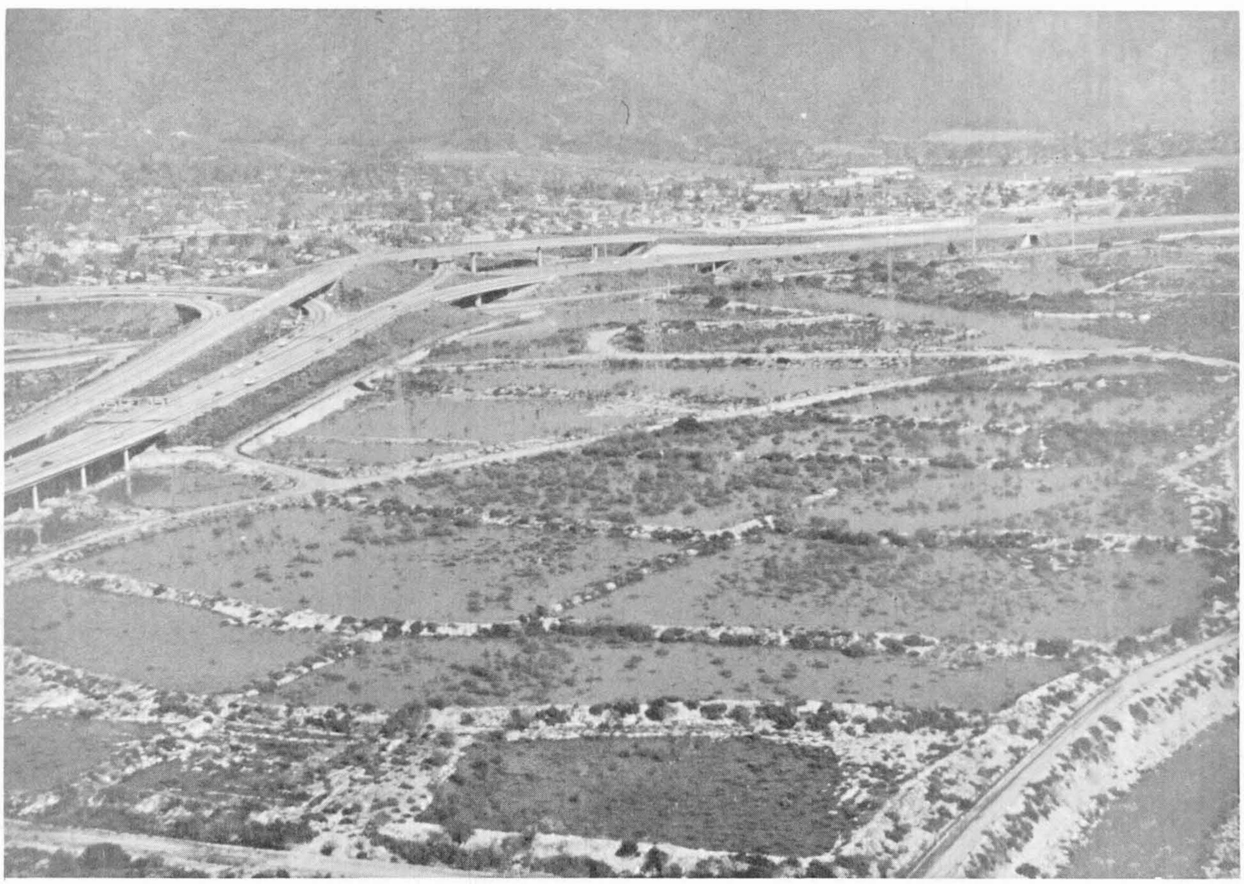


FIGURE 6 - SANTA FE SPREADING GROUNDS (SHALLOW, OFF-STREAM)

FIGURE 7 - SAN GABRIEL RIVER DOWNSTREAM FROM SANTA FE DAM (SHALLOW, ON-STREAM)

FIGURE 8 - EATON SPREADING BASIN (DEEP, OFF-STREAM)

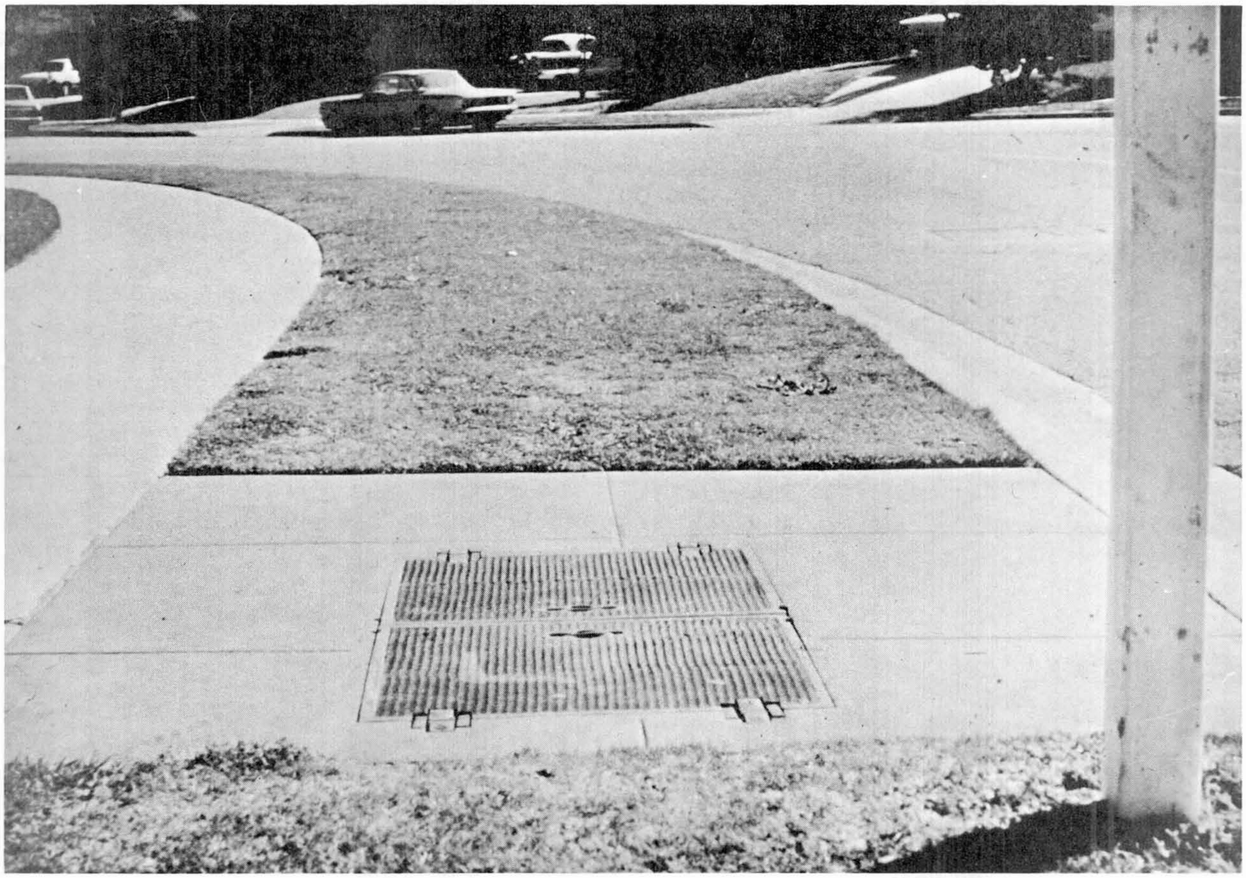


FIGURE 9 - ALAMITOS BARRIER PROJECT WELL

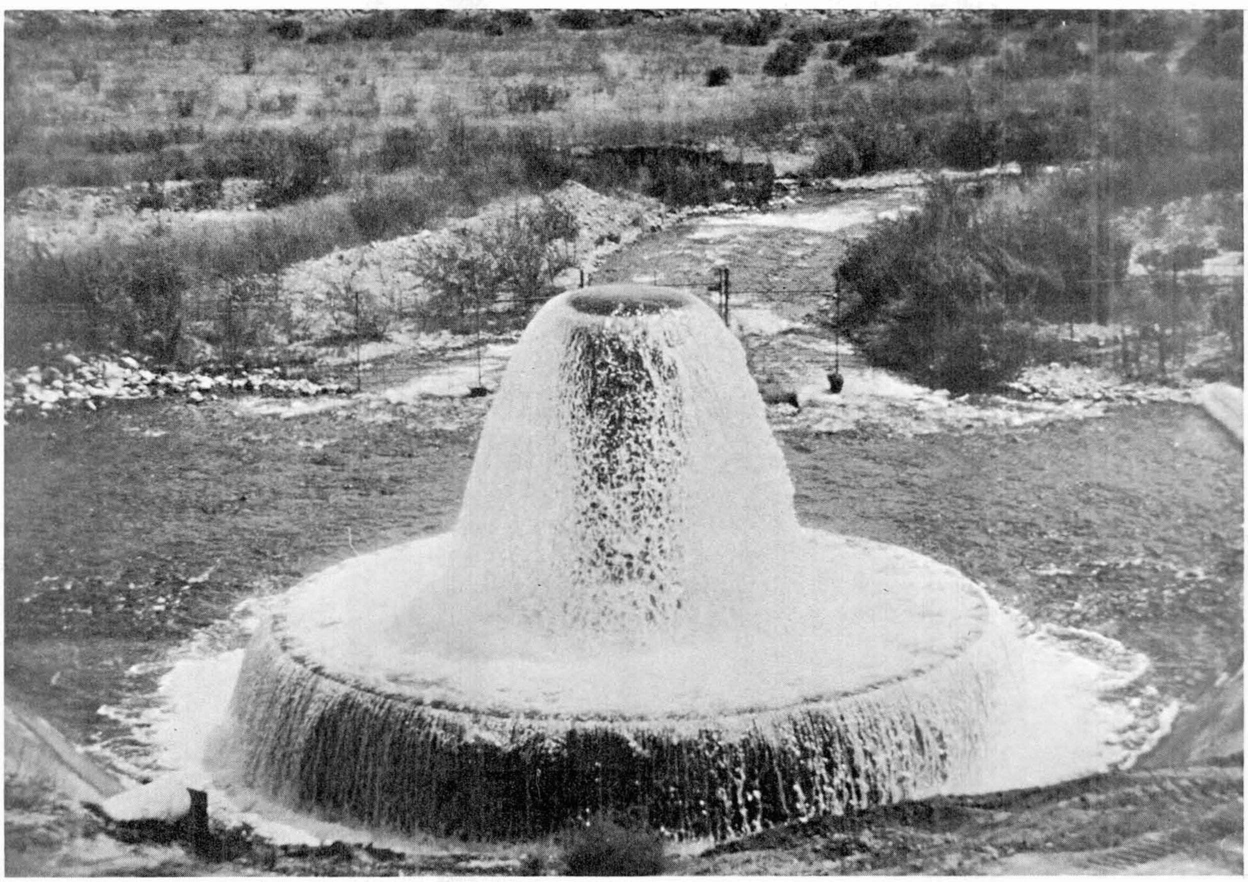


FIGURE 10 - SLIDE CB-48 OUTLET ON SAN DIMAS WASH

FIGURE 11 - RUBBER DIVERSION DAM AT SAN GABRIEL SPREADING GROUNDS

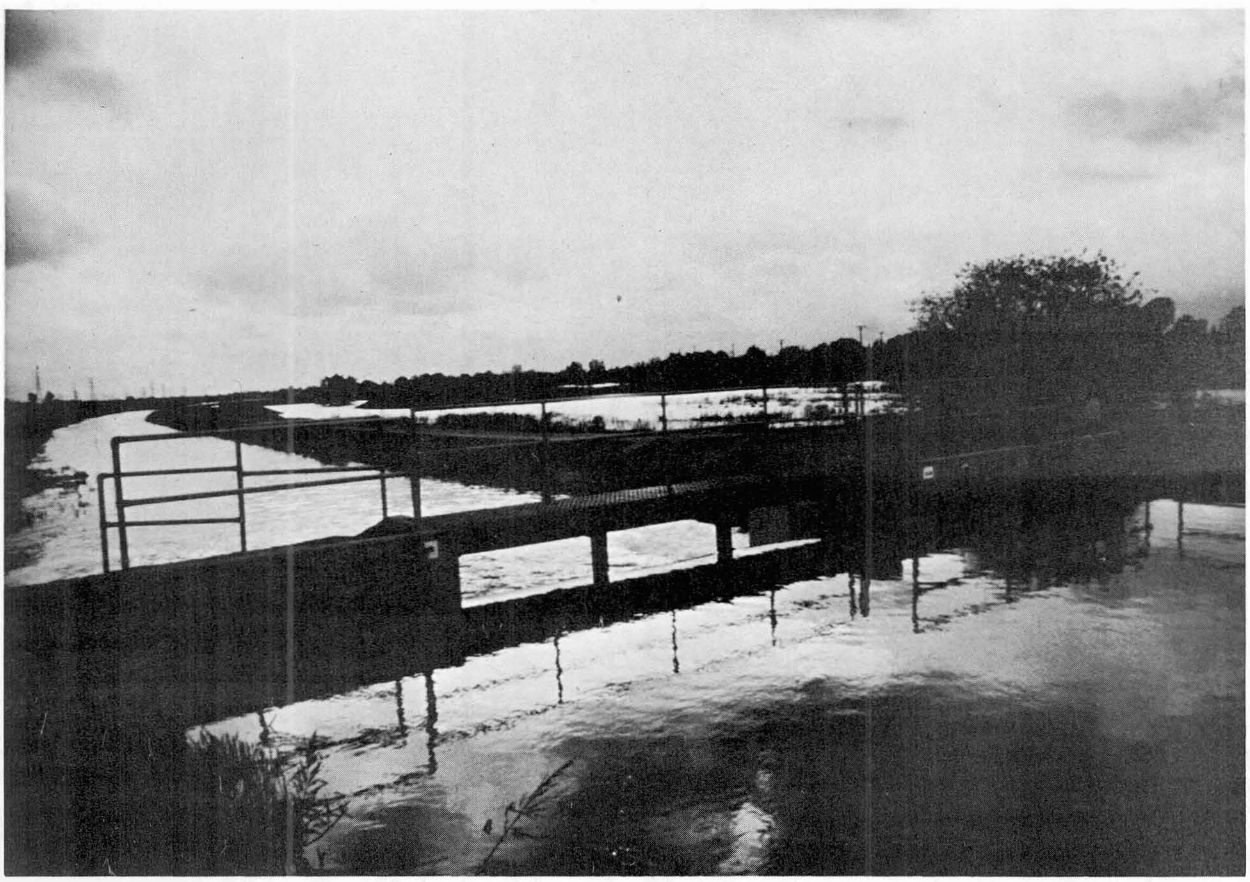


FIGURE 12 - STRUCTURES C-3 AND T-3 AT SAN GABRIEL SPREADING GROUNDS

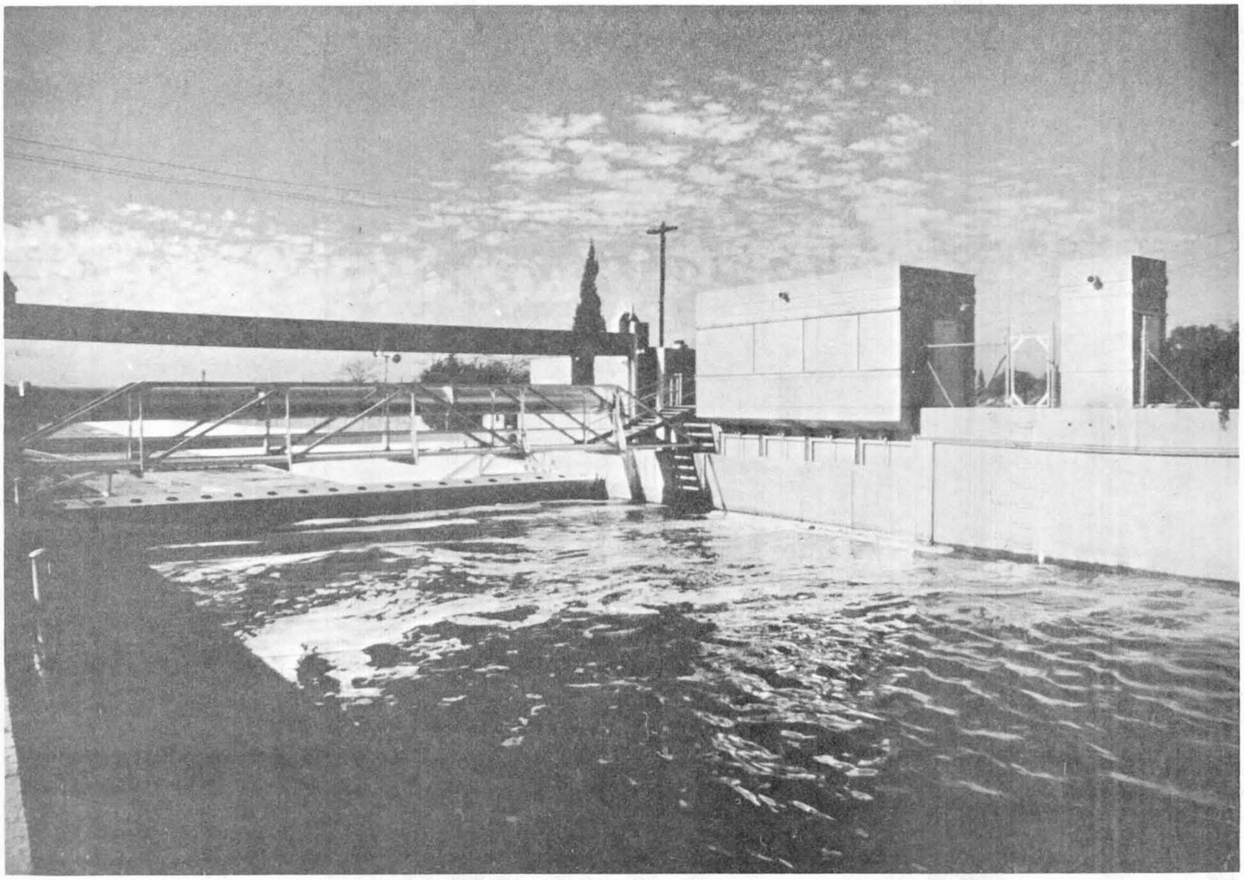


FIGURE 13 - HEADWORKS AT HANSEN SPREADING GROUNDS

FIGURE 14 - SUMP INLET AT FORBES SPREADING BASIN

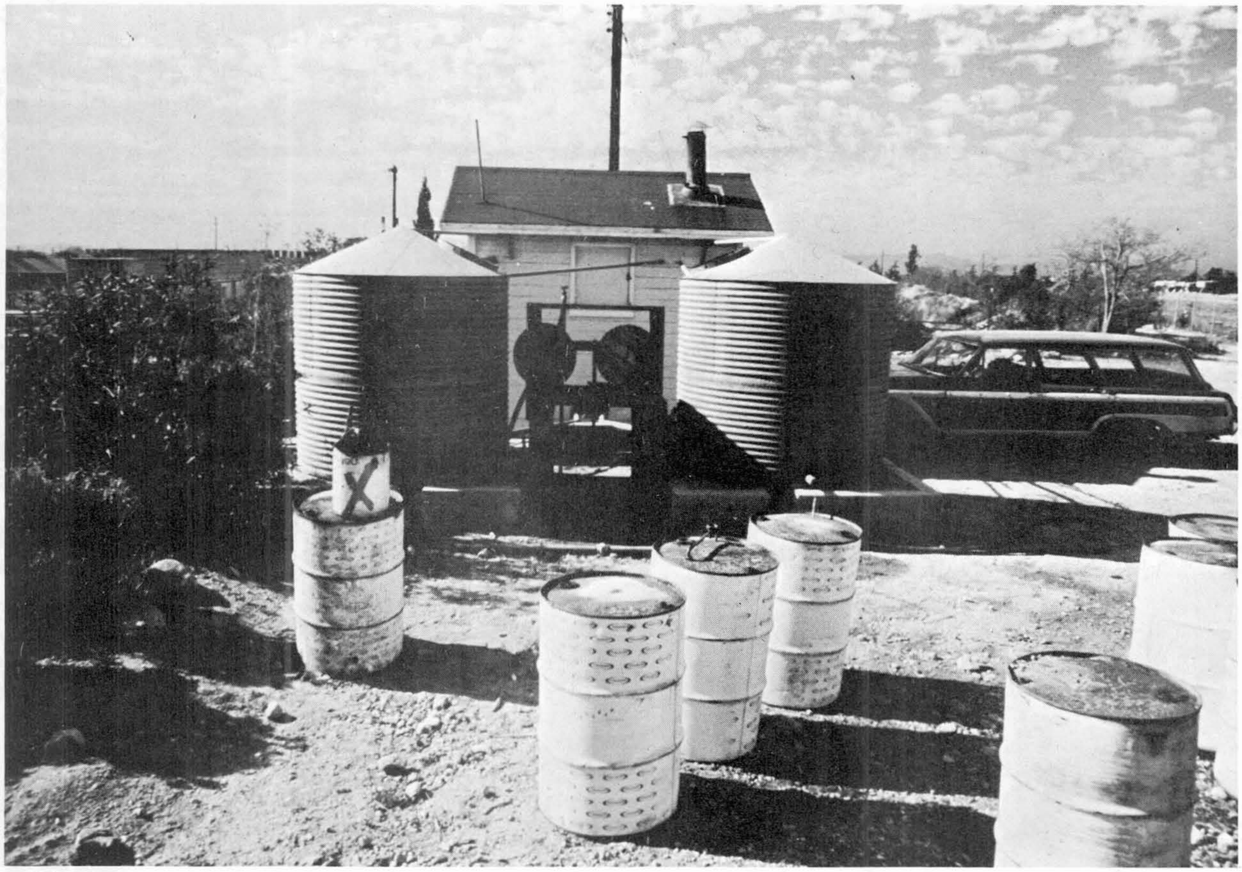


FIGURE 15 - FLOCCULATION INSTALLATION AT HANSEN SPREADING GROUNDS

FIGURE 16 - BULLDOZER WORK AT SAN GABRIEL RIVER

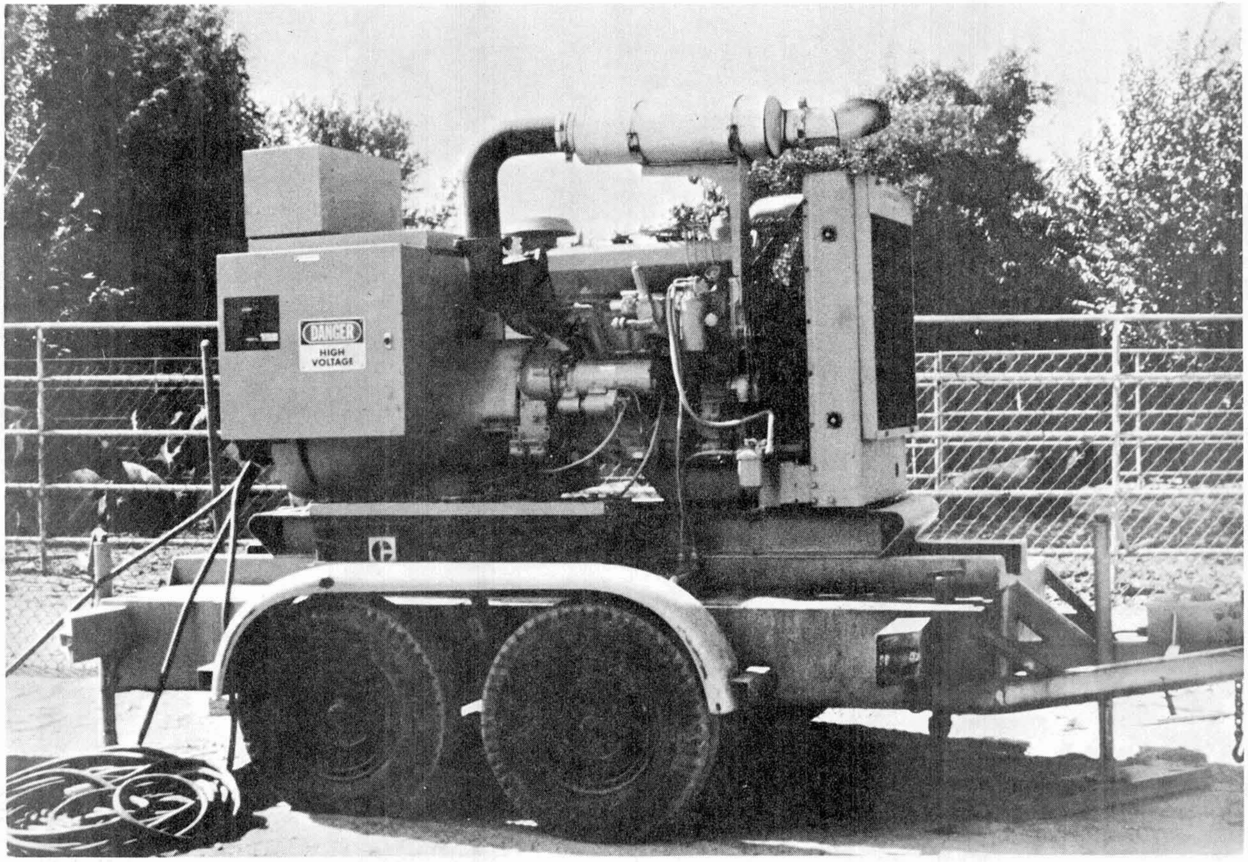


FIGURE 17 - ELECTRICAL GENERATOR

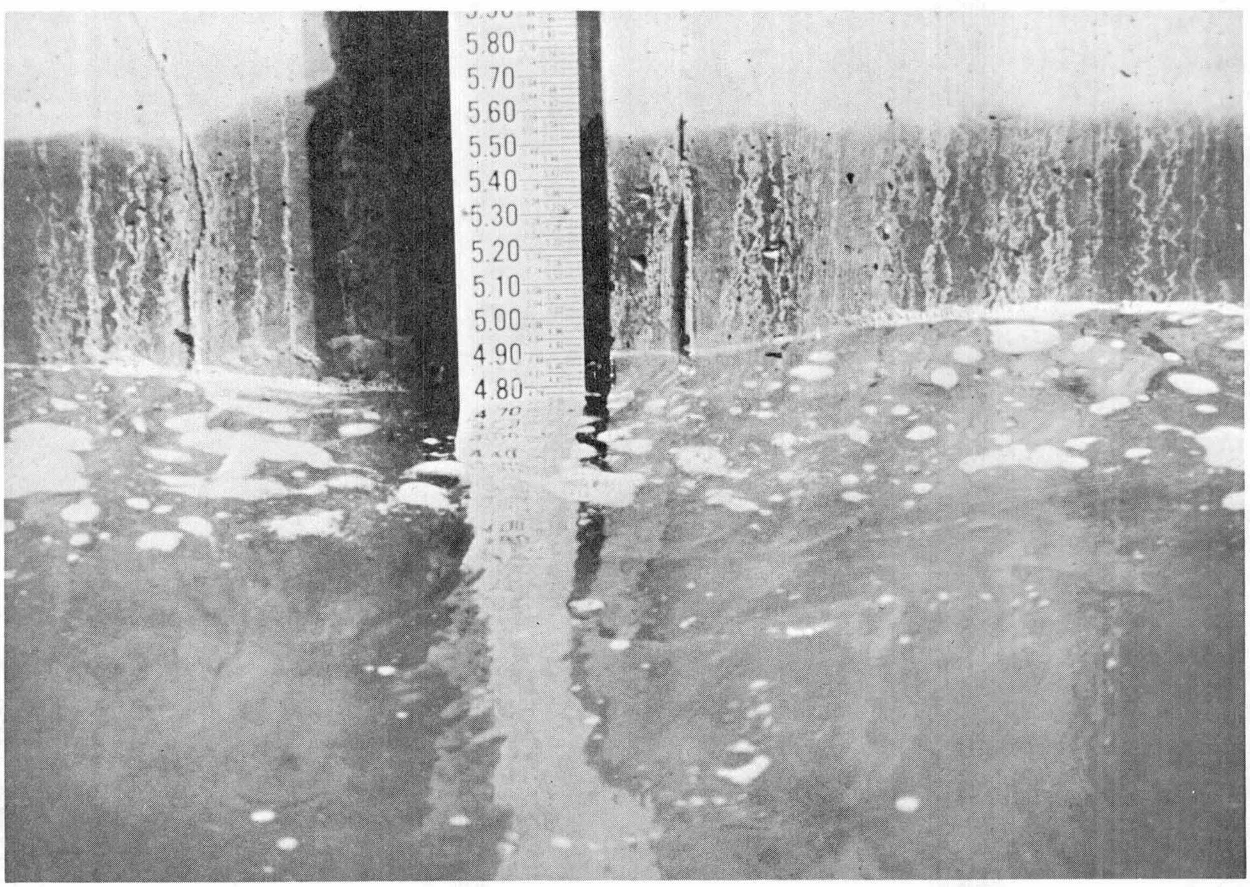


FIGURE 18 - GAGE BOARD AT CB-2

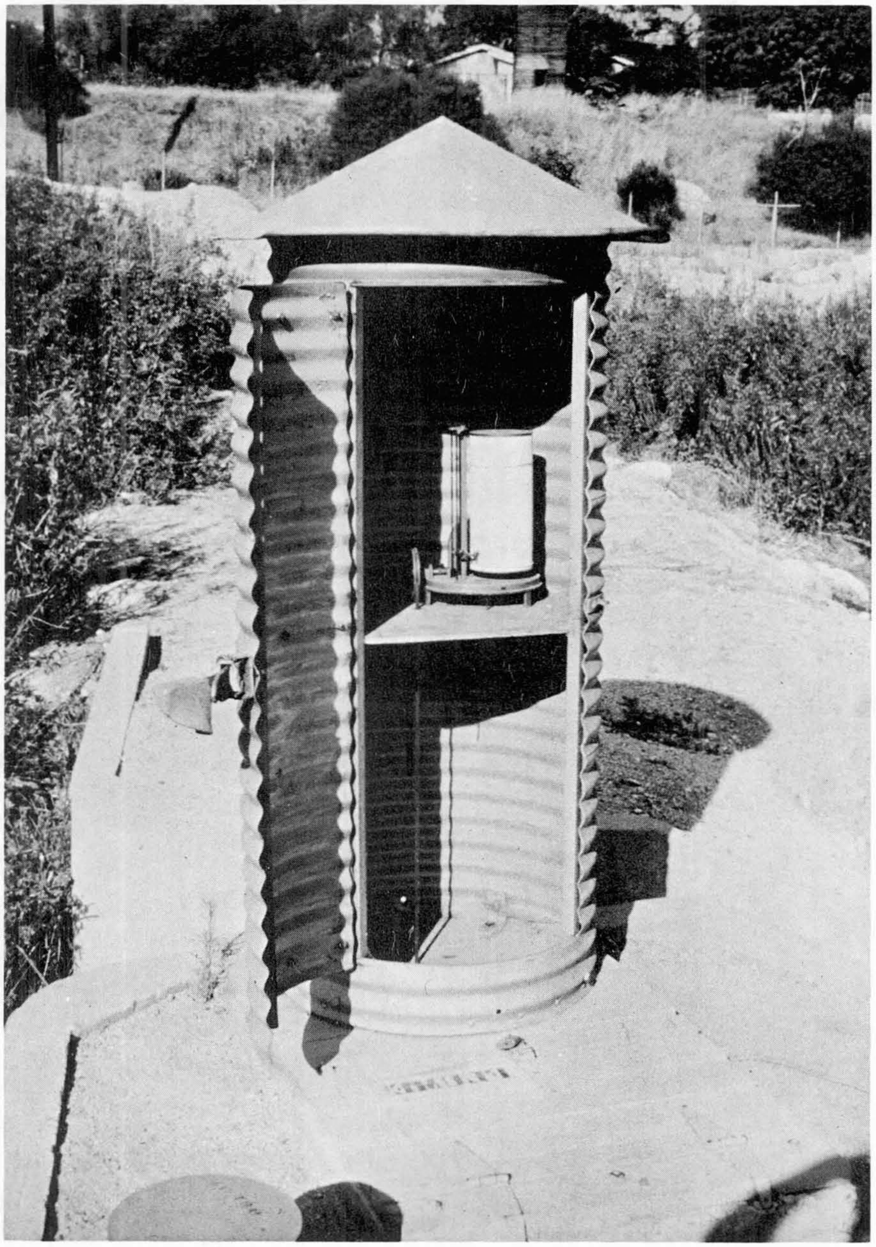


FIGURE 19 - RECORDER HOUSE AT SANTA ANITA SPREADING GROUNDS

FIGURE 20 - WELL 3030F

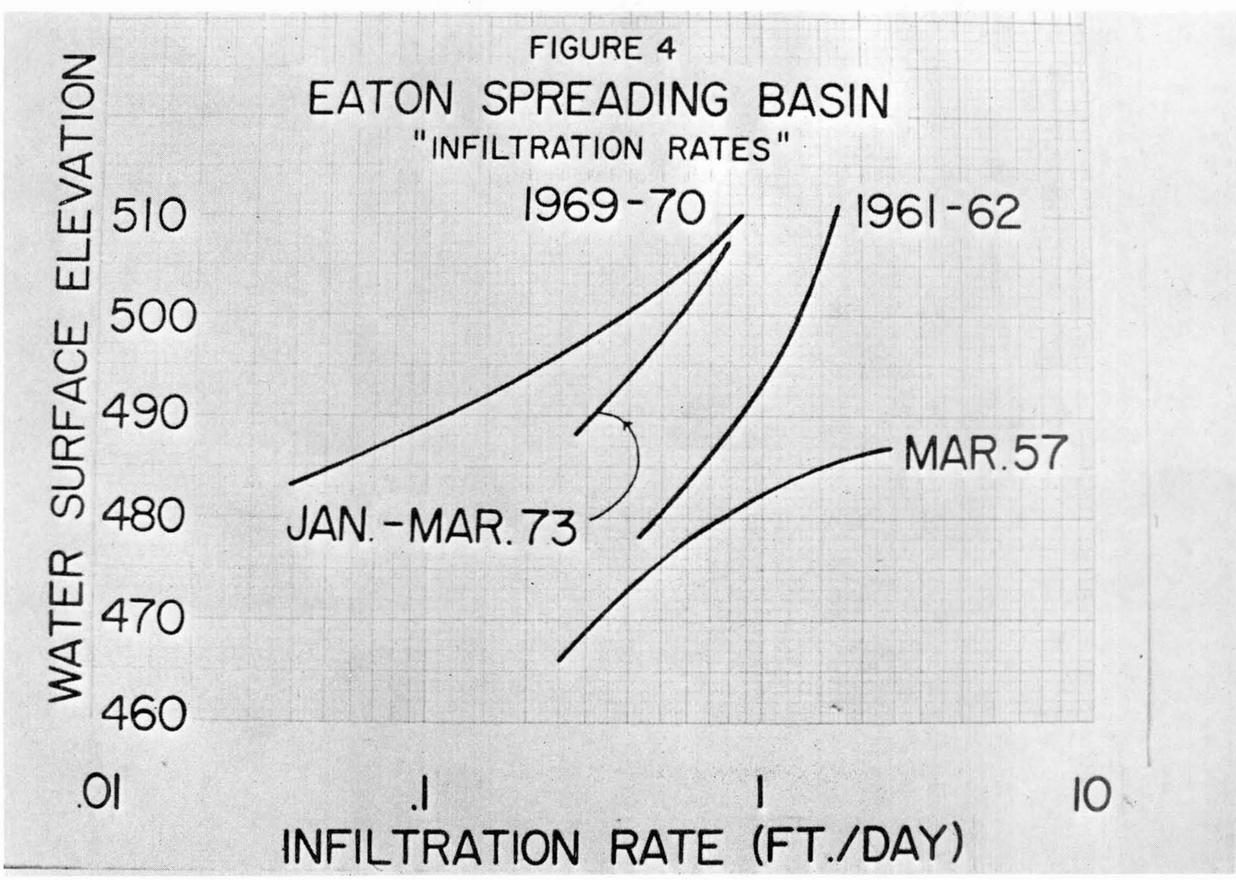


FIGURE 21 - INFILTRATION RATES AT EATON SPREADING BASIN

AUTHOR'S BIOGRAPHICAL SKETCH

NAME: Kenneth D. Schmidt

EDUCATION: B.S. Degree in Geology from Fresno State College

M.S. Degree in Hydrology from the University of Arizona

PhD. Degree in Hydrology from the University of Arizona

JOB POSITION: Principal of Kenneth D. Schmidt Water Quality Consultant

EXPERIENCE: Worked as a hydrogeologist for consulting firms in Bakersfield, California and Tucson, Arizona

Has recently completed an extensive study of groundwater quality in the Salt River Valley

EFFECTS OF IRRIGATION ON GROUNDWATER QUALITY IN ARIZONA

by

KENNETH D. SCHMIDT

The topic of the effects of recharge on groundwater quality is very broad. Therefore, one particular aspect is discussed in this paper, namely irrigation. Irrigation can affect the quality of groundwater on a regional scale. This paper largely concerns the Salt River Valley and some of the other basins in Maricopa County, Arizona.

There are basically two types of situations that can be considered in these basins. One occurs in areas such as near Aguila in Rainbow Valley, and in Lower Harquahala Valley where the water tables are very deep. Groundwater levels are generally greater than 300 or 400 feet in depth, irrigation has only been practiced perhaps 25 or 30 years, and the influences of irrigation have probably not yet affected the water table. The second situation would be more evident in the Salt River Valley in areas such as the Salt River Project, Buckeye Irrigation District, and Roosevelt Irrigation District. In these areas, water levels are generally less than 200 feet in depth, irrigation has been practiced for a much longer time, and large amounts of return flow from irrigation are in the groundwater.

It is useful to consider approximate volumes of irrigation return flow in the Salt River Valley. As stated in the Arizona

Water Commission (1978) report prepared for the Maricopa Association of Governments, there are about 100 million acre-feet of water in storage in the upper 700 feet of alluvium. The amount of return flow from irrigation, according to some rough estimates is about 40 to 50 million acre feet since irrigation began. This averages about 700,000 acre feet per year in the Salt River Valley today. Thus there is a large enough amount of return flow in the aquifer that the influence on the chemical quality of groundwater should be obvious.

Groundwater quality in the Salt River Valley was the focal point of an investigation by the U.S. Army Corps of Engineers as part of the Phoenix Urban Study. Also, groundwater quality in the other major basins of Maricopa County was investigated as part of the Maricopa Association of Governments 208 program. Historical chemical analyses are extensive for well water in the Salt River Valley, and records for numerous wells extend back to the 1920's or 1930's. Figure 1 shows the East and West Basins of the Salt River Valley. Some of the numerous wells for which chemical quality data have been gathered are shown.

Figure 2 shows salinity of the groundwater in the Salt River Valley in 1976-77. Most of the groundwater beneath lands irrigated with Salt River water has a electrical conductivity ranging from 1,000 to 2,000 micromhos, and averaging about 1,500. The long-term average total dissolved solids content of Salt and Verde River water is about 400 milligrams per liter, which is equivalent to an electrical conductivity of about 700 micromhos. The salinity of the groundwater is lower under lands that are upgradient or above canals that distribute this water, as opposed to downgradient or below. This is apparent in the vicinity of Scottsdale near the Arizona Canal and also in the Queen Creek area. The same is true along the Arizona Canal in the West Basin. Some of the U.S. Geological Survey reports in the 1940's noted that chloride contents were higher in groundwater beneath lands irrigated with Salt River water, as opposed to adjacent lands (McDonald, Wolcott, and Hem, 1947). The groundwater in areas of very low salinity was recharged from mountain-front recharge or sources other than the Salt River under natural conditions over many years.

Besides evaluating the distribution of salinity in a geographic sense, it is important to evaluate the vertical distribution in the aquifer. Figure 3 shows two of the predominant trends in large parts of the Salt River Valley. These are from data collected during drilling by the cable-tool method, where samples have been bailed from the well and the electrical conductivity measured. The results for the well on the right side show what happens at depths of about 700 feet in some areas. There is a change in the geological formations at that depth, to the equivalent of the lower conglomerate unit, as defined by the U.S. Bureau of Reclamation (1977). In this case, there are commonly sharp decreases in salinity at that depth. This pattern is more common near the mountains fronts, or at the edges of the basins in a geologic sense. The results for the well on the left side show the opposite pattern. The pattern shown on the left is more predominant in wells that are drilled near the center of basins, for example, in the Luke area. In this area, a formation termed the "middle fine-grained unit" is penetrated at depths of about 800 feet, and the salinity increases. This is apparently due to the presence of evaporite deposits in the middle fine-grained unit. Both the horizontal and vertical distribution of salinity must be known before discussing changes in salinity with time.

Many investigators have reported for decades that salinity of the groundwater in the Salt River Valley is increasing. They have added up the amount of salts that are in the surface water that comes in, and added up the salts that are in the surface water that goes out. There is a great imbalance, and it has been assumed that great quantities of salts are accumulating in the groundwater. Table 1 shows the major items of salt input and output in the Valley in 1975. Shown are the items of largest magnitude in evaluating salt input and output. The amount of salt in water from the Salt and Verde Rivers averages about 500,000 tons per year. The items of output under present conditions are primarily drainage pumpage from the Buckeye Irrigation District and irrigation tail water, which together average about 170,000 tons per year. There is obviously an imbalance in those two figures. There is some evidence that indicates that these are not the only factors to be considered in an evaluation of groundwater salinity. Furthermore, the fact that more salts enter the Valley in the surface water than leave in the surface water does not unequivocally mean that the groundwater salinity will increase.

Table 2 shows the projected conditions in 1990. Deliveries from the Central Arizona Project, as currently projected, will about double the amount of salt input. However, there are some significant new sources of salt output. Namely, the export of sewage effluent to the Palo Verde Nuclear Generating Station and increases in drainage pumpage that have been projected by Halpenny and Greene (1975). A substantial imbalance in salt input and output is projected.

As part of this investigation, hydrographs of well water salinity were prepared. Records extend back to the 1920's for many Salt River Project wells. Records for the Buckeye Irrigation District wells extend back to 1930. Records for wells of the Roosevelt Irrigation District and Goodyear Farms extend back to the 1950's. Records for municipal wells in the Valley do not generally extend back more than 20 years. One of the complications in interpreting these records is that water levels have significantly declined in this area. Because of this, wells have commonly been replaced or deepened. Thus records for an individual well often only extend for several decades. For example, wells 1,000 feet deep were not generally present to be sampled in the 1930's. Instead the existing wells were several hundred feet deep, and they were later deepened or replaced by a deeper well as the water level declined. Although this complicates the interpretation, it also supplies some very meaningful information. In conjunction with well construction data, variations of salinity with depth can be evaluated independently of other more direct methods.

Figure 4 shows long-term trends in salinity of well water in the Salt River Valley. For the East Basin, two trends are shown. One is a very predominant trend in the Salt River Valley, namely a decreasing salinity with time. This happened particularly during the first few decades of large-scale pumping, which commenced in the 1920's. Groundwater in the shallow strata was higher in salinity in the 1920's than deeper groundwater. As the shallow water was removed by overdrafting, the salinity of pumped water decreased. There is a trend toward constant salinity with time in recent decades. Another trend, in the East Basin, is increasing salinity during recent decades. This trend is occurring in the Gilbert area, where there is a regional perched groundwater zone. There are only three areas in the Salt River Valley where salinity has actually increased.

For the West Basin, three trends are shown. One pattern is where the salinity is fairly constant, and the well was deepened. The salinity dropped remarkably after the well was deepened, but after several decades, gradually increased toward the level in water from the original well. It is my interpretation that this is due to the downward movement of shallow water into deeper parts of the aquifer. Records for a second well in the West Basin show a decreasing salinity with time, as discussed previously for the East Basin. A third trend is predominant for wells in the area between Liberty and Goodyear. Rather abrupt increases in salinity have occurred in this area since the early 1960's. I have attributed this to the movement of groundwater of higher salinity from the south toward a pumping depression in the Luke area.

Figure 5 shows the geographic distribution of salinity trends for the past several decades in the Salt River Valley. There are obviously many factors that influence the groundwater salinity. In the East Basin as a whole, the salinity of well water has not changed in most of the area during recent decades. In the Scottsdale area, the salinity has actually decreased in water from some wells. The salinity has increased in only the Gilbert area and near Chandler. In the West Basin, the salinity has decreased in recent decades in north Phoenix and Glendale. However, the predominant trend is one of constant salinity. The salinity has increased in the area between Liberty and Goodyear. This appears to be similar to what has occurred near Chandler. Substantial decreases have occurred in the Buckeye area, where large volumes of sewage effluent have been imported. The sewage effluent has a salinity of about 800 milligrams per liter, which is lower than the groundwater in the area. In summary, there are only three areas in the Valley where the salinity has increased. Two of these appear to be due to altered pumping patterns, rather than from the direct influence of return flow. However, in the Gilbert area, the increase may be due to return flow, the effects of which are accentuated by numerous cascading wells.

Figure 6 is a diagramatic view of a perched layer. A perched layer could be a caliche deposit or a clay layer. Water percolating down from the land surface will be retarded and this will allow saturated conditions to develop. A monitor well could be drilled into the perched zone and a water sample collected. By sampling water in these perched zones, one can determine the composition of the return flow above the water table. There are many domestic wells that tap such perched layers in the Salt River Valley. One of the predominant sources of information on the composition of perched groundwater are hydrogeologic investigations near the Palo Verde Nuclear Generating Station in the Lower Hassayampa area. The salinity of water in the main aquifer is about 600 to 800 milligrams per liter (mg/l). There is a perched zone present above the Palo Verde clay in the area. Water levels in wells tapping the perched zone are rather shallow, ranging from about ten to eighty feet in depth. The salinity of water in the perched zone ranges from 3,000 to 11,000 mg/l.

Another example is presented for the Lower Harquahala Valley. Table 3 shows chemical analyses for samples from a deep irrigation well in the Valley. This well was sampled in 1974 when it was still used as an irrigation well with a deep well turbine pump installed. It was resampled in 1978 after it had been abandoned for irrigation use, and when a small domestic pump was in place. Apparently the small pumping for domestic purposes produced water indicative of shallow groundwater. A regional perched zone has recently been delineated in this area by the Arizona State Land Department. Both salinity and nitrate are thus high in the shallow groundwater as opposed to the deep groundwater. The high salinity and nitrate are thus due to irrigation return flow.

The effects of irrigation in the basins outside the Salt River Valley have not yet been manifested in water pumped from most large-capacity wells. However, increasing salinity and possibly nitrate content should be of great concern in future decades. It may take from 50 to 100 years before the effects of irrigation return flow in these basins are shown by pumping wells. This problem does not appear to exist where surface water is available, such as in most of the Salt River Valley.

Figure 7 shows a diagram illustrating cascading water. This can occur where openings in the well extend above the main water table. Where perched zones are present, water can enter the well. This water then falls down the well and enters the aquifer somewhere in the perforated interval. If a well is inactive for three or four months, which might be normal in this area for an irrigation well where there is no double cropping, then the cascading water tends to accumulate in the aquifer around the well. This zone might extend from 50 to 500 feet or so from the well, depending on aquifer characteristics and other factors. The cascading water can be sampled several ways. One way is to lower a device down the well when the pump is removed. Another method is to intentionally sample wells immediately after they have been idle for a long time. A sample can be collected minutes or hours after the pump has been started. Although this may not be meaningful in terms of regional aquifer chemical quality, it could be of interest in terms of monitoring irrigation return flow.

Table 4 includes analyses of water from two wells in the Tucson Basin. The sampled wells had been idle for several months, and the pumps were turned on at the beginning of the following irrigation season. The wells were sampled during the first day of pumping when pumping had been in progress for several hours. On the other hand, the samples taken during the second day reflect more than 24 hours of pumping. The water pumped from these wells soon after pumping began reflects the chemical quality of irrigation return flow. In this case, both salinity and nitrate appear to be higher in the return flow than in the deeper groundwater. Surface water was not used in this area for irrigation.

A very important factor in the Salt River Valley is the canal seepage. The estimated 700,000 acre-feet of irrigation return flow each year is comprised of two components. First, is canal seepage or losses before the water arrives at the field. Second, are the on-farm percolation losses. Previous studies in the Salt River Valley indicate that canal seepage is very important. It may comprise up to 40 percent of the total return flow. There is no significant increase in salinity during percolation from canal seepage. This has been an important process to keep the salinity from increasing in groundwater of the Salt River Valley.

Table 5 shows chemical analyses of water from a well 350 feet deep near Chandler. The U.S. Geological Survey collected a water sample from the well discharge in March 1972. Later, when the pump was pulled from the well, they sampled cascading water, which was entering the well at a depth of 130 feet. The salinity was lower in the cascading water than in the underlying groundwater. This is diametrically opposed to what might be expected. According to a simple concept, the water is pumped from the well, used for irrigation, and the salts are concentrated by evapotranspiration. Thus the return flow would be of much higher salinity than the groundwater. However, if the well was near a canal, there could be substantial recharge of water with lower salinity. There are no canals near this particular well. Instead, the well is in an area where the salinity of well water has increased due to altered groundwater flow patterns (Figure 5). My interpretation is that the cascading water originated several decades ago. If it was originally pumped from this well more than 25 years ago for irrigation, then the well water was of much lower salinity than it is today. Return flow from such a source, even though degraded to a degree, could be of lower salinity than the underlying groundwater. Samples of the cascading water could thus substantiate that increasing salinity in the area was not due to irrigation return flow. The nitrate content is much higher in the cascading water than in the well discharge. This may indicate the impact of irrigation on nitrate content of groundwater. This example illustrates one of the greatest difficulties in monitoring the impact of man's activities on groundwater in arid lands--namely, the lag time between when the activities take place at the land surface and when the quality of water from a pumping well is subsequently impacted.

In conclusion, some of the effects of irrigation have already been manifested in groundwater of parts of Maricopa County. Present data indicate that where surface water is available and canal seepage is large, irrigation has largely been beneficial to groundwater. However, in areas where surface water is not available and water tables are relatively deep, irrigation return flow has not yet reached the water table in large volumes. Perched zones that have been sampled in such areas indicate that substantial problems can be expected in future decades. Specific monitoring has been proposed as part of this investigation that would provide essential information for future management of groundwater.

SALT RIVER VALLEY
SALINITY EVALUATION
1975

	Volume of Water (1,000 acre-feet)	Salinity (mg/l)	Amount of Salt (1,000 tons)
Input			
Salt and Verde River	910	400	495
Output			
Drainage Pumpage	12	3,700	58
Irrigation Tailwater	23	3,500	110

TABLE 1 - SALINITY EVALUATION FOR THE SALT RIVER VALLEY IN 1975

SALT RIVER VALLEY
SALINITY EVALUATION
1990

	Volume of Water (1,000 acre-feet)	Salinity (mg/l)	Amount of Salt (1,000 tons)
Input			
Salt and Verde River	910	400	495
Central Arizona Project	510	735	510
Output			
Drainage Pumpage	28	3,700	140
Irrigation Tailwater	23	3,500	110
PVNGS (Five Units)	107	800	117

TABLE 2 - SALINITY EVALUATION FOR THE SALT RIVER VALLEY IN 1990

LOWER HARQUAHALA VALLEY
CHEMICAL ANALYSES FOR WATER
FROM WELL (B-2-9) 14bbb

Constituent (mg/l)	Irrigation Well	Domestic Well
Calcium	32	190
Magnesium	14	14
Sodium	144	795
Carbonate	0	0
Bicarbonate	140	103
Sulfate	150	132
Chloride	120	648
Nitrate	21	200
Fluoride	1.6	5.2
Hardness ($CaCO_3$)	163	552
pH	7.8	7.9
Electrical Conductivity (micromhos/cm @ 25° C)	1,005	-
Total Dissolved Solids	589	3,206
Date	8/8/74	4/28/78

Perforated Interval 294 to 1,452 feet

TABLE 3 - CHEMICAL ANALYSES OF WATER FROM A WELL IN LOWER HARQUAHALA VALLEY

SAMPLING RESULTS FOR TWO PUMPED IRRIGATION WELLS NEAR TUCSON, ARIZONA

	WELL NO. 1		WELL NO. 2	
CONSTITUENT	DAY 1	DAY 2	DAY 1	DAY 2
Calcium	100	74	64	44
Magnesium	9	12	3	8
Sodium	40	43	38	40
Potassium	3	3	4	2
Bicarbonate	210	181	134	132
Chloride	14	14	21	14
Sulfate	100	144	75	87
Nitrate	74	22	51	8
Total Dissolved Solids	466	390	332	272

Values are in mg/l. The wells both have cascading water and had been inactive for several months prior to sampling.

TABLE 4 - WATER SAMPLES COLLECTED FROM TWO IRRIGATION WELLS IN THE TUCSON BASIN

COMPARISON OF WATER QUALITY FOR CASCADING WATER AND WELL DISCHARGE

WELL (D-2-5)5dbb
SALT RIVER VALLEY, ARIZONA

	Well Discharge (1800 gpm)	Cascading Water
Calcium	390	180
Magnesium	110	61
Sodium	350	430
Potassium	9	4
Bicarbonate	205	218
Sulfate	520	320
Chloride	1,120	690
Nitrate	48	88
Boron	0.79	0.70
Silica	42	76
Phosphate	0.01	0.43
Hardness ($CaCO_3$)	1,400	700
Sodium Percentage	35	57
Iron	0.20	0.01
Electrical Conductivity (micromhos/cm at 25°C)	-	3,340
Total Dissolved Solids	-	1,960
pH	7.4	8.3
Depth (feet)	350	130
Date	3/13/72	8/13/73

TABLE 5 - CHEMICAL ANALYSES OF WATER FROM A WELL NEAR CHANDLER

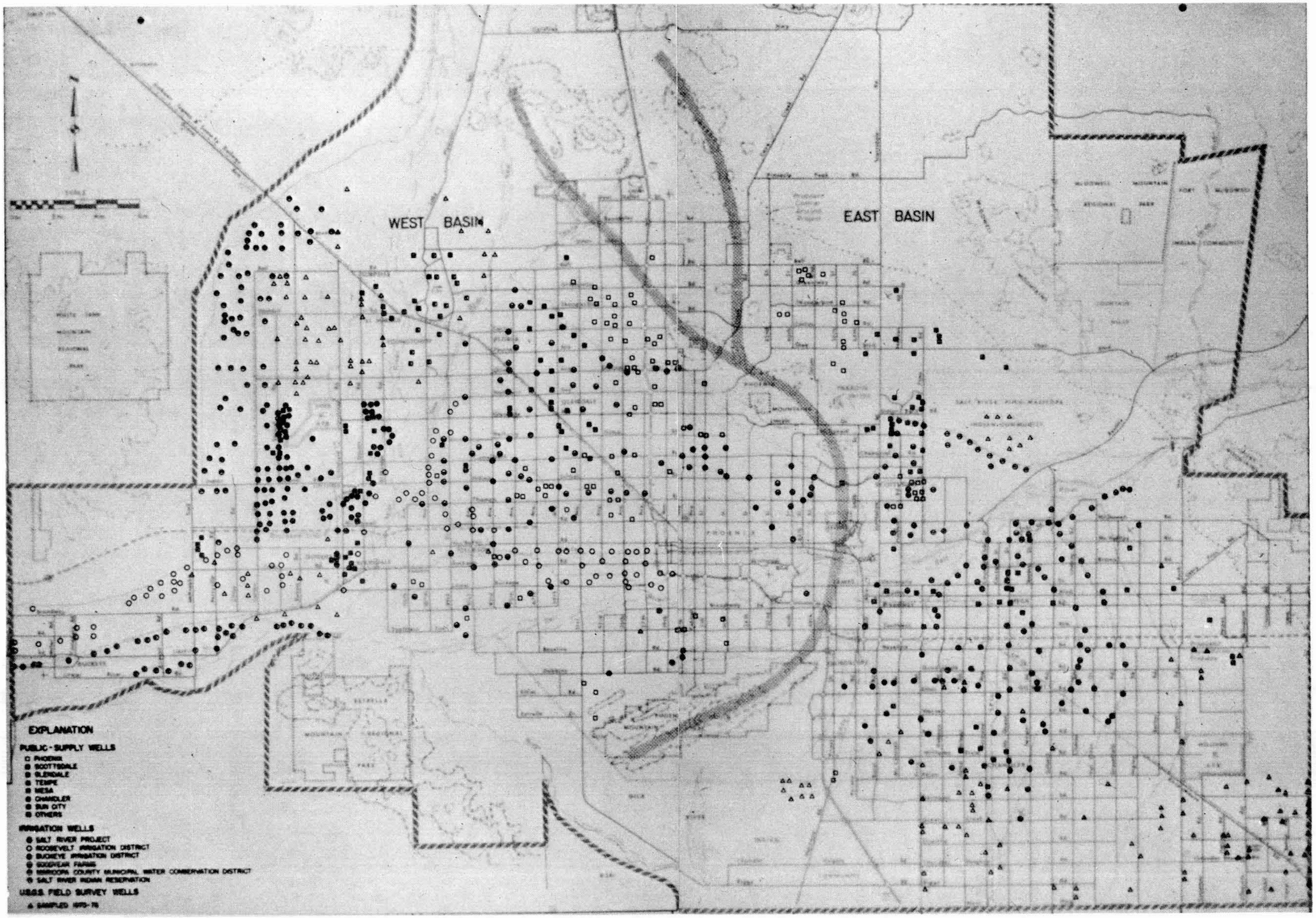


FIGURE 1 - LOCATION OF SELECTED WELLS WITH CHEMICAL QUALITY RECORDS IN THE SALT RIVER VALLEY

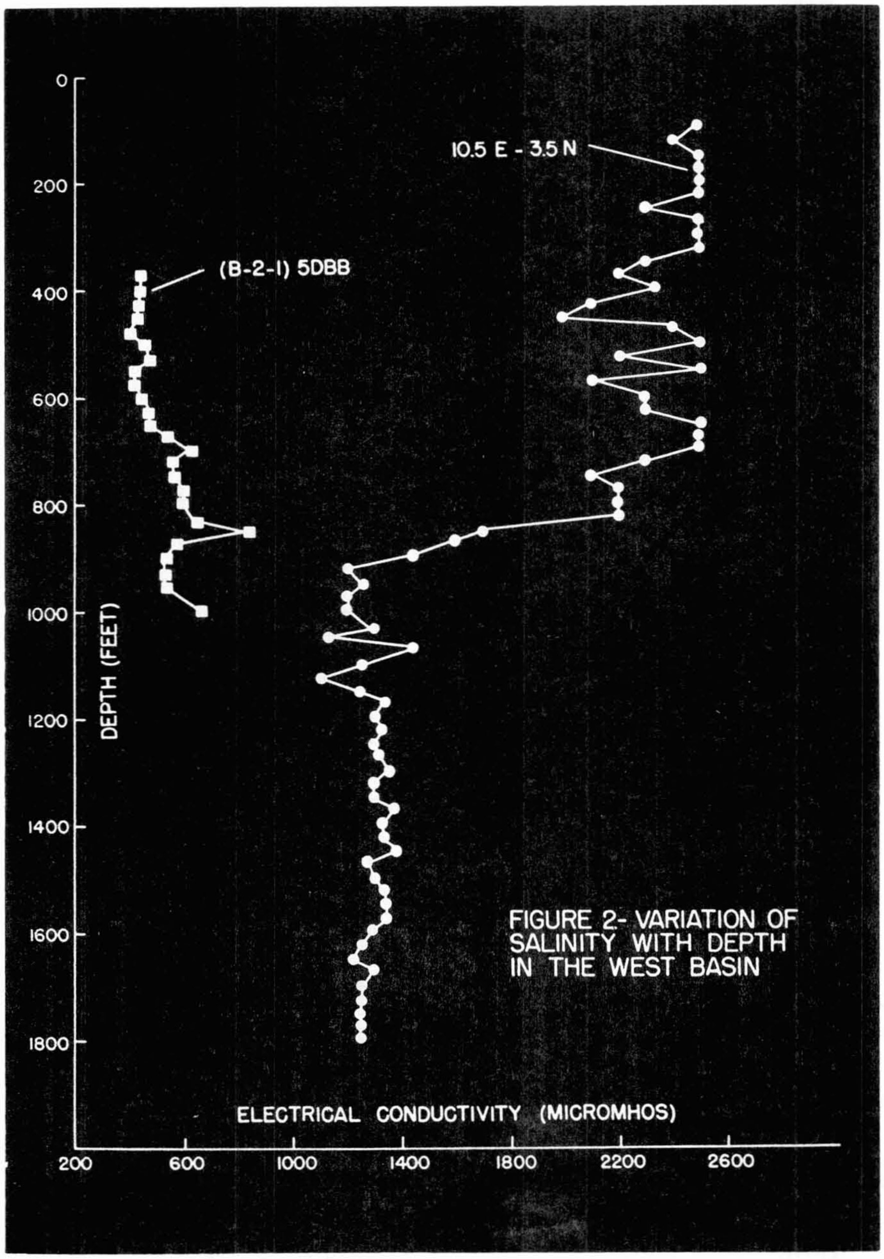


FIGURE 3 - VARIATION OF SALINITY WITH DEPTH IN THE SALT RIVER VALLEY

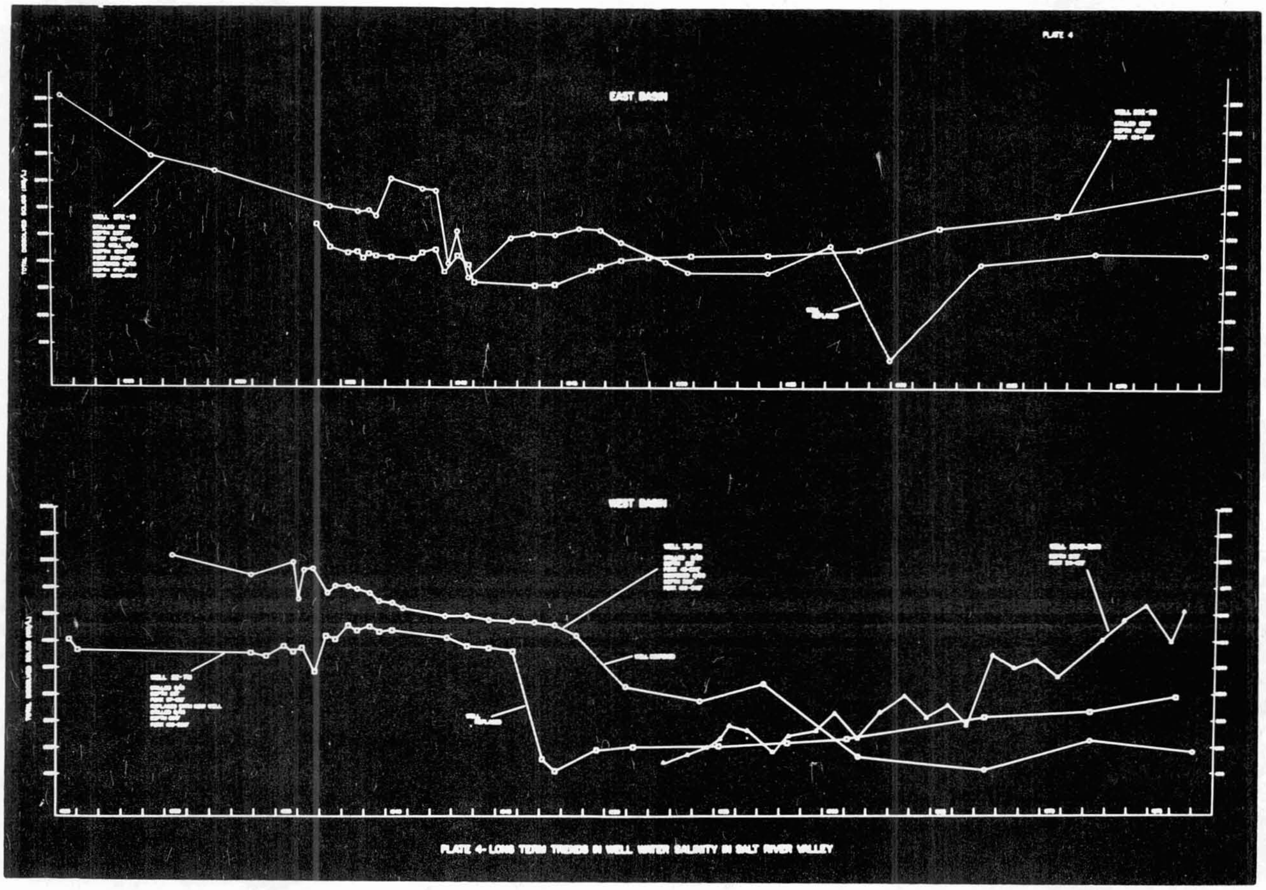


FIGURE 4 - LONG-TERM TIME TRENDS IN WELL WATER QUALITY IN THE SALT RIVER VALLEY

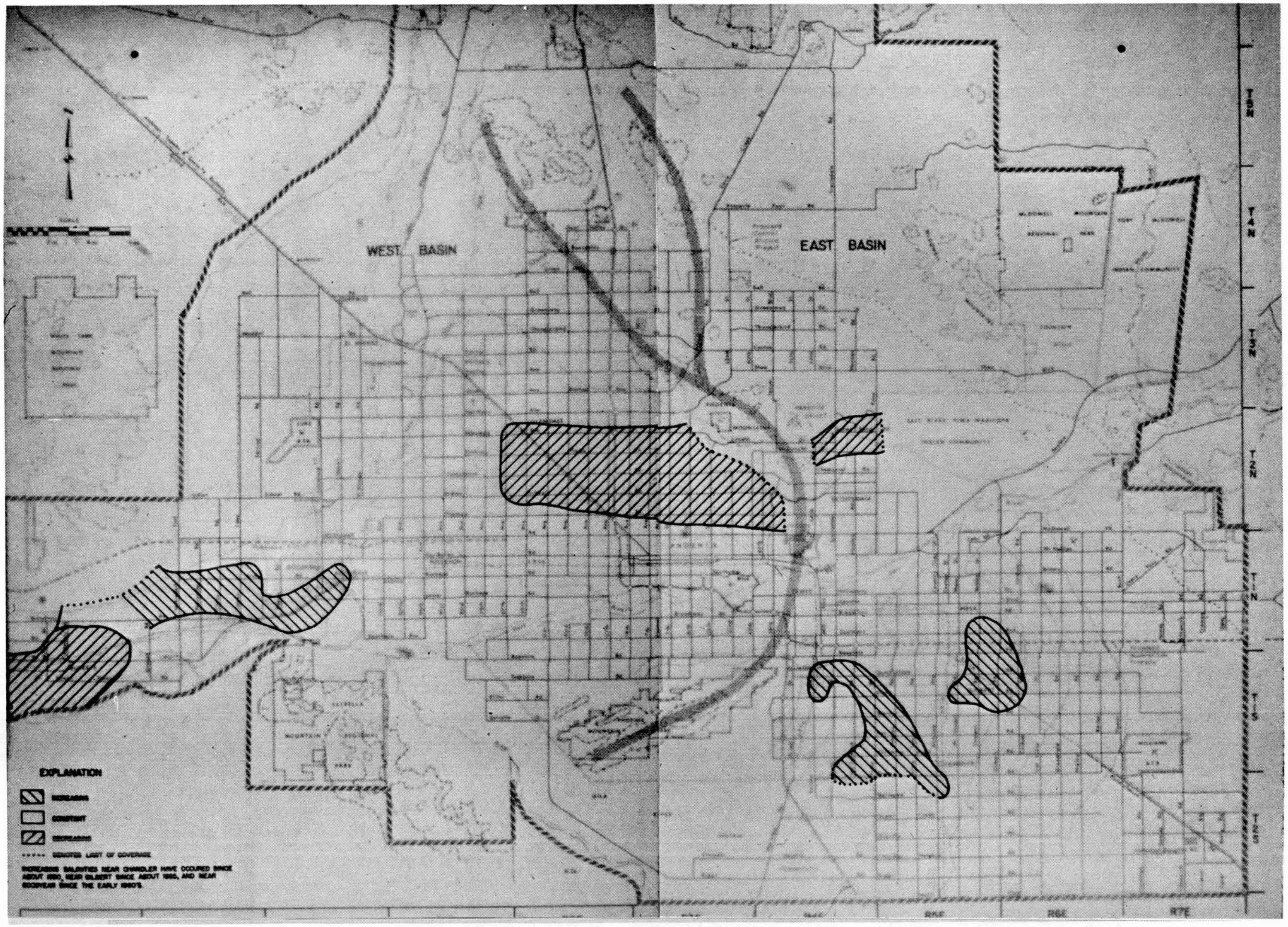


FIGURE 5 - GEOGRAPHIC DISTRIBUTION OF SALINITY CHANGES WITH TIME IN THE SALT RIVER VALLEY

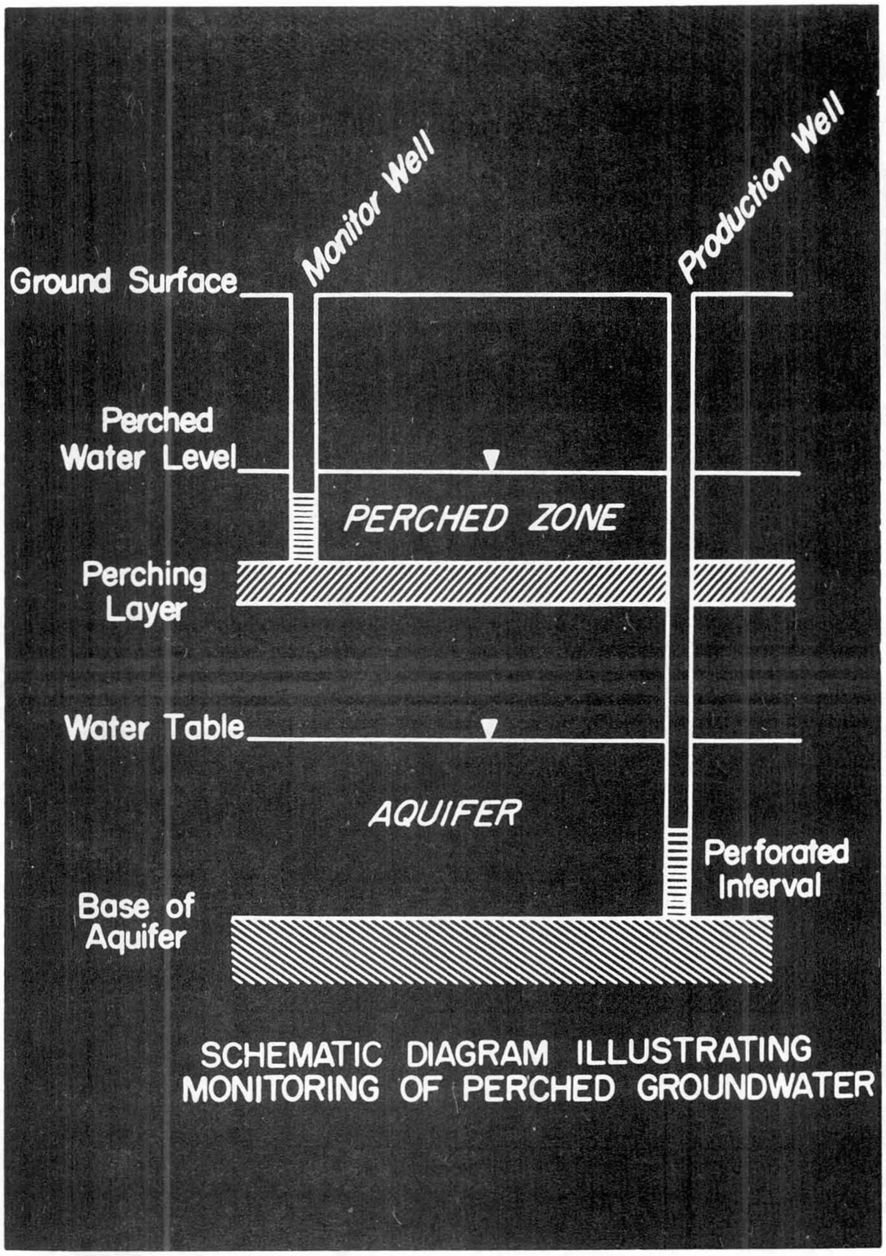


FIGURE 6 - SCHEMATIC DIAGRAM ILLUSTRATING A PERCHED WATER ZONE

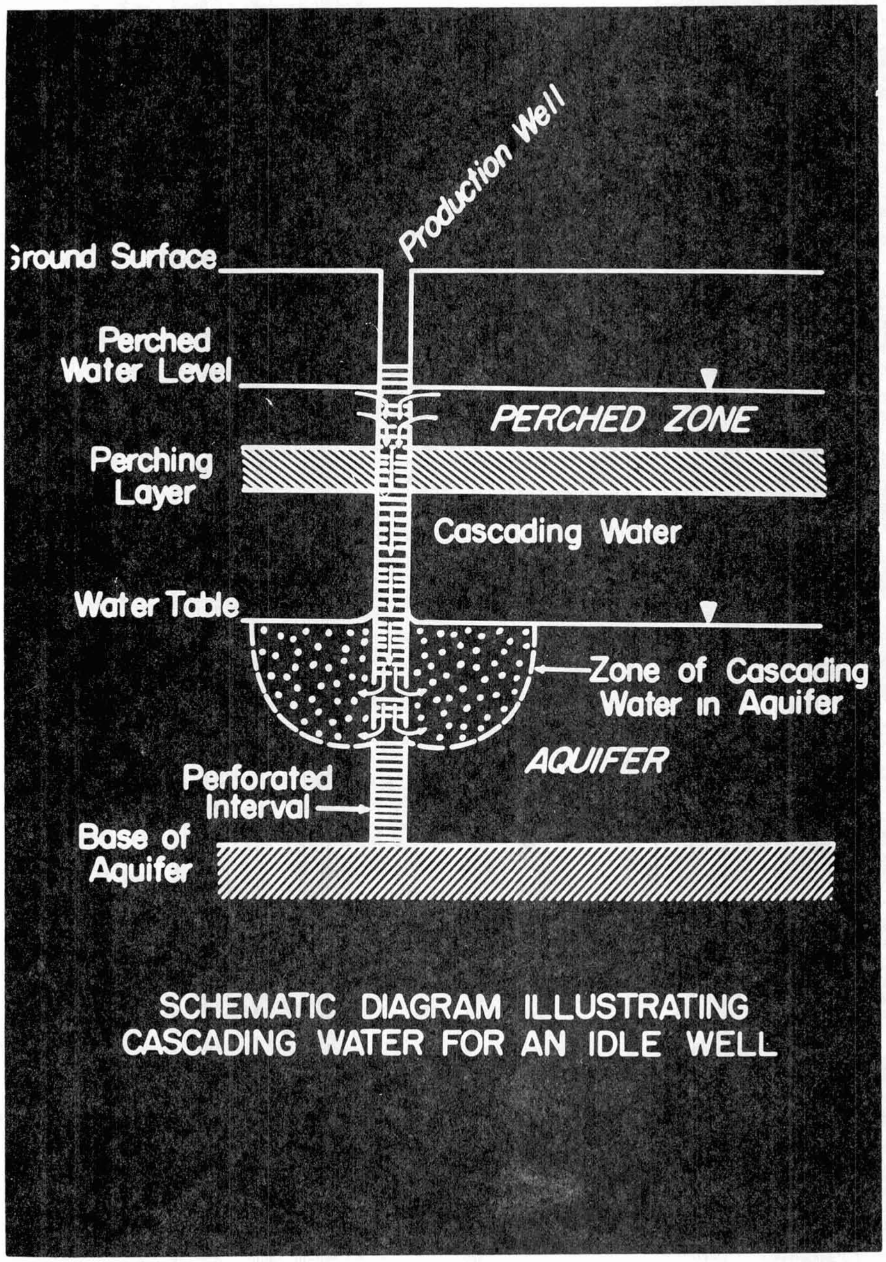


FIGURE 7 - SCHEMATIC DIAGRAM ILLUSTRATING CASCADING WATER FOR AN IDLE WELL

AUTHOR'S BIOGRAPHICAL SKETCH

NAME: Harry I. Nightingale

EDUCATION: B.S. & M.S. Degrees in Soil Chemistry from New Mexico State University

PhD. Degree in Soil Chemistry from Utah State

JOB POSITION: Research scientist for the United States Department of Agriculture in Fresno, California

EXPERIENCE: Has been associated with the U.S. Department of Agriculture, Science and Education Administration, Agricultural Research, since 1965

Responsible for the soil, groundwater chemistry and environmental aspects of research projects on artificial groundwater recharge for the U.S. Department of Agriculture

ENVIRONMENTAL FACTORS OF GROUNDWATER RECHARGE

by

HARRY NIGHTINGALE

In the planning phases of Leaky Acres by the Water Department of the City of Fresno, no consideration was given to the ecology and the environmental impact of this recharge facility on the surrounding urban area. Looking back now, we can say that generally the environmental factors fall within three categories which are not necessarily independent of each other. The first category is the plants, animals and insects and their interaction with the surrounding urban area. These are the factors that have appeal to the news media. The second category is the aquatic plants and animals plus the benthic organisms that live in the basin soils and their impact on the permeability and porosity of the surface few centimeters of soil. Basically, this is a biological clogging phenomenon directly related to level of plant nutrients and, therefore, is subject to some management control. The third category of factors is the non-living; namely the suspended silts and clays in the water delivered for recharge. There is also soil erosion from the levees and intrabasin erosion generated during filling the basins. The accumulation of fine sediments on the surface of soil not only reduces the permeability but also raises the plant nutrient level and encourages aquatic plant growth. But these factors can also be managed if considered during the planning phases and the construction of the recharge facility.

The following presentation will illustrate these factors, their magnitude and their interrelationships as observed at the Leaky Acres Recharge Facility, which is in an urban environment and a semi-arid climate.

Figure 1 is an aerial view of Leaky Acres taken from a U-2 flight film strip in 1975. There are ten basins for a total of about 117 acres of wetted surface. North is at the top. Presently, to the west of Leaky Acres, is another 80 acres being developed for recharge. Note the closeness of the airport runways.

Figure 2 shows the type of vegetation that was in the eastern half of the recharge site before construction. The vegetation was mostly annual grasses. The ground squirrel was the most common animal in this semi-arid area.

Figure 3 shows the type of vegetation in the western half of Leaky Acres. About one third of this area was in irrigated pasture. Note the nearness of the houses on the south side of Leaky Acres as well as the jackrabbit in his native habitat. Gopher snakes (Figure 4) were also common in this area. The question is what happens to these native land animals when their natural habitat is flooded and converted into an aquatic environment.

Figure 5 shows water coming into a basin the first time and is proceeding down a ground squirrel hole which makes for fine recharge. But, the problem is that as the basin filled up, the ground squirrels were drowned out by the water. This, of course, generated a body disposal problem (Figure 6) to control the odors. All the native birds, quail, pheasants and many small species of birds left the area when the basins were full. As soon as the basins were filled, the aquatic birds began arriving. Figure 7 shows the common mud hen, American coot, and her young which she raised at Leaky Acres. This bird and the killdeer were the first aquatic birds to arrive. The American coot has remained as the most common bird at Leaky Acres.

Figure 8 shows the migratory black-neck stilt. They come in the spring and usually leave in the fall before the water is turned off. The population level of this bird was not high, but reproduction did occur. Figure 9 shows three black-neck stilts on the ground surrounding one jackrabbit. Is this balanced ecology or one confused jackrabbit?

Figure 10 shows the American avocet, a migratory bird at Leaky Acres. The American avocet is a very beautiful bird. Only a few of these birds were usually present at one time and they did not reproduce.

Figure 11 shows a few of the mallard ducks at Leaky Acres. They also reproduce and raise young. Other species of ducks were occasionally present at Leaky Acres. The total bird population, of course, must be kept quite low on account of their interference with airplanes on their final approach to the airport (Figure 12). The bird population at Leaky Acres has been low because of the limited food supply caused by a low nutrient recharge water.

Figure 13 shows a muskrat at Leaky Acres, and of course, the muskrat must be controlled as these animals, as well as the gophers, can tunnel into the levees and cause breaks and flooding in the urban area. At Leaky Acres, the birds feed on the aquatic plants and animals, but also the birds can be food as we observed in the summer of 1973 when we found numerous mud hens without their heads (Figure 14). Later we did find this weasel (Figure 15) near a headless mud hen. And so life goes!

Figure 16 shows some of the sea gulls at Leaky Acres. Groups of sea gulls that arrived at Leaky Acres stayed a few days and then left. Thus, high populations of sea gulls did not build up.

When water is turned off at Leaky Acres in the fall, usually in October, the basin soils are drained. At this time, there is quite an influx of western sandpipers, greater yellowlegs and other marsh birds that will feed on the insects and aquatic plants on the bottom of the basins (Figure 17). Figure 18 is an illustration of the ducks trying to figure out where the water went. When the basins were drained, we did have the opportunity to catch and identify the aquatic vertebrates.

Figure 19 shows one of the nice sized bull frogs at Leaky Acres. During the summer there are numerous tadpoles and young frogs.

At this point, it should be pointed out that the recharge water used at Leaky Acres presently comes from the Kings River below the Pine Flat Dam and delivered through irrigation canals. Thus, the fish present in these waterways can be transferred to the basins.

Figure 20 shows a golden shinner, a fairly common fish in the basins. Figure 21 shows a large blue gill. Most of them are not this big. A large green sunfish is shown in Figure 22. This fish did reproduce in the basins and was probably the most common fish present. Mosquito fish were also planted in the basins in the spring by the Mosquito Abatement District as part of their mosquito control program. The largest largemouth bass that we observed at Leaky Acres is shown in Figure 23. Unfortunately, the bass population was usually quite low. Figure 24 shows a carp about a half a meter long. This is the largest carp yet observed at Leaky Acres. The brown bullhead (Figure 25) was also common, but only a few catfish have been observed.

The next few figures will show some of the types of the aquatic plants at Leaky Acres. When water was first put into the basins, an algea mat would form on the bottom and would eventually break away from the soil and rise to the surface (Figure 26). This process repeated itself with decreasing intensities during the first three years of recharge. Figure 27 shows the accumulation of this bottom grown algea in the down-wind corner of a basin where it undergoes decay with some odor production and Figure 28 illustrates the accumulation of this organic matter in the corner of a basin when the water is drained. This organic material can cause biological clogging of the soil as it undergoes decomposition by the soil micro-organisms during the next recharge period. Figure 29 shows the most common algea at Leaky Acres, spirogyra. Oscillatoria and hydrodicon were the next most common. Many other minor species of algea were observed, but algea has not been a problem at Leaky Acres.

Figure 30 shows an aquatic weed problem, cattails and the California primrose. These plants did quite well when the water depth was less than about 30 to 40 centimeters during the first three years of recharge. These plants must be controlled or the basins will begin to look like a swamp. A massive build-up of cattails occurred in the north half of one of the upper basins during the second year of recharge (Figure 31). Note what was the relatively shallow depth of water. Mechanical removal of the cattails took place (Figure 32), plus increasing the depth of the water. Figure 33 shows the same area in September of 1978, and it is still clear of cattails. Small stands of cattails can, however, be effectively controlled by hand-spraying with Dalpon without water contamination.

The environmental factor that really made a hit with the newspaper was the midge problem in April of 1973, the third year of recharge. Figure 34 shows the use of light traps for the study and identification of the aquatic insects that were attracted to the outdoor lighting in the urban area. A night's catch of insects is illustrated in Figure 35. There were very few mosquitoes, mostly midges. The larvae of the midges feed on the organic matter in the soil under water. With time, the organic matter is oxidized which lessens the midge problem. One of the methods to control the midges is by draining the basins, then dry and disc the soil (Figure 36). It was an effective midge control method, but not effective for recharge. It was suggested that carp, which feed on larvae, would aid in the control of the midges so the City's Water Department obtained some carp and put them in this basin. We did observe that the carp made the water quite muddy with their bottom feeding. On draining this basin, we found it completely full of pot holes (Figure 37) with deposition of finds on the soil surface. So carp probably should not be used for the control of midge larvae.

It should be pointed out again that the most effective way to control the aquatic plants and hence, control of the animal food supply, is to use recharge water naturally low in plant nutrients, particularly nitrogen and phosphorus. If high nutrient water is used, such as treated sewage wastewater, then we have a new set of problems which have been studied by Dr. Herman Bouwer in Phoenix. But, at Leaky Acres, the water is essentially snow-melt from the Sierra Nevada.

A five-year monthly average for the specific electrical conductivity (SEC) of the water used to recharge at Leaky Acres is shown in Figure 38. This water is delivered to Leaky Acres by the Fresno Irrigation District. A 50 micromhos/cm value corresponds to about 33 milligrams of total dissolved solids per liter. Recharge has normally been done from February or March through September or October. The nitrate content of the recharge water has generally a monthly average of less than two milligrams per liter, and chlorides, less than three milligrams per liter and for most of the year. During the recharge season, the turbidity of the recharge water has been less than five turbidity units, so it is very clean water. The water also has a dissolved oxygen content averaging between eight and ten milligrams per liter, which is nearly saturated. Thus, the chemical and nutrient levels of the recharge water have not been favorable for the massive growth of aquatic plants, except during the first two years when apparently nutrients were available from the soil. There are, however, enough nutrients in the water to get some aquatic plant growth each year. Plant growth is presently mostly confined to areas near the levees and where the water depth is less than 40 centimeters. Here, plants include large crabgrass, dallisgrass, and swamp smartweed. The battle against these unfavorable aquatic plants is continuous at Leaky Acres and is absolutely essential.

The groundwater quality is also part of the environment, especially when pumping the water back out to use. Figure 39 shows the decreasing groundwater salinity with time, because of the low salinity recharge water used. Each data point is the monthly average for the ten quality wells at Leaky Acres. In the beginning, when recharge first started, a slug of salts from the soil profile was flushed into the groundwater. A slug of salts is more or less characteristic of the start of each recharge period. The average groundwater salinity has decreased, and as the regression equation (Figure 39) shows, after 96 months (December 1978) concentrations should show about 55.2 micromhos/cm as the average electrical conductivity. The sampling this month (November) showed a concentration 55.3 micromhos/cm, so this regression equation fits the data quite well.

The groundwater quality associated with recharge becomes a very important environmental factor to the consumers of recharge water. One of the effects of using such low salinity water for recharge has been the dispersion and the removement of colloidal material, apparently mostly from the first 3.9 meters (13 feet) of soil into the groundwater beneath Leaky Acres. Of course, there has been some lateral movement of the turbid water away from Leaky Acres. Figure 40 presents the average turbidity in 1973 for our ten water quality observation wells. The highest turbidity observed was at the coordinates, 1 west and 1 south. A quality observation well located at 6 west and 5 south and about 200 metres from a tile collector and recharge well system was monitored for turbidity and salinity in 1974 during a study on the effect of gypsum applied over the tile lines on turbidity. Figure 41 shows the relationships that were observed in the field at observation well 5W6S. Essentially the same relationship between turbidity and salinity were observed under laboratory conditions. At the start of the 1974 recharge season (Figure 41), the usual peak of salts was observed. As the groundwater salinity continually decreased, an increase in turbidity was noticed from about 4 on up to about 24 FTU. In July, the gypsum was applied over the tile lines and in a very short time the peak of the salinity from the gypsum was picked up 200 meters away. At the same time, a large drop in the turbidity of the groundwater occurred. However, as the salts were leached out of the system, the groundwater turbidity increased again until the end of the recharge period. At the end of the recharge period the last little salinity peak (Figure 40) was observed, which is characteristic, and was also associated with an increase in turbidity.

The main environmental factor that will limit the life of a basin-type recharge facility is to allow turbid storm run-off water to enter the basins. Figure 42 shows such storm water entering a basin at Leaky Acres during a spring storm. The fine silts and clays will eventually seal the surface, unless removed periodically, without soil compaction, by some removal method. Figure 43 illustrates turbid water in one of the recharge basins.

The sediments that accumulate in a very thin layer right on top of the sandy loam soil surface is illustrated in Figure 44. Another source of sediment for sealing a basin can be erosion of soil from the levees by wave action. At Leaky Acres, railroad ballast (crushed rock) was placed on the slope as shown in Figure 45. This proved to be a very effective control method. But, the crushed rock still tends to work its way downhill. Figure 46 illustrates the failure of the crushed rock surface, primarily because the basin water was too high and the waves were breaking where the crushed rock was too thin. Figure 47 illustrates a simple way of moving the crushed rock back uphill and to improve the levee protection.

Figure 48 shows another source of sediment to seal the soil surface, and this is basin soil erosion during the filling of the basin. This has been a major problem in the western half of Leaky Acres. It is a relatively simple problem to solve, by a proper grade control or by putting the water in at the lowest point at the basin. The potential for this type of erosion must be determined before construction.

Figure 49 illustrates a type of erosion that can develop when the barrow strip for the levee is right next to the levee. Erosion can occur from the center of the basin into the barrow strip area. Figure 50 shows another environmental factor and that is the hazard of driving down narrow levees.

It is hoped that the preceding Figures have illustrated the significance of some of these environmental factors. There are other factors that are unique to other recharge facilities. In review, the factors discussed are important from two viewpoints. One, as they impact upon the surrounding urban area and, two, most importantly, as they impact upon the hydraulic conductivity of the surface few centimeters of soil. The research and observations at Leaky Acres support the essentiality of careful, on-site studies of the environmental factors that will influence the infiltration and the purification of percolated water before the construction of the facility. This preconstruction information is site-specific and is essential for developing the construction plans, operation and maintenance procedures to control the problems and thus increase the longevity of the recharge facility.

The knowledge gained from this operation leads to the following seven planning phases. Briefly, and in order of priority, they are: First, a cursory site evaluation. This is desk work, working with soils maps, well logs of the recharge area and including perhaps a few site walk-throughs to develop the first "go" or "no-go" decision on construction. The second phase would be to take a look at the soil profile and the subsurface geology. This is to develop enough data to substantiate a "go" or "no-go" decision relative only to an initial projected recharge rate for the site and for the period of recharge. The third phase would be a look at the recharge water quality. In this phase, develop enough data on the water quality parameters to substantiate a decision relative only to the affect on the projected recharge rate. A no-go decision would then require a feasibility study of the methods to control the unfavorable water quality parameters, such as for sediment control. Fourth would be the biological considerations. Develop sufficient data for the land and aquatic plants and animals to predict their effect on the recharge rate and the impact upon the surrounding urban area and to develop the biological control plans. At this point, which would be a pilot test basin or fifth planning phase, generate subsurface hydrologic information. At the conclusion of the pilot test basin, a fair "final" projected recharge rate should have been developed. The sixth planning phase would be the formulation of construction plans, and the seventh would be operation, maintenance and performance evaluation plans. Any future groundwater recharge facility must be environmentally acceptable to the general public as well as economically functional.

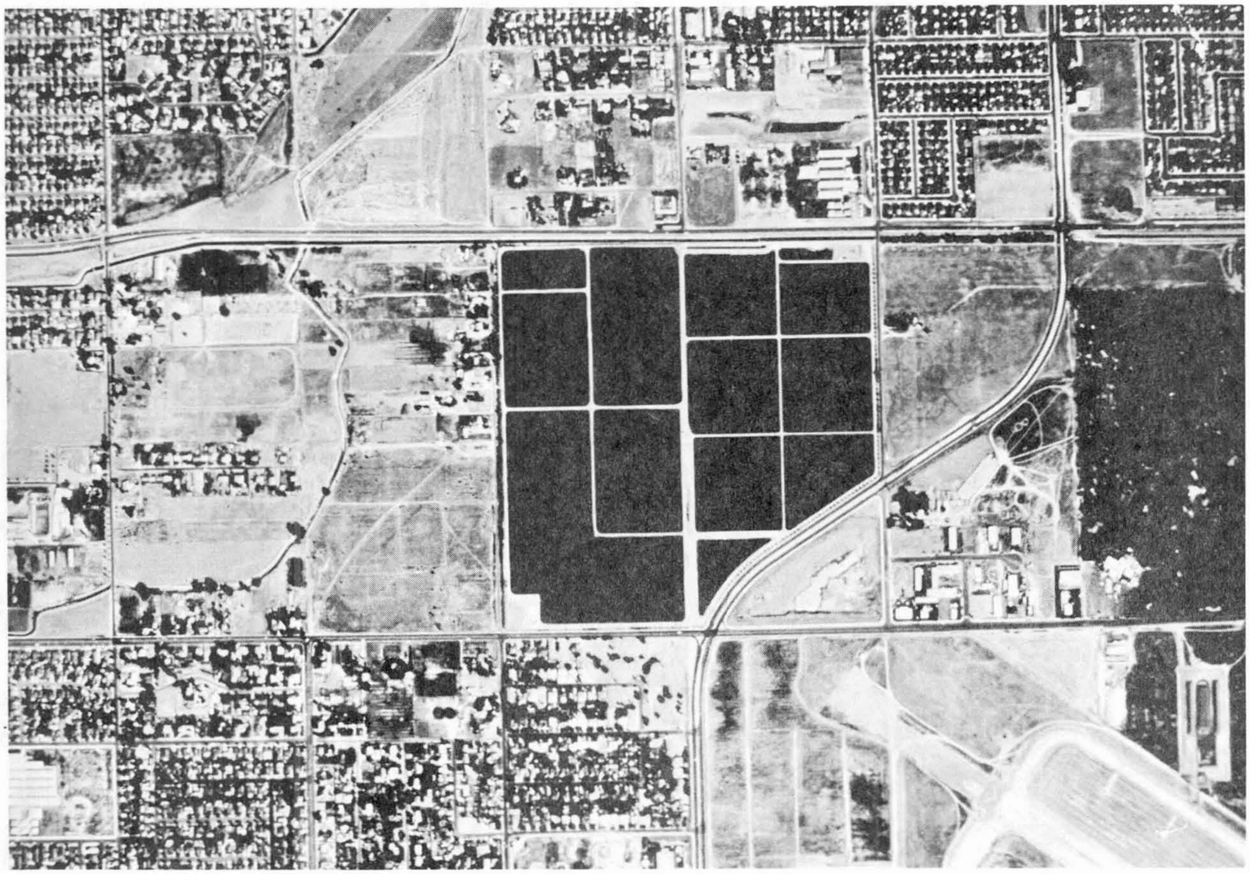


FIGURE 1 - AERIAL VIEW OF LEAKY ACRES

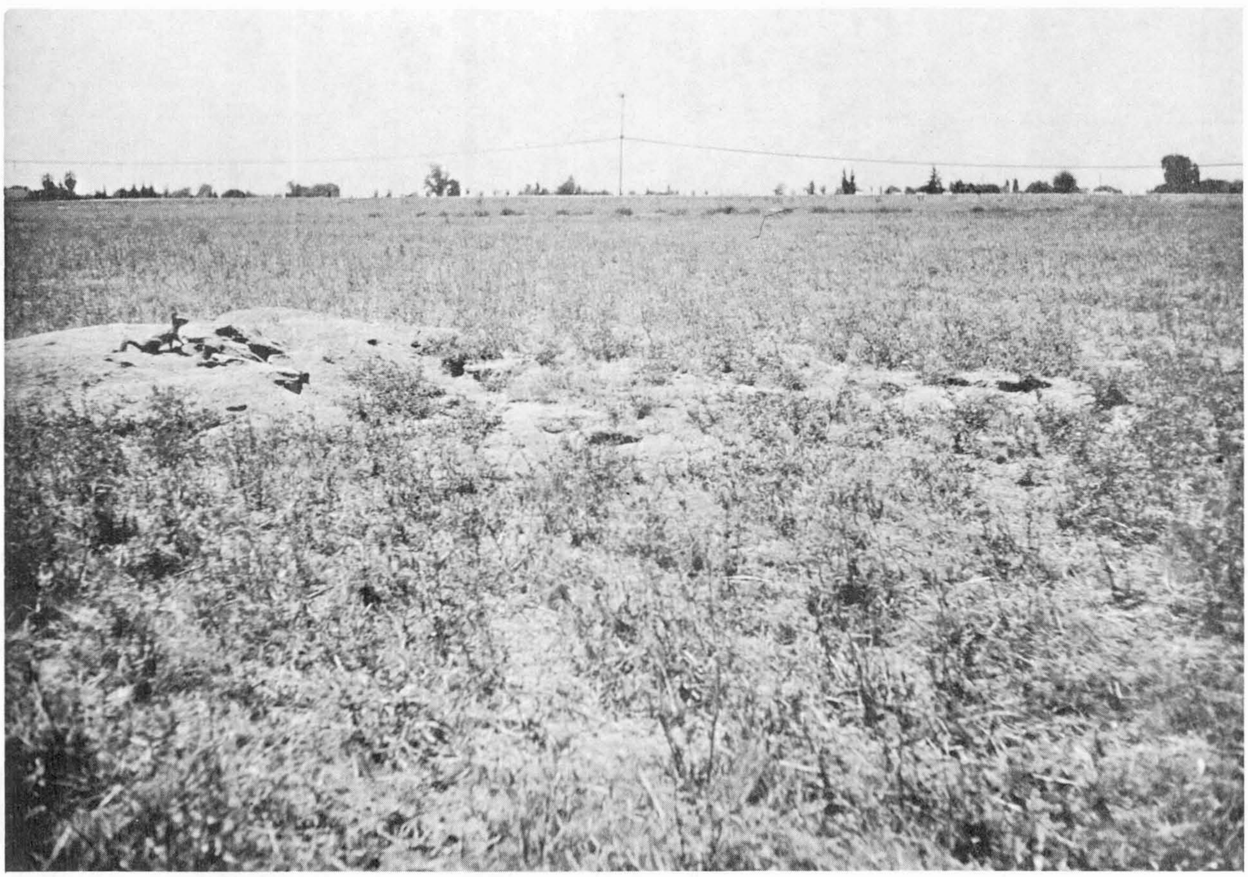


FIGURE 2 - VEGETATION IN EASTERN HALF OF THE RECHARGE SITE BEFORE CONSTRUCTION

FIGURE 3 - VEGETATION IN WESTERN HALF OF THE RECHARGE SITE BEFORE CONSTRUCTION

FIGURE 4 - GOPHER SNAKES ARE PRESENT IN THE AREA

FIGURE 5 - WATER IN THE RECHARGE BASIN FLOWING INTO A GROUND SQUIRREL HOLE

FIGURE 6 - BODY DISPOSAL PROBLEM IN RECHARGE BASIN

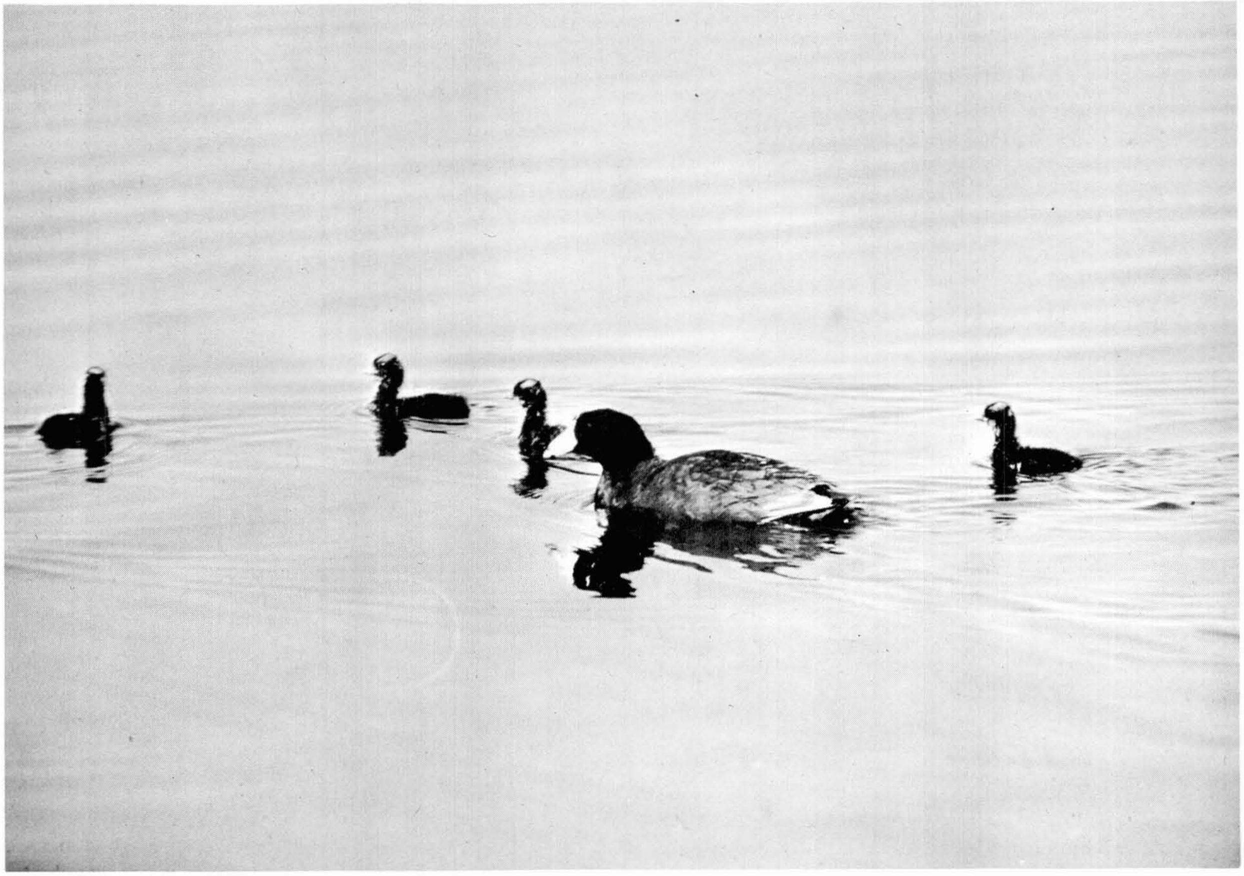


FIGURE 7 - AMERICAN COOT AND HER YOUNG

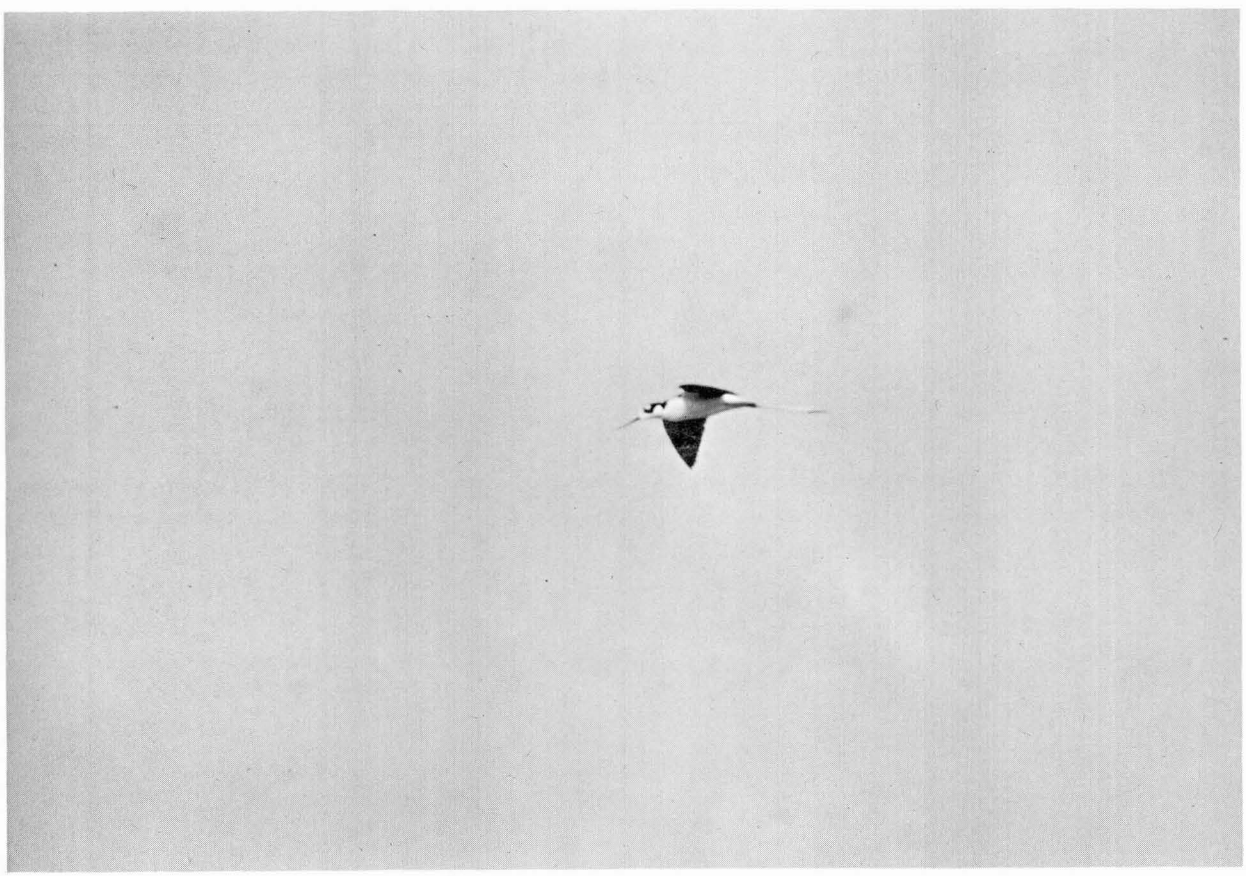


FIGURE 8 - BLACK-NECK STILT IN FLIGHT OVER RECHARGE BASIN

FIGURE 9 - BLACK-NECK STILTS AND JACKRABBIT AT LEAKY ACRES

FIGURE 10 - AMERICAN AVOCET

FIGURE 11 - MALLARD DUCKS

FIGURE 12 - LEAKY ACRES IS LOCATED WITHIN THE FLIGHT PATH OF THE AIRPORT

FIGURE 13 - MUSKRAT SWIMMING IN THE RECHARGE BASIN

FIGURE 14 - HEADLESS MUD HEN

FIGURE 15 - WEASEL THOUGHT TO BE THE CAUSE OF HEADLESS MUD HENS

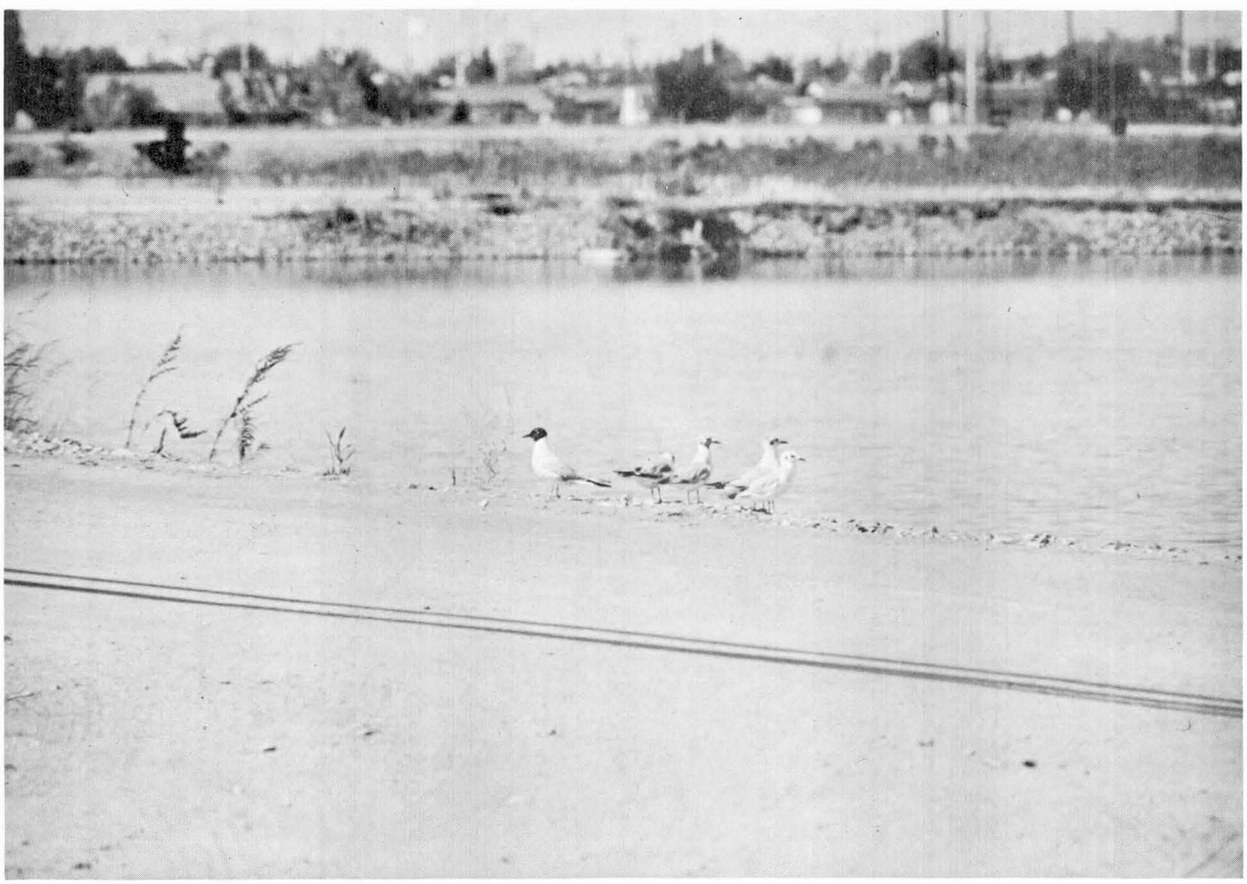


FIGURE 16 - SEA GULLS AT LEAKY ACRES

FIGURE 17 - WESTERN SANDPIPERS & GREATER YELLOWLEGS FEEDING ON INSECTS AND AQUATIC PLANTS

FIGURE 18 - DUCK LEFT HIGH AND DRY DURING DRAINING PERIODS

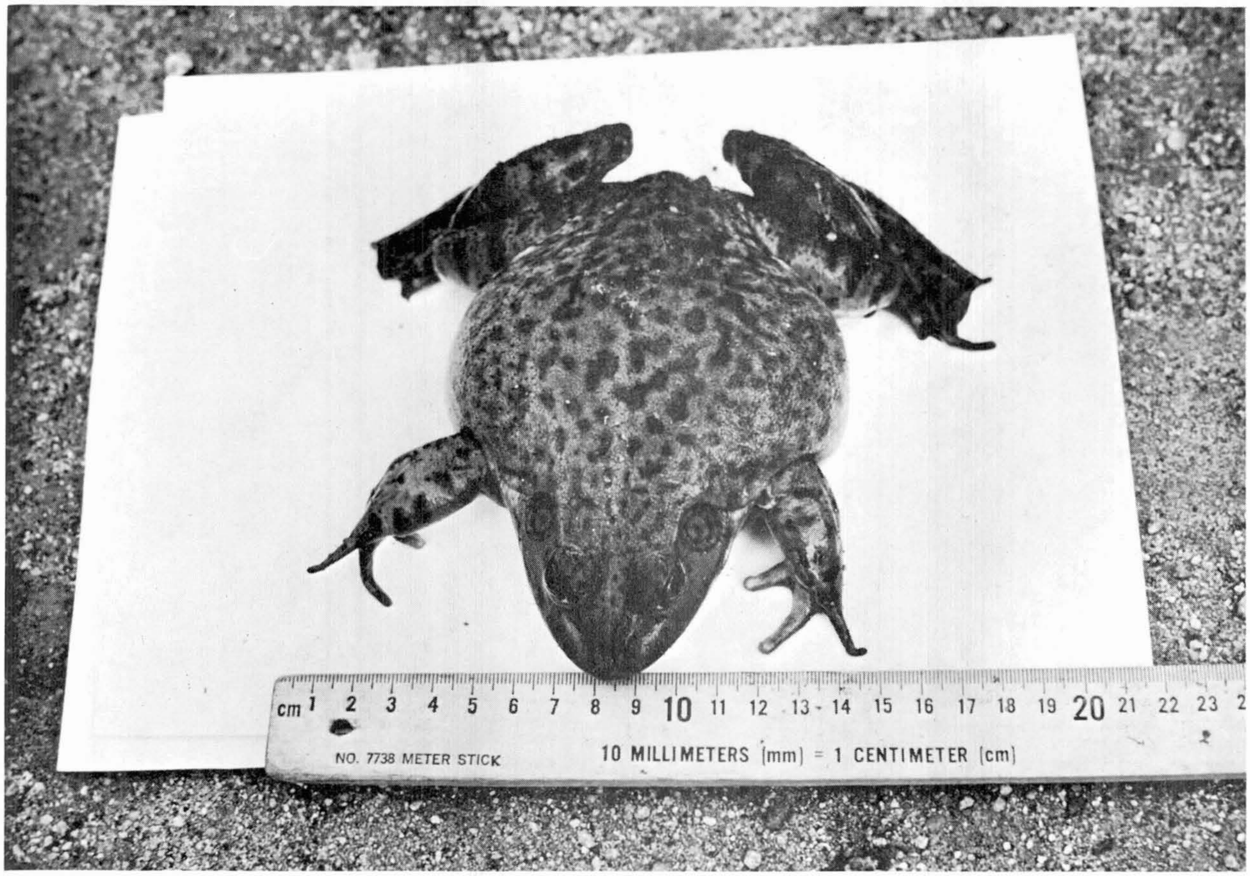


FIGURE 19 - BULL FROG SIZE AT LEAKY ACRES

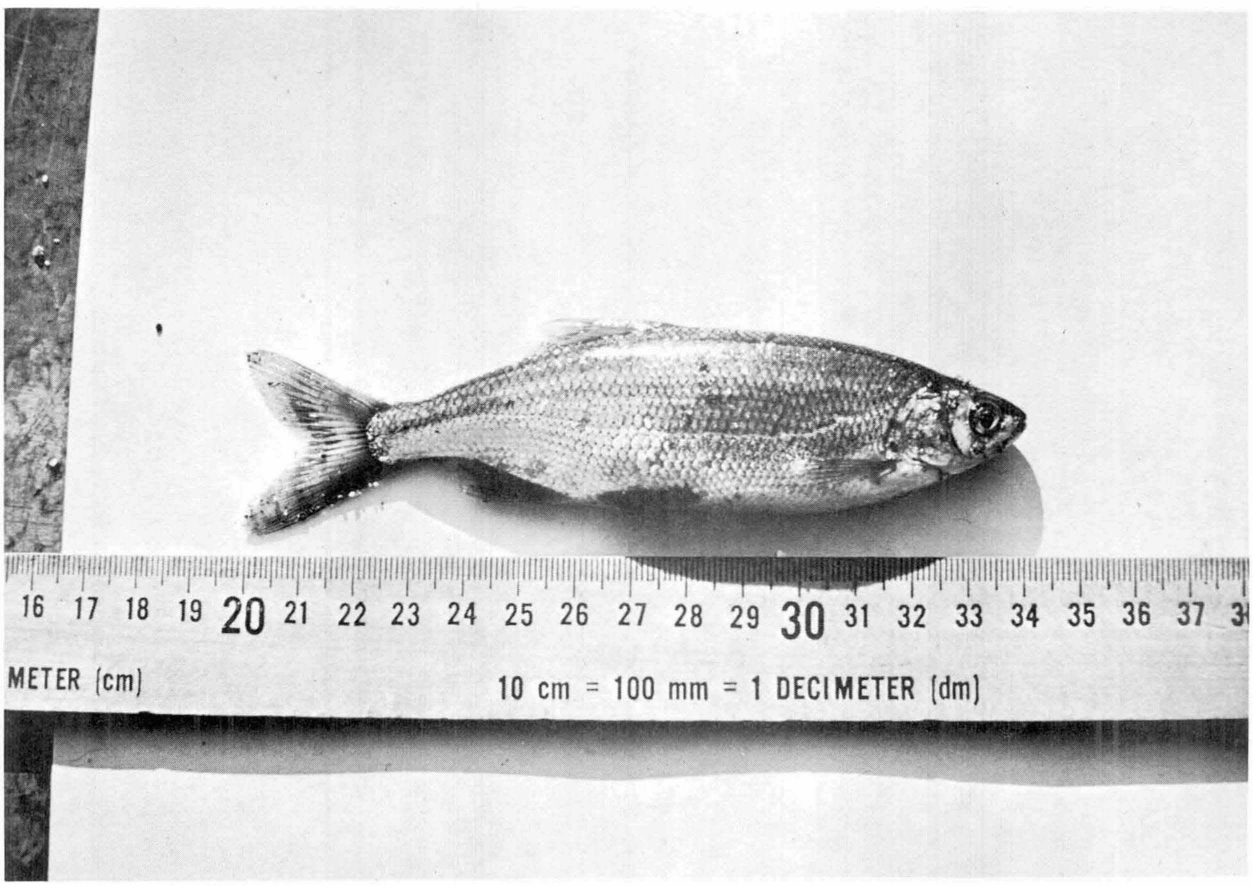


FIGURE 20 - GOLDEN SHINNER

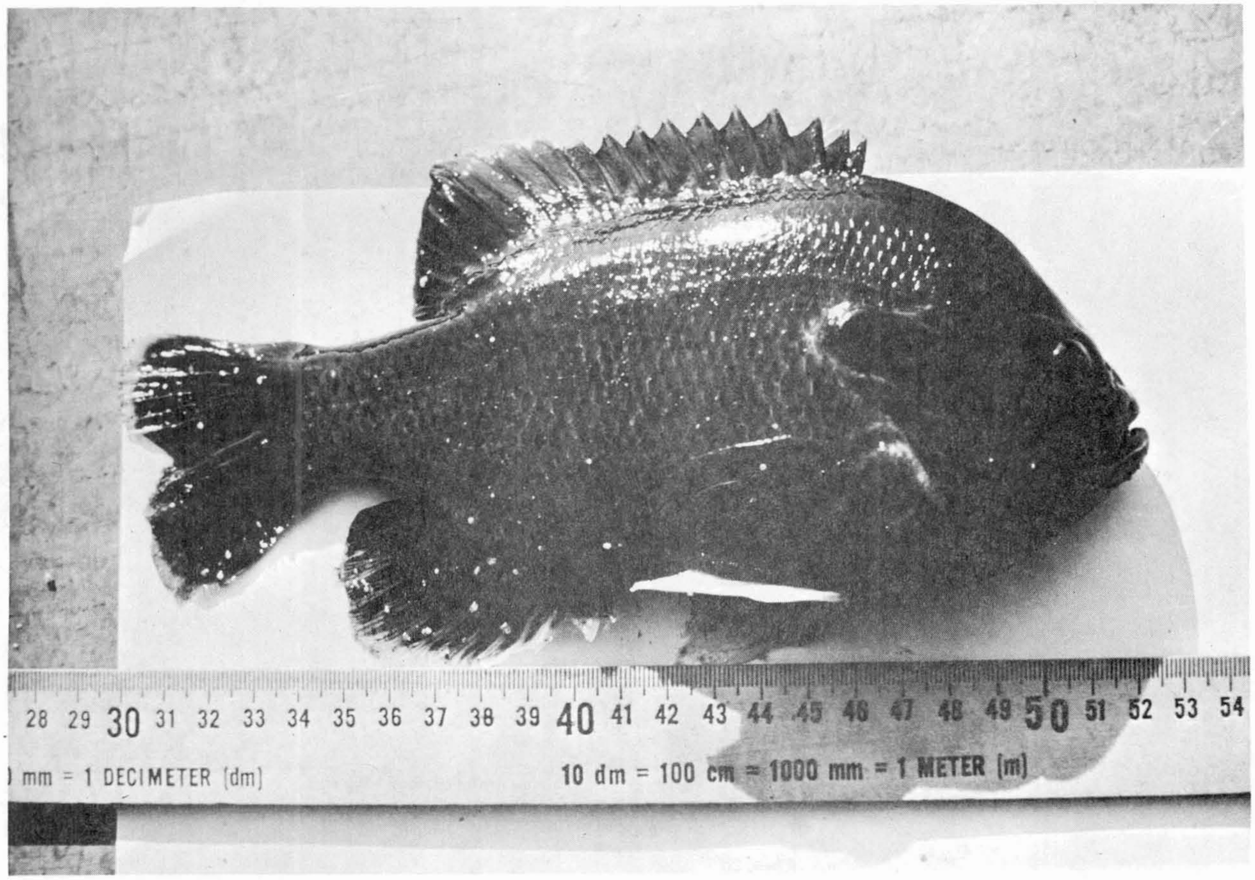


FIGURE 21 - BLUE GILL

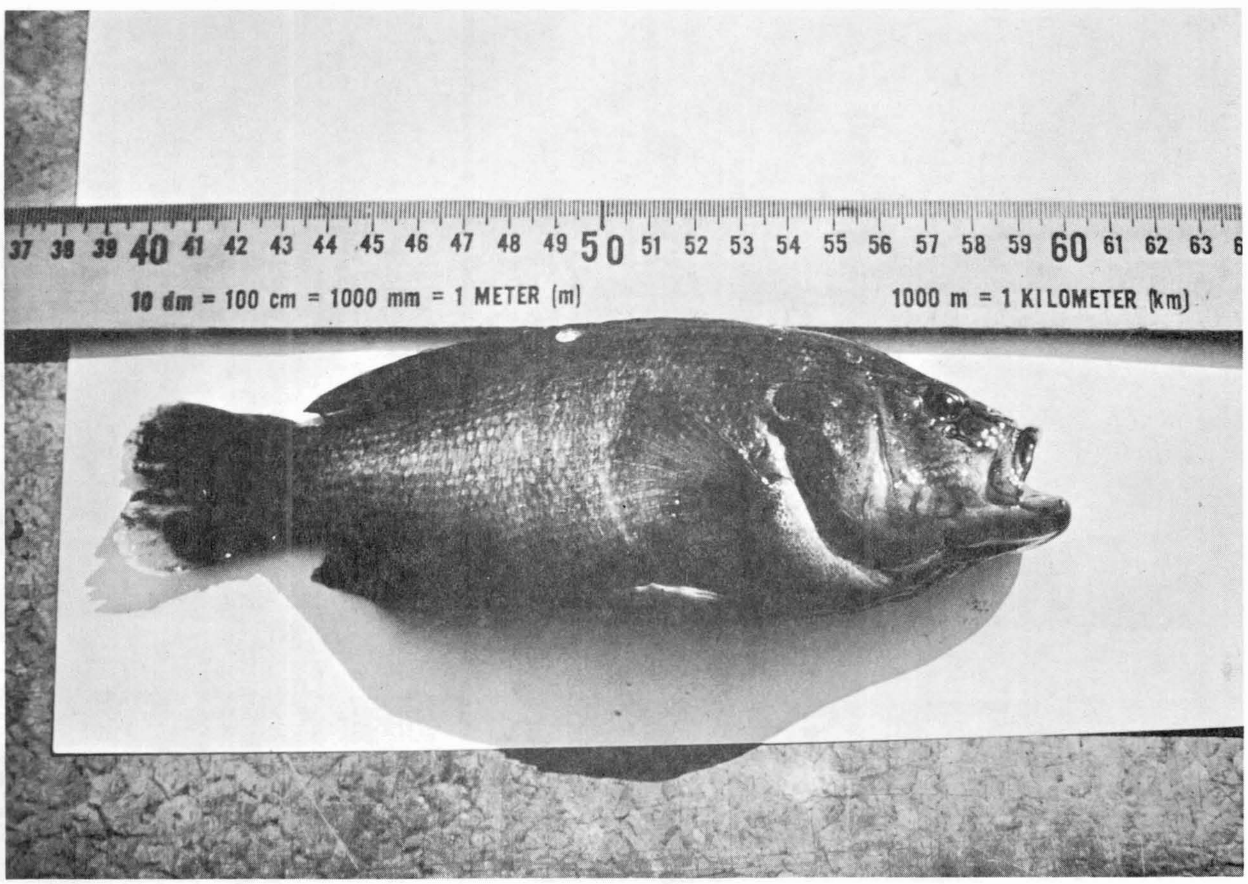


FIGURE 22 - SUNFISH

FIGURE 23 - LARGE MOUTH BASS AT LEAKY ACRES

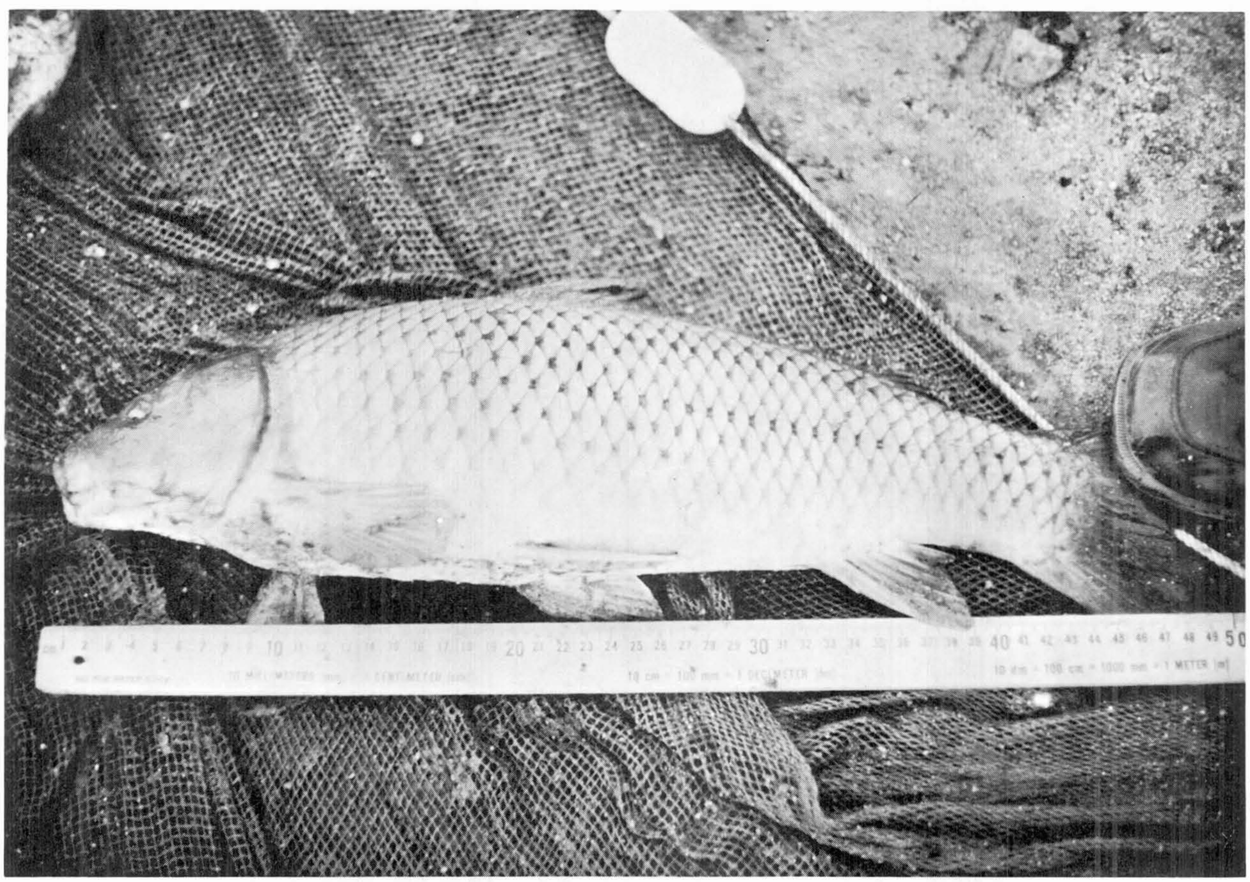


FIGURE 24 - CARP

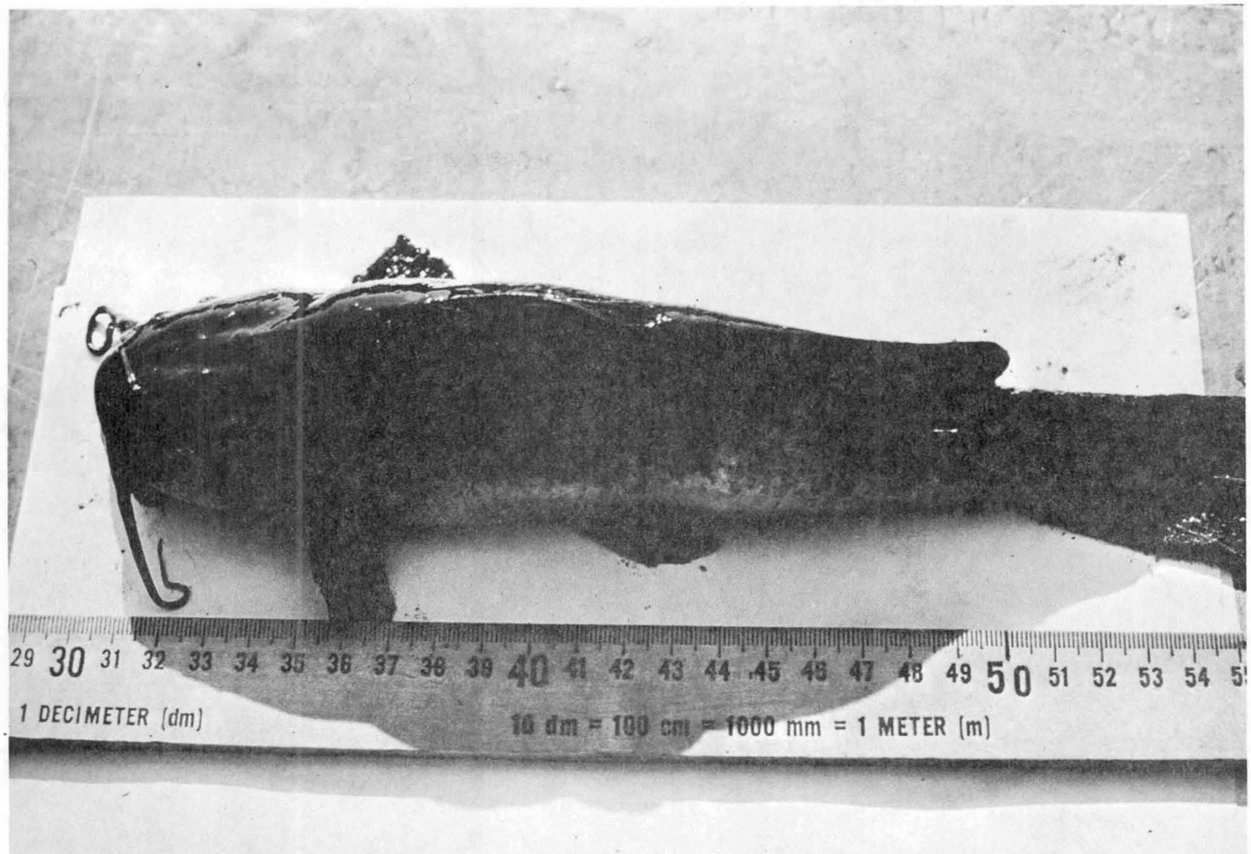


FIGURE 25 - BROWN BULLHEAD

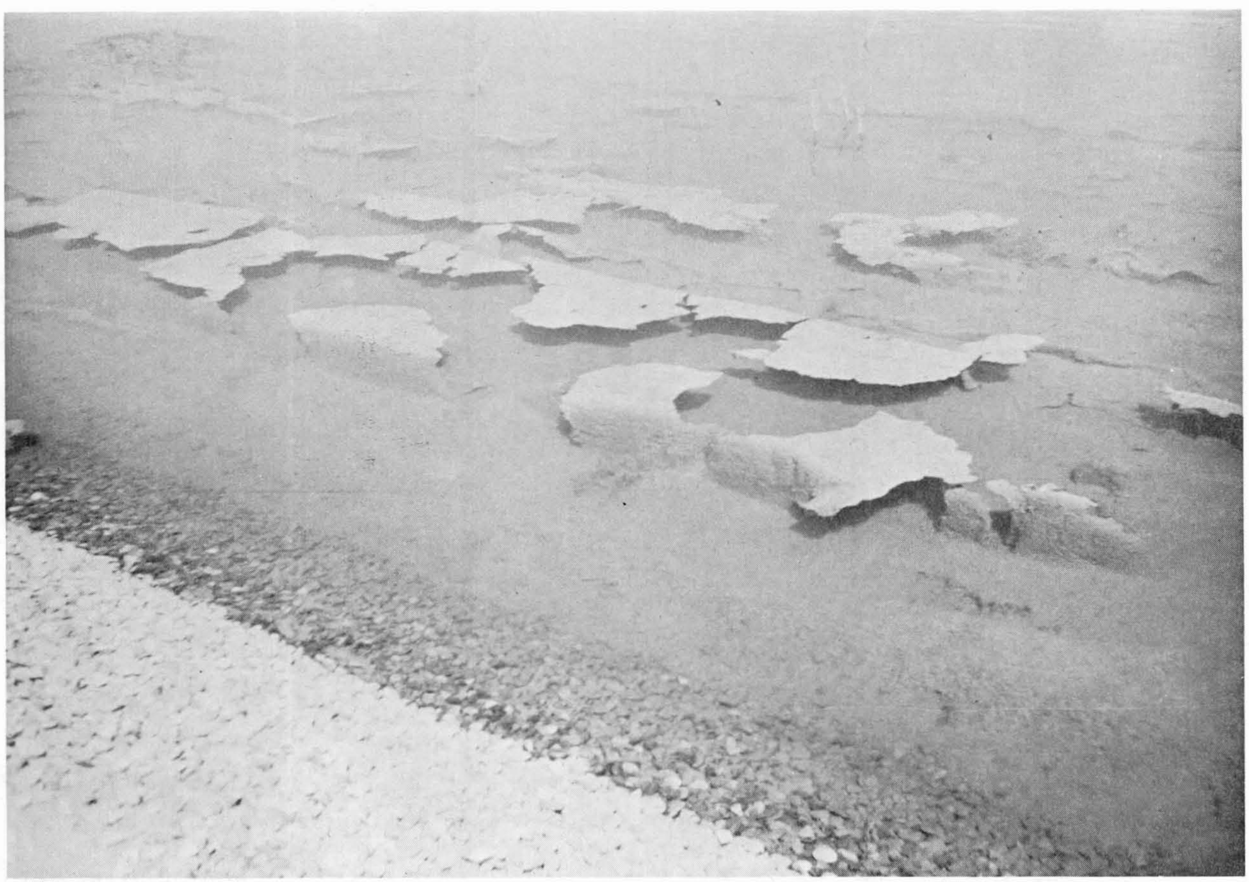


FIGURE 26 - ALGEA MAT RISING TO THE WATER'S SURFACE

FIGURE 27 - ACCUMULATION OF BOTTOM GROWN ALGEA

FIGURE 28 - ACCUMULATION OF ORGANIC MATTER

FIGURE 29 - SPIROGYRO IS THE MOST COMMON TYPE OF ALGEA OBSERVED AT LEAKY ACRES

FIGURE 30 - AQUATIC WEED PROBLEM

FIGURE 31 - CATTAILS IN THE UPPER BASIN

FIGURE 32 - MECHANICAL REMOVAL OF CATTAILS

FIGURE 33 - SAME AREA CLEARED OF CATTAILS

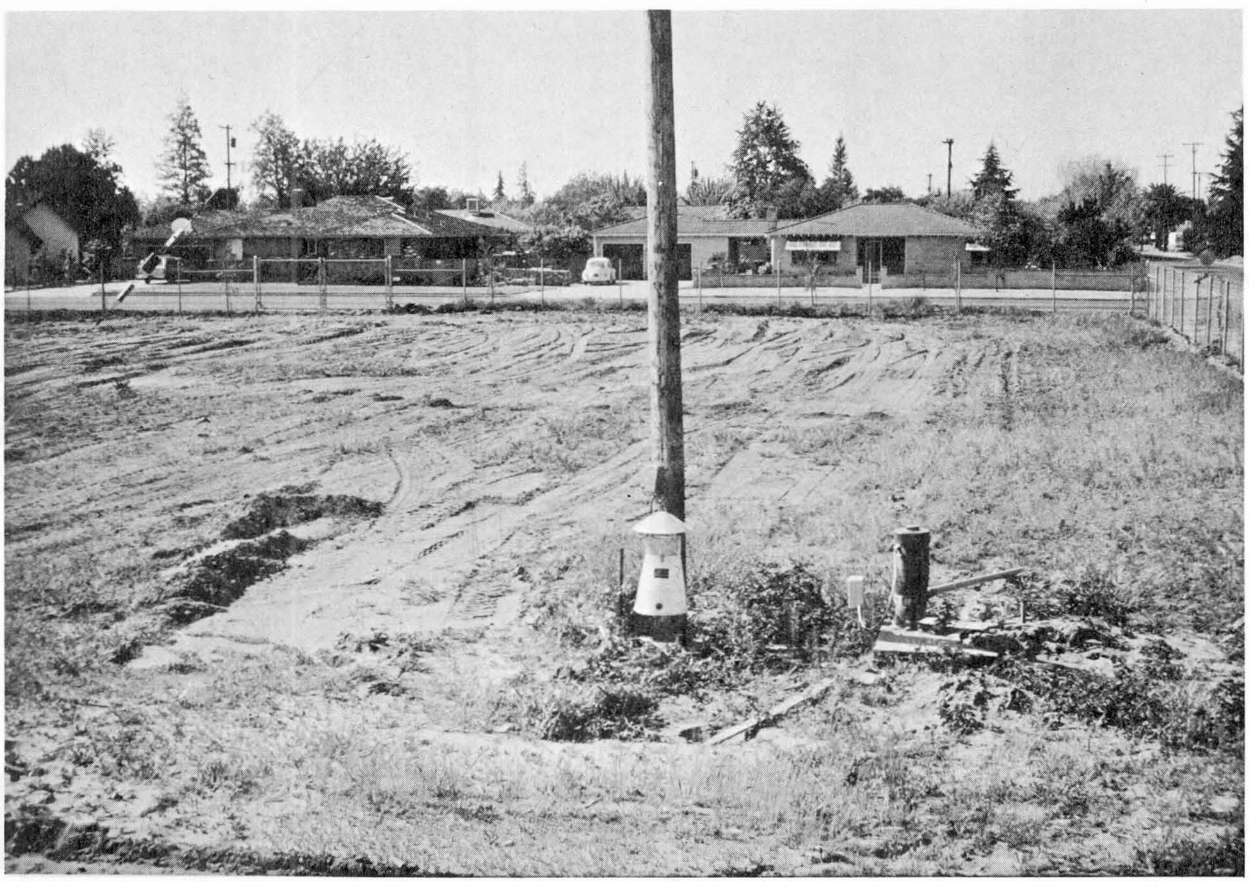


FIGURE 34 - LIGHT TRAPS USED FOR THE COLLECTION OF AQUATIC INSECTS

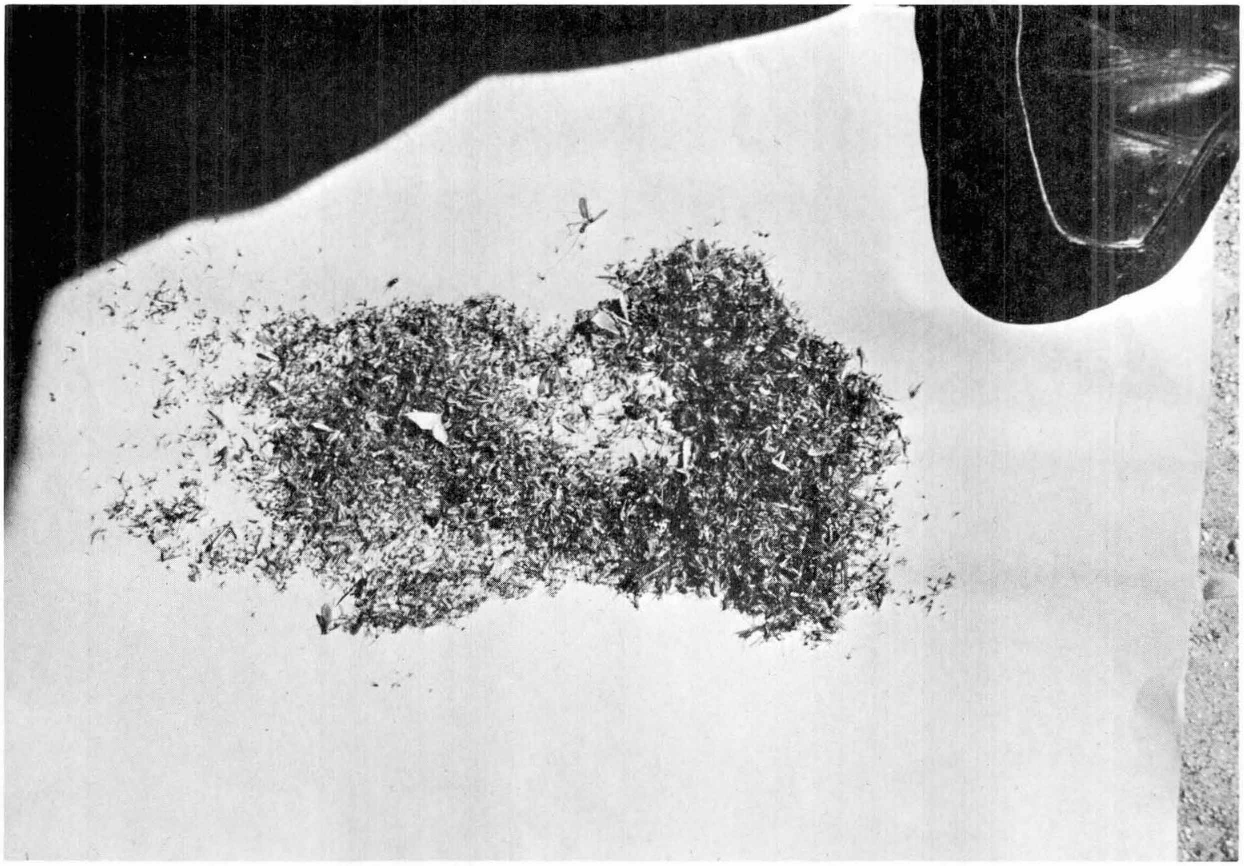


FIGURE 35 - ONE NIGHT'S CATCH OF INSECTS

FIGURE 36 - MIDGE CONTROL

FIGURE 37 - POTHOLES FOUND IN THE BOTTOM OF THE BASIN

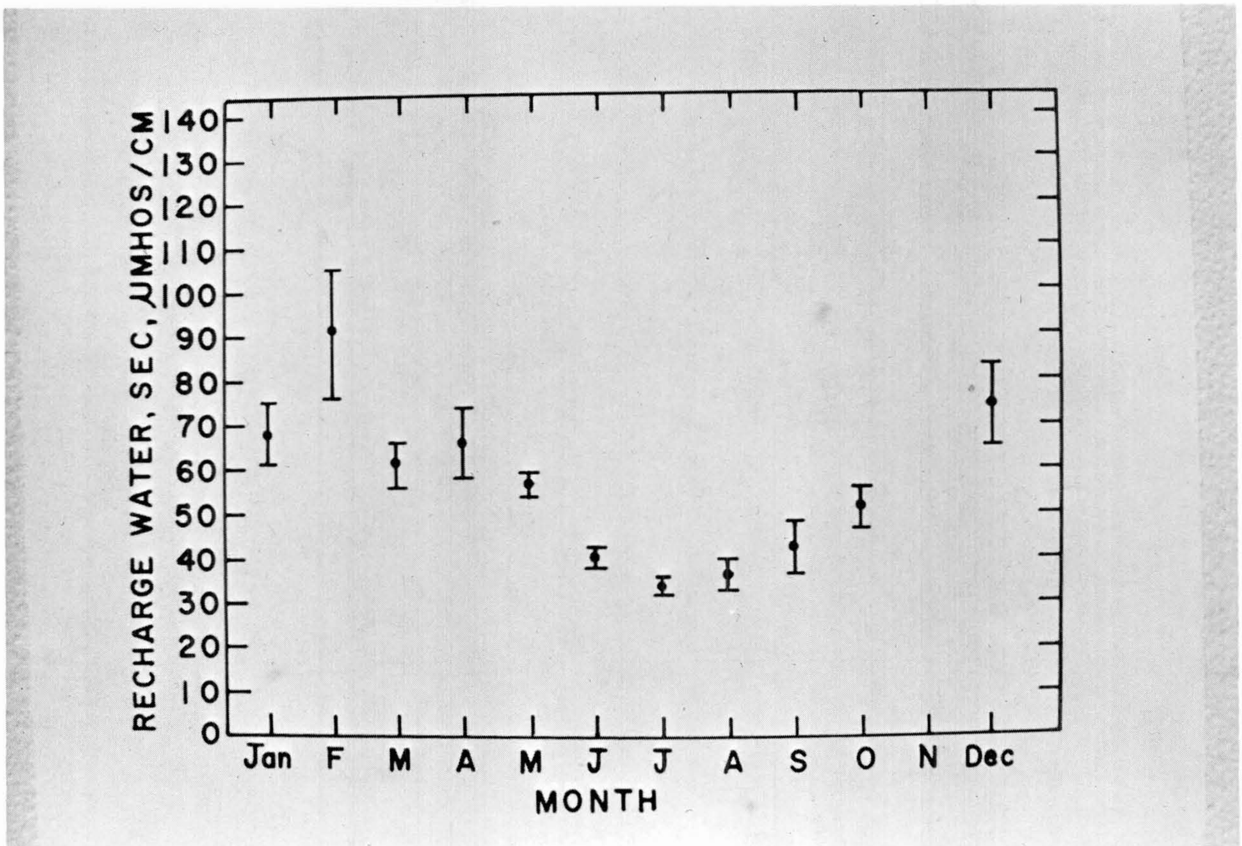


FIGURE 38 - SPECIFIC ELECTRICAL CONDUCTIVITY OF RECHARGE WATER

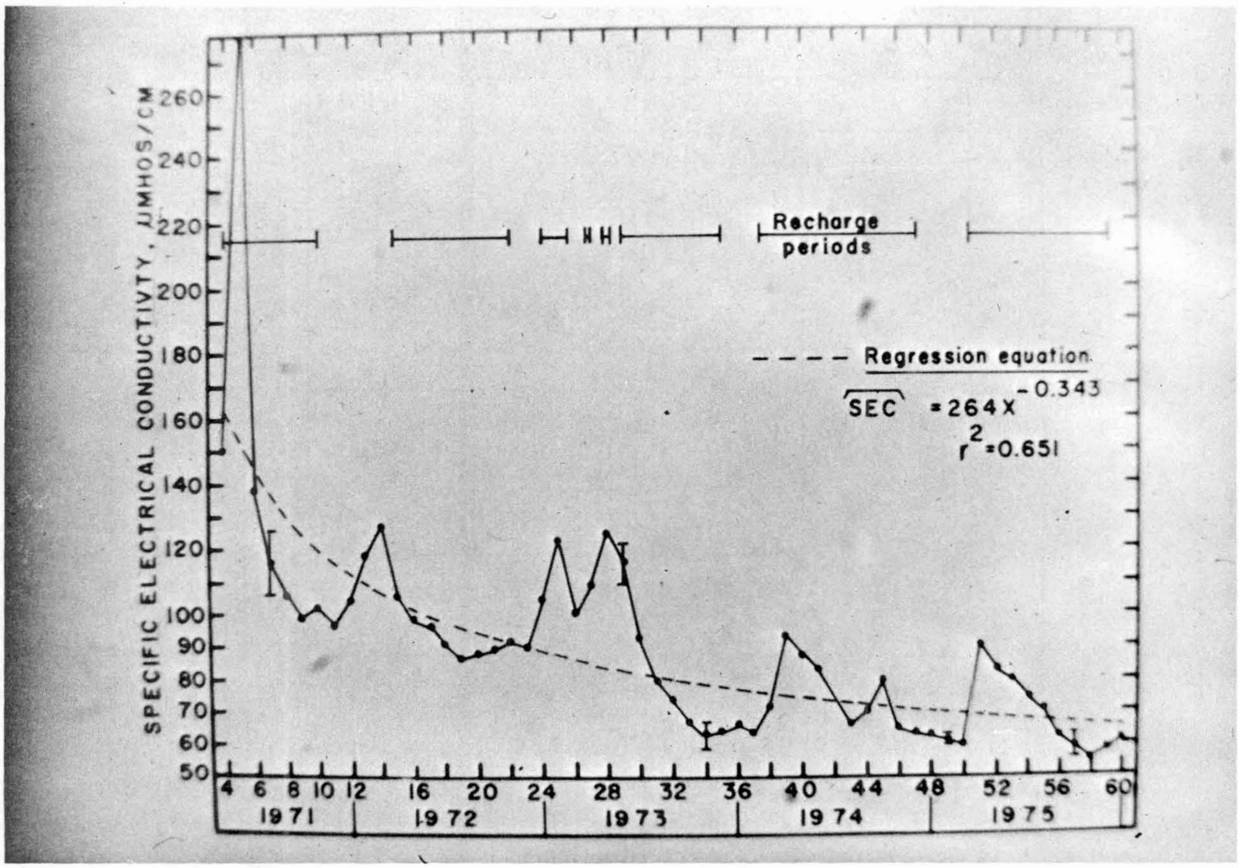


FIGURE 39 - GROUNDWATER SALINITY

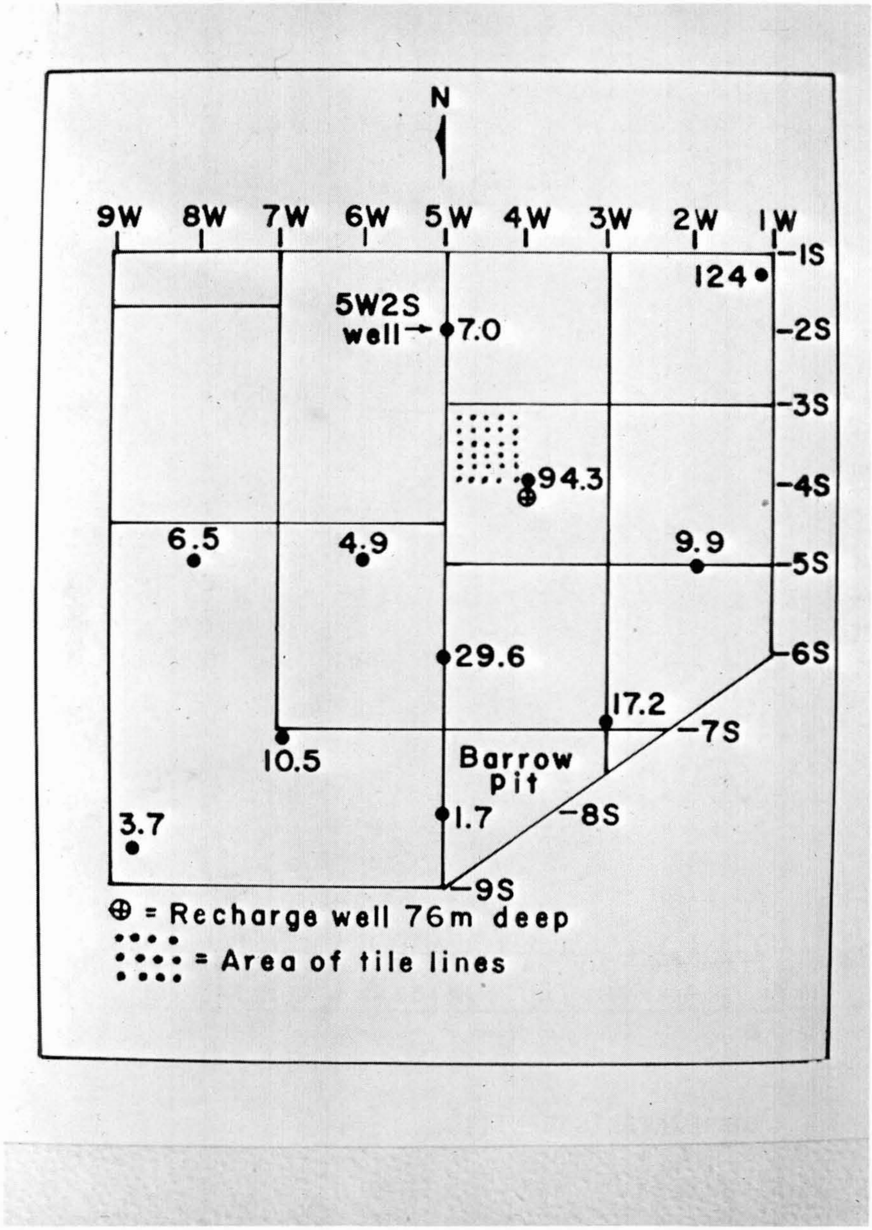


FIGURE 40 - AVERAGE TURBIDITY IN WATER QUALITY OBSERVATION WELLS

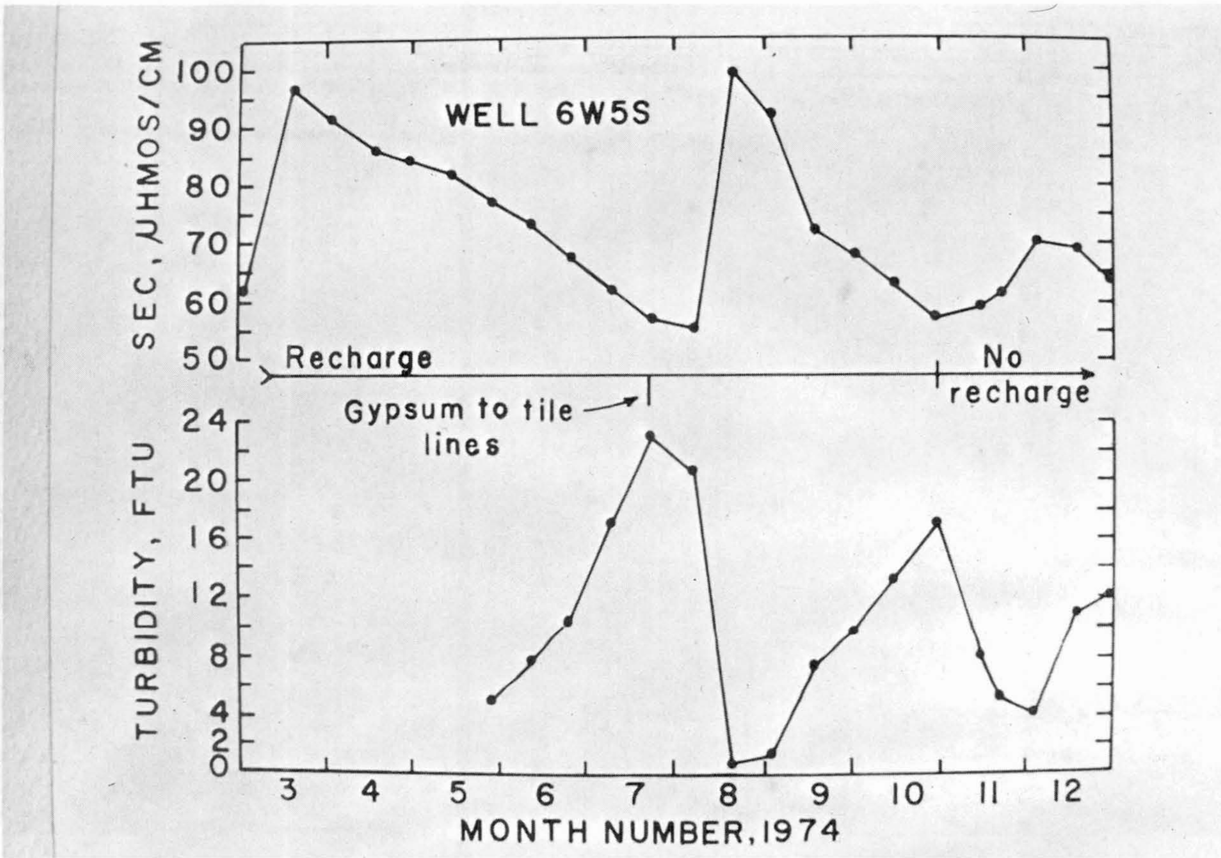


FIGURE 41 - SALT CONCENTRATIONS IN WELL 6W5S

FIGURE 42 - STORM WATER ENTERING THE RECHARGE BASIN

FIGURE 43 - TURBID WATER IN THE RECHARGE BASIN

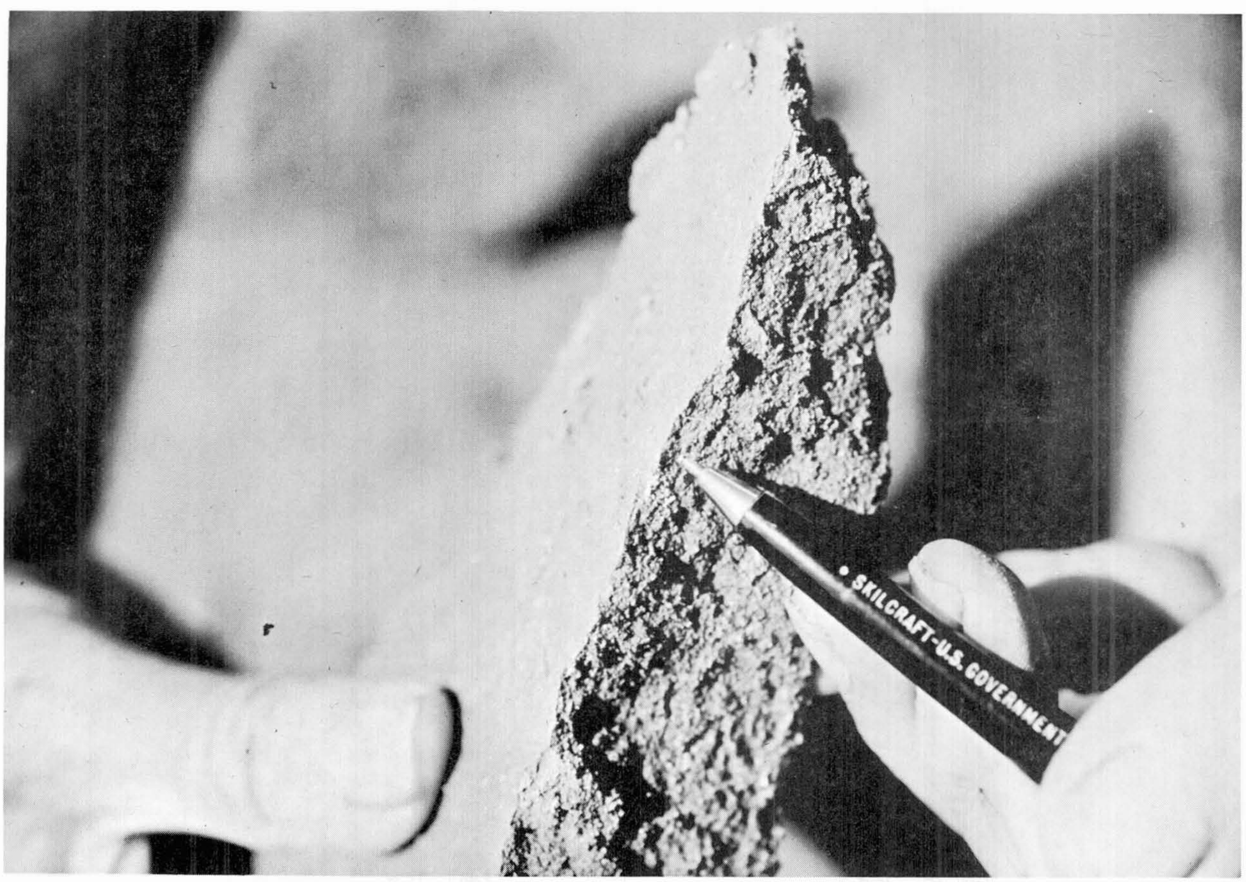


FIGURE 44 - SEDIMENT ACCUMULATION

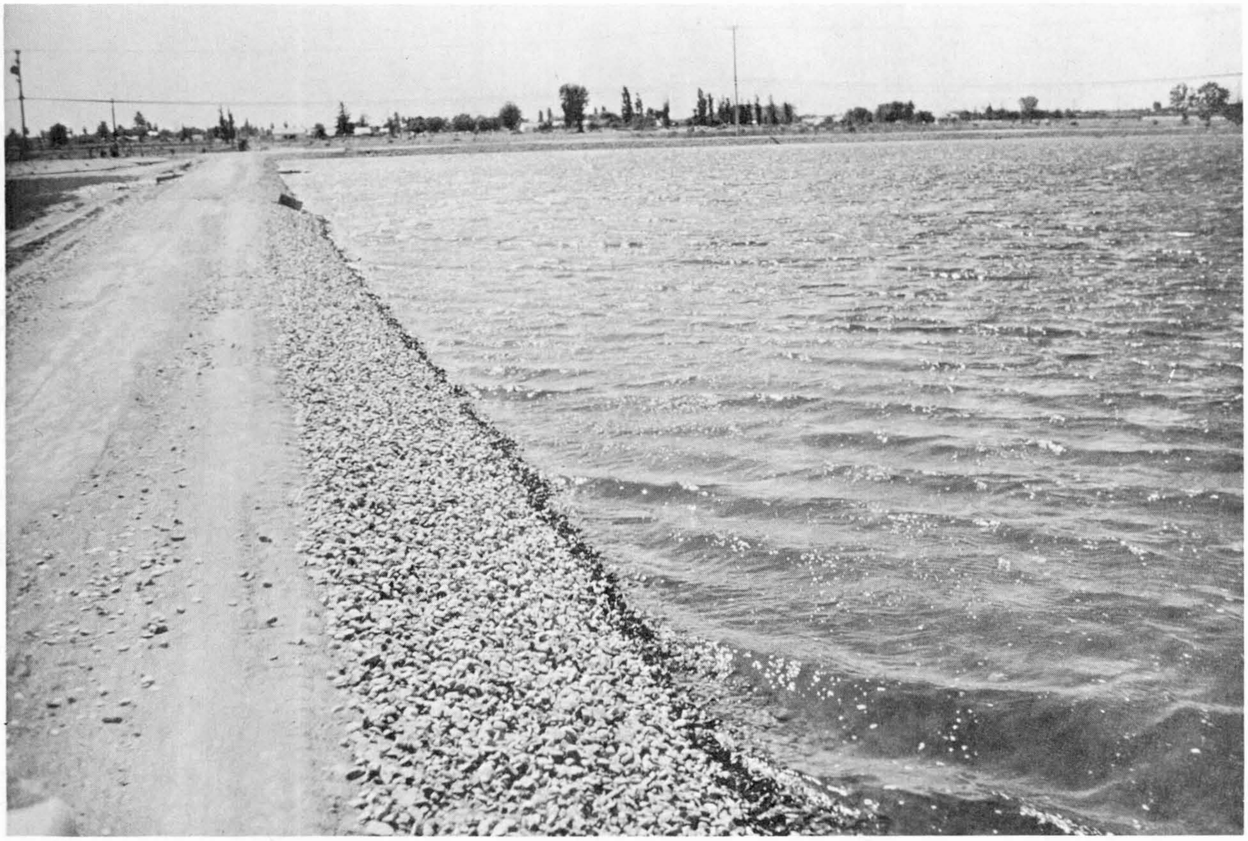


FIGURE 45 - CRUSHED ROCK USED AS SLOPE CONTROL

FIGURE 46 - FAILURE OF CRUSHED ROCK SURFACE

FIGURE 47 - GRADING CRUSHED ROCK UPHILL

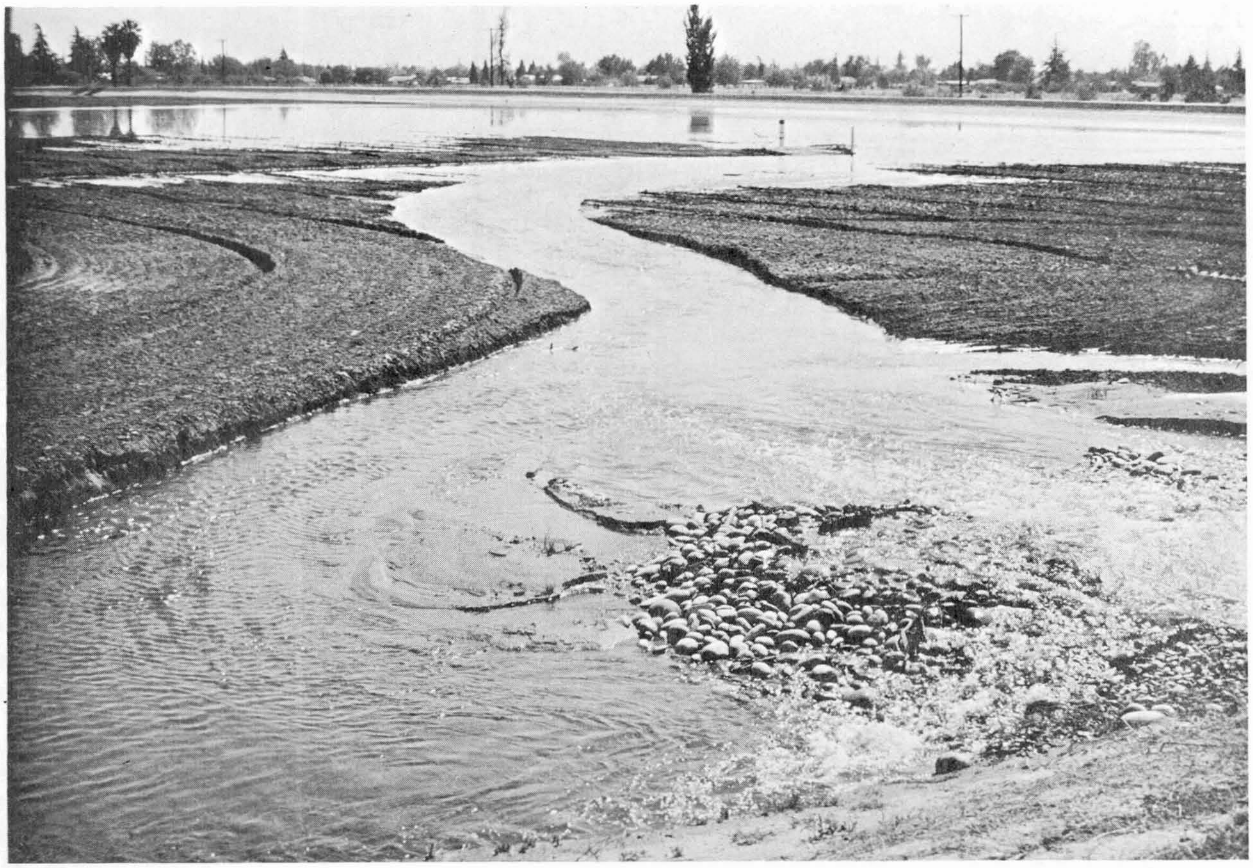


FIGURE 48 - BASIN SOIL EROSION DURING FILLING

FIGURE 49 - SOIL EROSION IN THE BARRON STRIP AREA

FIGURE 50 - HAZARD OF DRIVING DOWN NARROW LEVEES

AUTHOR'S BIOGRAPHICAL SKETCH

NAME: Tom Burbey

EDUCATION: B.S. Degree in Civil Engineering from the University of Wisconsin

JOB POSITION: Chief, Studies Branch of the Operations Division, Arizona Projects Office, U.S. Bureau of Reclamation, Phoenix, Arizona

EXPERIENCE: U.S. Bureau of Reclamation, Water Resource Planning-Hydrology, Grand Island, Nebraska

U.S. Bureau of Reclamation, Fryingpan-Arkansas Project, Pueblo, Colorado

U.S. Bureau of Reclamation, Central Arizona Project, Phoenix, Arizona

Served as chairman for the Regulatory Subcommittee of the Interagency Task Force on Orme Dam alternatives

U.S. Bureau of Reclamation representative on the Navajo Generating Station Engineering and Operating Committee

BACKWATER STUDIES OF HYDRAULIC STRUCTURES

by

TOM BURBEY

As many of you are aware, we are currently engaged in a period of major policy changes with respect to water resource development and utilization both here in Arizona and nationally.

On the local scene, there is the Groundwater Management Study Commission, which was established by the Arizona State Legislature last year, and charged with recommending revisions to Arizona's Water Code dealing with groundwater. And on the national scene, President Carter has been extremely active in Western water matters. First, through the water projects review early in 1977, and through his water policy announcements in June of this year and most recently by his veto of the Public Works Bill in October. The focal point of the efforts of the Groundwater Management Study Commission is to seek better, yet acceptable ways to control and manage Arizona's groundwater resources, to preserve this vital resource for future generations and to insure its efficient use. This same theme, Water Conservation and Efficient Use, is a central feature also of the President's water policy. So a renewed emphasis is being placed today on water conservation and, as all of you know, this was a subject that was brought into truly sharp focus in the droughts of 1976 and 1977.

I want to point out that the concepts of water conservation and efficient use of water, while very similar and complimentary in many cases, are not the same. Conservation in the present vernacular generally means reducing the depletion of a resource to protect it from being used completely, while efficiency refers to how well the resource is used, that is, producing the desired effect, but without waste. So efficiency is only one factor in conservation, and greater efficiency in water use does not necessarily result in conservation of water, particularly in the arid Southwest.

We have all heard the old saying that one user's waste becomes another user's supply. In fact, many efficient river basin systems, our own Salt River Valley included, depend on inefficiency within individual water user systems. The water users in the Salt River Valley annually withdraw about 2.7 times the volume of the dependable supply by recycling groundwater and by sequential use of return flows from inefficient water user systems. If we take the Phoenix metropolitan area municipal users as an example, these users generate a large volume of sewage effluent, which from the standpoint of the primary user, the urban dweller, is an inefficient use. But these effluent waters are not being wasted, they are being discharged to other water users: the Buckeye Irrigation District, the Fred J. Wiler Greenbelt, a fish hatchery, the Flushing Meadows Project and soon, the Palo Verde Nuclear Generating Station which will be using effluent waters as a source of cooling water. The net effect of all of this reuse is that from a basin prospective, the

Salt River Valley is an extremely efficient composite user of its water resources. Obviously, there are still some problems left and we can't rest at this plateau as much remains to be done in the area of water conservation. Groundwater recharge is just one of the several techniques that can assist us here in central Arizona in realizing a better balance between our water supplies and our ever-increasing demands for water.

Groundwater recharge, of course, is an ongoing and natural process in this area. Rainfall, crop irrigation and canal seepage all contribute in some measure to adding water to our underground aquifers. Infiltration of floodwaters along our normally dry stream beds is also a major source of natural groundwater recharge. In fact, our past experience has shown that the Salt River flood plain is a very effective infiltration and recharge medium. Our past experience also shows that there are some negative aspects to the status quo. Despite the rather large magnitude of ongoing recharge in the Valley, our groundwater tables continue to decline, and despite the porous nature of our river beds, at times we have large amounts of surface waters escaping our control and causing flood damages along their way.

So the existing order of things leaves us with some problems. In addition to flood damages, there is recharge taking place today in areas where it is neither welcome nor desirable. I am sure many of you are aware of the situation that exists below Painted Rock Dam in the Wellton-Mohawk area. So the idea of recharge as a water resource management and conservation tool is not only to increase the amount of ongoing recharge, but also, to redirect it to when and where it will do the most good. It is this redirection of the ongoing process that means that we have to intervene in some way in the present order of things. Changes have to be made if we are to receive the maximum benefit from artificial recharge. As we heard yesterday, some of these changes might be political or institutional and obviously some physical on-the-ground changes also have to be made.

First, we ought to take a look at where we are today. Since 1966, on four separate occasions, significant quantities of surface water have spilled past the Salt River Project diversion works. We heard yesterday morning a few of the statistics and facts about those spills or surplus releases. During March of this year, over an eight-day span, more than a half a million acre-feet churned down the Salt River as a result of several days of very heavy rains over the state. In the spring of 1973, a major snow melt event occurred which brought approximately 1.2 million acre feet through the Phoenix area over a four-month period. In 1968, while only a moderate runoff year, the storage reservoirs in the Salt River system were virtually full, much as they are this year, and over a hundred thousand acre feet were dumped into the Salt River in several sporadic discharges over a three-month period. And then, in 1965 and 1966, a three-month period of wet channel conditions resulted from heavy rains, and another half a million acre feet was effectively wasted to the Salt River channel. So, since 1966, just the last twelve years, in excess of two million acre feet of surplus Salt and Verde River runoff has been discharged to the Salt River channel.

The question is, what has happened to all of this surplus water? Well, somewhat more than half of it has reached Gillespie Dam, which is a diversion structure on the Gila River some seventy-five miles downstream, and effectively flowed out of our Valley. The remainder has either infiltrated, becoming natural recharge, or has been lost to evapotranspiration. So we do have a large and significant amount of ongoing recharge from flood waters today, but to achieve this measure of recharge from our surplus waters, we have also had to pay a price. We have suffered untold millions of dollars in property damage as one way in which we pay for our natural recharge. Another is the snarl of air and surface transportation traffic that occurs each time the river flows.

Changes need to occur. Changes which can reduce the cost that we have to pay for natural recharge, and changes which can hopefully convert the destructive forces of floods into positive useable water supplies.

It is quite clear that here in Central Arizona, we are confronted with a water dilemma. On the one hand we have an overall need for more water, and on the other hand we have a periodic need for less water as the recent Phoenix area floods so clearly demonstrate. The antithesis to less water on a periodic basis is that we need, at a minimum, better ways than exist today to control floodwaters and hopefully to conserve them. There are some people in Arizona that view groundwater recharge as the obvious and utopian solution to this water dilemma, and their thinking goes thusly; we have these occasional surplus surface waters escaping our primary storage and diversion systems resulting in flood damages. But we also have groundwater aquifers which are being depleted at a much greater rate than which they are being replenished. So why not attack both of these problems with a simple single solution? Just recharge the surplus floodwaters; this will raise the levels of our groundwater aquifers, we've conserved these floodwaters for future use, and at the same time we've reduced or eliminated the amount of excess surface flows and reduced flood damages. After hearing the number of very excellent speakers that we heard yesterday, I hope that most of you have gotten the impression at this time that it isn't all that easy.

I would like to interject at this point that I don't view the purpose of our being here this week as to discredit artificial recharge or the destruction of a utopian recharge dream. I do view our purpose as being to inspect the idea of groundwater recharge from several different perspectives so as to better define what an appropriate role for groundwater recharge might be in resolving our water resource problems. I personally believe that artificial recharge can assume a major role in Arizona's efforts towards improving water conservation so as to better manage the limited available water resources. I further hope that this symposium will lead all of you to a better understanding of groundwater recharge and how it can best fit into the overall solution to our multi-faceted water resource problems.

When Mr. Teeples first contacted us to ask the Bureau of Reclamation to furnish a speaker at this symposium, we had very little idea of the make-up of the overall program and just how backwater studies might fit in. After I received the symposium program, I, quite frankly, had even less idea of how I was going to relate this topic. Part of the problem is that I found that none of the speakers that preceded me was to discuss or define a plan for implementing artificial recharge in the Salt River Valley. This left me with no established framework to fit backwater into, and I also have a very strong feeling that backwater studies of hydraulic structures is not necessarily a self-explanatory subject. As it might need a little clarification, I should probably start at the very beginning.

A hydraulic structure is nothing more than a water control structure. Some typical kinds of water control structures of which all of you are familiar are storage dams or flood detention dikes or diversion dams. And backwater relates to a very common problem in open channel flow or in rivers. The basic idea of backwater is that of determining the influences of changes in a river channel or a water conveyance structure on the depth to which water will flow in that channel under given discharge and channel conditions. The Salt River channel through Phoenix is normally dry, it has an alluvial bed and banks and undergoes numerous changes from year to year. Being dry much of the time, the channel is used for various purposes; one of the more insignificant ones is carrying water. Its flood plain is being constantly modified by landfill operations, by vegetative growth, by the construction of bridges and roadways and other obstructions, and by the removal of sand and gravel. Also, the alluvial nature of the Salt River channel puts the bed of the river in constant motion. Many channel modifications occur between flow events. Each of these changes in some way alters where and how the water will flow.

Those of you who live in the Valley and are familiar with the Salt River can testify to the fact that during the flood of March 1978, there were significant changes in the apparent size and shape of the Salt River channel. These facts tend to underscore the need to know what may happen to the flow-carrying characteristics of the river channel if we plan to make major modifications to it for accomplishing artificial recharge, and thus the need to conduct thorough hydraulic or backwater analyses in relationship to such a proposal. Earlier I defined backwater studies as a common problem in river hydraulics. As such, there are a number of textbooks and handbooks all readily available which detail and define the theory, processes and the equations for conducting backwater studies. Considering the hour, I don't feel there is any need to bore you with all of the technical aspects or jargon. I also said that backwater is simply determining the depth of flow in the channel under certain discharges and channel conditions.

So if we were to take the Salt River channel as it exists today, as an example, we might find that under a discharge of say one hundred thousand cubic feet per second, the depth of flow at some point X in the river channel might be ten feet, and the depth of flow at some downstream point Y might be two feet. We would find by applying our knowledge of river channel hydraulics that the depth of flow at point X in the channel is dependent to a great extent on the size and the shape and the stability of the channel and flood plain at that point. We might find however, that the depth of flow at point X is also dependent to a great degree on the depth of flow that exists down stream at point Y. That is to say, the depth of flow at any given point along the channel is not only dependent upon the channel characteristics at that point, but may also be dependent on channel conditions on downstream. To better visualize this, we can think in terms of having a flowing river and suddenly plunking a dam down in the middle of that channel and what the influences of that dam might be on the flow regime at several upstream points. So, if we are to impose a major channel modification at our point Y, we might find that the depth of flow which, in my example, previously was two feet may now increase to eight feet, while the depth at upstream point X may have changed from ten to twelve feet, despite the fact the channel has not changed at point X.

It is this upstream propagation of altered flow depth that we attempt to analyze in conducting backwater studies. With respect to the theory of open channel hydraulics, it is generally true that the depth of flow increases as the area available to pass the flow is either reduced or obstructed. Therefore, we must exercise great care in choosing the kind of recharge facilities and where they will be located in order to avoid creating a greater problem upstream of these facilities than may already exist.

Before it is possible to evaluate hydraulic implications of our proposed channel modifications, we should have some idea of what those modifications are; what are the options, and what are the plans. A partial conceptual plan has been developed by the Corps of Engineers, and later on this morning you will be hearing more about the Corps of Engineers' efforts and their future program for continued studies of the feasibility of artificially recharging the local groundwater system. In essence, the Corps of Engineers' proposal calls for the construction of infiltration ponds within the flood plain of the Salt River below Granite Reef Dam near Mesa. This would be in the area adjacent to the Salt River Indian Reservation. The reasons for selecting this area on a preliminary basis are some of the very reasons you heard yesterday, available storage capacity in the underground aquifers, a permeable medium with which to recharge or infiltrate the waters, these types of things.

The proposed infiltration ponds would be capable, based on the Corps of Engineers' preliminary estimates, of infiltrating up to two thousand cubic feet per second of water into the underlying aquifers and would occupy approximately twelve hundred acres of the flood plain area. This equates roughly to two square miles of land area, and about four thousand acre feet per day of infiltrated water. The plan does not identify the source of water to be recharged or how it is to be controlled, and both of these are very vital pieces of information for determining backwater effects, and also in assessing the ultimate feasibility of recharging the local groundwater. But if the source of water is to be the surplus flows of the Salt and Verde River system, there must be a way provided to separate and control that portion of the flow to be recharged.

The most obvious method that comes to my mind to do this, but not necessarily the best way, would be the construction of a diversion dam immediately upstream of the proposed recharge area. Such a diversion structure would likely be similar in size and height to the Granite Reef Diversion Dam. Granite Reef is a concrete structure with a hydraulic height of eighteen feet and a total crest length of eleven hundred and thirty feet. Its purpose is to raise the water level in the Salt River for diversion into the main water conveyance canals on both sides of the river. The flows in the Salt River which exceed the capacity of the canals go past the dam and into the normally dry channel downstream and become the surplus waters which we might consider as being eligible for recharge.

A plan then, could be the construction of a new diversion dam across the Salt River channel below Granite Reef Dam, sufficiently high to direct the water out of the channel and into the recharging ponds to be located along the flood plain.

This plan would result in two major modifications to the existing flood plain. The new diversion dam itself would be an absolute blockage of the natural channel, which would force floodwaters up and over it in order to proceed downstream.

The second major modification would be from the recharge ponds themselves. These ponds might consist of low earthen dikes or berms within the flood plain which have the effect of reducing the area available to pass floodwaters. The backwater effects of both of these channel changes would need to be thoroughly studied to understand not only the upstream implications, but also to allow proper and safe design of the recharge facilities themselves. It would appear that the backwater effects from the ponding dikes, by themselves, would probably be of small consequence. A new diversion dam, however, could present several rather major problems. There is a possibility of innundating several square miles of the Salt River Indian Reservation lying between the river channel and the Beeline highway. There is also potential impact on the stability of the downstream banks of the South Canal. Neither of these potential problems is insurmountable, and either of them could be handled quite easily in an engineering sense, but to protect against them would add cost to a recharge project.

As an alternative to a new diversion dam to supply water to the recharge area, the Corps of Engineers identified three other possiblities, all of which would make use of the existing Granite Reef Dam, thus eliminating some of the backwater problems I just mentioned. One of the alternatives would be the enlargement of one of the existing canals, the Arizona and/or the South Canal between Granite Reef Dam and the proposed recharge area. This would also involve, however, the reconstruction of the headworks at Granite Reef Dam to increase the capacity and would require the installation of new control gates, hoist motors and similar equipment.

The second option might be construction of a new, separate canal from Granite Reef Dam to the recharge area. This option would also require the reconstruction of at least one of the headworks, or the installation of a whole new one at Granite Reef Dam. The third alternative involves construction of small collection berms across the natural river channel to direct flow out of the river channel into the pond areas. It would appear that sufficient releases could probably be made through the existing sluicegates of Granite Reef Dam without other modifications. But a source of supply other than floodwaters would be needed to make this plan workable since all these small collection berms would wash out very quickly during any flood period.

The Corps of Engineers' preliminary study was largely conceptual and it does not develop or display cost estimates for accomplishing any of these options, and I haven't gone that step either. But several obvious costs would have to be incurred to put an artificial recharge plan into effect. Irv Sherman, yesterday, gave us an excellent laundry list of the types of costs involved in operating a recharge type of situation. One of them, land on which to site the necessary recharge facilities, would have to be obtained, and real estate values in the urban area are not insignificant.

I know that many people view the river bottom lands as being valueless, but in fact, they are not. A recent resolution of a long standing boundary dispute between the Salt River Indian Community and the adjacent landholders places an average value of about $17,000 per acre on river bottom lands to be purchased by the government and added to the Salt River Indian Reservation. All the recent land transactions in the same general area running from about 1974 through 1977, indicate a land value of from $6,000 to $15,000 per acre. So our twelve hundred acre recharge area could, right off the top, cost in the neighborhood of ten million or so dollars just in rights-of-way.

The cost to construct and prepare the infiltration ponds would depend largely upon their desired life. If they are intended to be a permanent installation, then the ponds should be properly protected from floods by revetment of the downstream slopes, or by the inclusion of channelization through the recharge area.

Flow control and measurement devices would also have to be constructed. Provisions would also have to be made to periodically dry each pond, maintain and rework their bottoms to avoid clogging; etc. Further costs would be incurred to construct the necessary dams, diversion structures, gates and canals which bring water to the recharge area.

If Granite Reef Dam is to be modified as part of the plan, then additional provisions would have to be made, and costs incurred, not to unduly interrupt the water service in the Phoenix area while the modifications are being made. Add to these the legal fees, the engineering and design costs, and other incidentals, and we can see that artificial recharge is not going to come cheaply, and it certainly is not free as some people might imply.

To conclude, in addition to the many other questions which must be answered regarding the economics, the environment, water quality, soils mechanics, law, sub-surface characteristics, and others, in order to properly plan an artificial recharge project in the Salt River flood plain, a thorough analysis must be made of the effects that these plans have on the water-carrying capabilities in the Salt River flood plain. We need to know in advance the hydraulic implications of carrying out our plans, and what other measures must be taken to avoid adverse implications.

I would like to leave you with a final thought. Water resource management and development today is an exceedingly complex subject. I would just like to suggest that you be wary of those people who come to you with apparently simple solutions, because the Southwest long ago used up all the cheap and easy ones.

AUTHOR'S BIOGRAPHICAL SKETCH

NAME: William C. Bianchi

EDUCATION: B.S. Degree in Irrigation Science from the University of California at Davis

PhD Degree in Soil Physics from the University of California at Davis

JOB POSITION: Research Scientist for the U.S. Department of Agriculture, Fresno, California

EXPERIENCE: Staff member of the U.S. Department of Agriculture, Science & Education Administration, Agricultural Research since 1959

Responsible for developing and testing new techniques of artificial recharge and the evaluation of recharge as a tool to manage groundwater in the framework of total water resource management.

CASE HISTORY - GROUNDWATER RECHARGE IN SAN JOAQUIN VALLEY "LEAKY ACRES RECHARGE FACILITY"

by

WILLIAM BIANCHI

It's rather odd that the reason I am here and that we are working with the City of Fresno is because of an Arizonian in coming to the San Joaquin Valley, and advising the City of Fresno in a consulting report on the ongoing future status of their water problems. It was because of John Carollo's report. After it laid on the shelves a few years, the city water division came into our office and asked if we had any ideas. Having worked with the irrigation districts in the San Joaquin Valley for several years trying to find solutions within their irrigation operations for groundwater management, it came as an excellent opportunity for us to look at a completely different economic base for recharge, other than the irrigated agriculture cost base. For that reason, we commenced the joint research activities that we will be looking at today.

California is in the same situation as the Salt River Valley, in general. The people that promote artifical recharge are looking at this terrific reservoir in California which totals around 142,000,000 acre feet of available groundwater storage. When you look at the current active surface storage of only 34,000,000 acre feet you can see the magnitude of availability there. The problem is to access water to that storage and this is not a simple process.

In California they estimate approximately 200,000,000 acre feet is precipated annually. Around 130,000,000 acre feet is lost on the watershed due to evapotranspiration, leaving about 70,000,000 acre feet as runoff. About 37,000,000 acre feet of this is lost due to flood flows, predominately in the north coast area where approximately 27,000,000 acre feet flows to the ocean. Thus around 40% of the total available runoff is lost. The water is there, but how do we get at it from the standpoint of the hydrology involved and how do we get it into the groundwater system as far as the phenomenon involved in artificial recharge.

The San Joaquin Valley predominately has the greatest body of available groundwater storage. Yet it is also increasing in available groundwater storage at the rate of 1.5 million acre feet of overdraft per year. This, is concerning not only the hydrologist, but also the politicians and legal people involved in the water management picture. The West, in general, is looking at the water problem as they have never looked at it before. The amazing thing is, this interest and concern is spreading eastward with time as the value of groundwater, in terms of its availability and low cost extends into the "humid eastern U.S." where water demand is also increasing with time. Thus, we see the technology that could be developed to improve the efficiency of groundwater recharge is a worthwhile research effort nationally.

With this I would like to go to the figures and hope to extrapolate our experience in the San Joaquin Valley, through the geology and hydrology of the valley, to give you some reference as to where Arizona stands in terms of using our results.

Fresno sits approximately in the central part of the Sierra and Southern San Joaquin Valley (Figure 1). The predominate source of water is snow melt from the Sierra-Nevada Mountains. High quality water is stored behind reservoirs on most of the main drainages now and predominately distributed through major canal works (Figure 2). These run down the east side of the San Joaquin Valley and all the way into the southern part of the valley (Figure 3). The geology of the San Joaquin Valley is significantly different from the Salt River Valley. Predominately the east side of the San Joaquin Valley is associated with the granitic Sierra-Nevada Mountains (Figure 4). Deposition of continental alluvial deposits has occurred on top of older marine deposits that originated at the time the valley was connected to the ocean. The fresh water continental deposits predominately are coarse grained on the east side of the San Joaquin Valley. On the west side, the origin of the alluvium is from the sedimentary rocks of the Coast Range; finer grained rocks leading to less permeable materials; higher salt contents in the associated soils and so less conducive to artificial recharge. Thus, if artificial recharge is to be a part of the total water management picture in the San Joaquin Valley, most of the recharge must be done on the east side of the valley.

Note (Figure 4) that the San Joaquin Valley also has a significant lacustrine clay deposit (the Corcoron Clay) occurring quite extensively across a major portion of the cross sections. This and other shallower clays are less permeable than concrete, thus, the potential for infiltrating water through these materials is practically nonexistent. The Corcoran Clay separates a lower artesian pressure zone from upper-confined to semi-confined zones. In echelon on top of the Corcoran Clay are also other clays, clays of lacustrine origin associated with the interglacial period.

There is a significant difference in the type of sediments that are associated with the deposition out of the east-side streams. Currently, as in the geologic past, the continuous flows occurring from these streams (Figure 5) produced well developed fans as braided channels deposited well segregated sediments. In this area is where efficient extraction of groundwater occurs. These well graded sands are the high-yielding aquifers. We have abrupt changes in the surface soils, with hardpan series soils on top of graded channel sands which are extremely permeable (Figure 6). At depth we also have sharp breaks in the nature of the aquifer materials here a very uniform grain size sand on top of a silt in an abrupt change in the profile (Figure 7). Figure 8 indicates the rather broad range of particle size that you have in the fans here in the Salt River Valley. But note that there is a continuous major segment of this profile which is the surface soil zone that has been deposited either from aeolian or subsequent sedimentry deposition on top of this profile. When you see these surface soils existing over extensive areas, the probability of similar layers existing at depth is also good.

On the east side of the San Joaquin Valley, sites for future artificial recharge projects would be the natural occurring high fans associated with existing main stream courses (Figure 9). These areas are associated with the more permeable surface and subsurface conditions necessary to actually accomplish artificial recharge.

Figure 10 is an example of a historic fan deposit of the Kings River. The Kings River currently flows southward down the San Joaquin Valley into Tulore false. These old channels of the Kings River are where the Consolidated Irrigation District now is doing artificial recharge on some of the soil and in old channel meanders. Such indications of more permeable zones can be found throughout the San Joaquin Valley on the east side.

Specifically, the area around Fresno, lies on the interfan area between the San Joaquin River and the Kings River (Figure 11). The City of Fresno is completely dependent upon groundwater for its municipal and industrial supply. The distribution system has been developed around groundwater, and as Carollo found, the layout of the piping system is such that accessing it into a surface filtered surface water supply would be extremely expensive. Thus, the City's first and almost only choice was to look at artificial groundwater recharge to stabilize the falling water table in their wellfield, and so originated the cooperative recharge research project at Leaky Acres (Figure 12). Leaky

Acres sits within the wellfield of the urban area (Figure 13). This urban area is made up of the City of Clovis, County of Fresno and the City of Fresno jurisdictions. Note that expansion of recharge at this location and the location of other spreading facilities in the urban area is going to be met with severe land use limitations.

The performance of the project has been very successful from the standpoint of the urban water supply. Since 1971, as the project was being started up and came on line, in excess of 80,000 acre feet has been recharged. This amounts to roughly one year's supply for the City of Fresno alone. The facility is due to be expanded to another 80 acres to the west. The approximate costs that we have come up with are between $3.50 - 4.50 an acre foot. The costs have not fully been evaluated for artificial recharge. There is a lot to be said for a more critical study on the economics of this facility.

One of the important operational factors is (Figure 5) the runoff that was occurring from the Kings River. The system is recharging extremely high quality water. This is water out of storage, very low in suspended solids, delivered from the irrigation canals during an extended delivery period. The other extreme is from floodwater deliveries that is being considered on the Salt River. The firmness of the City of Fresno's water supply is indicated in Figure 14. They have, under Bureau of Reclamation Contract, the eventual accessability to 60,000 acre feet a year. Through inter-changes with the Fresno Irrigation District another 40,000 acre feet for a total availability in excess of 100,000 acre feet a year by the year 2000. As far as the potential for Leaky Acres alone, with improving the total area of the project and its technology, eventual development might bring the potential total quantity of recharge up to 30,000 acre feet a year. But, this doesn't nearly meet the expanding demand for groundwater in the local area or the amount of available water.

Briefly going through the performance of the project, one of the questions that might be asked was the magnitude of the evaporation loss during pond recharge. During the period of record, (Table 1) evaporation was observed at approximately 2-1/2 to 3% of the total amount of water put into the project. A comparatively insignificant amount as compared to that which is lost associated with problems of interfacing water delivery with the spreading operations on the project. So you have efficiency problems even with a firm water supply just from delivery problems.

An important thing relative to the performance of Leaky Acres, it was developed on an agricultural soil. It is one of the more permeable soils in the Valley, a Tujunga Sandy Loam or loamy sand. Because of the nature of the deep profile, the extended time of water delivery has made the project successful. In an alluvial fan deposition you are going to have sub-layers within the profile. These sub-layers can be alternate gravel and sand or they can be sand to silt to clays and it will depend on the position in the fan. In the case of Leaky Acres (Figure 15) within the first 80 feet of profile there are some significantly thick and continuous sub-layers of silt. These sub-layers have a controlling influence upon the project's percolation rate.

There is a layer at approximately eleven to thirteen feet below ground surface (Figure 15). Another layer of continuous nature at forty to forty-five feet and still another one at sixty feet (Figure 16). To measure the hydraulic response of these layers we have in place a series of piezometers on top of these individual layers. This response is seen in Figure 17. A rapid rise in head on top of the first layer and a lag in the response of head on top of the second. The major portion of the pond's hydraulic head is lost across the second perching horizon that controls the project's recharge rate. The initial water table only rises in the 317 days of spreading to a point of just above the top of the second perching horizon. Quite obviously, a sub-surface rate is controlling the restriction in the profile.

The simplest way to increase recharge through these sub-layers is to use recharge well. In 1973 we put our operations budget on recharge into what we call the "Glory Hole." This is a drilled injection well directly in the center of the project (Figure 18). This well was a 34 inch reverse rotary bore hole to a depth of 250 feet. The problem in artificial recharge through wells is clogging. We have utilized the surface sandy soil as a slow sand filter and collected the water in the sub-surface in the saturated zone on top of the perching layers in corregated plastic agricultural drain tile. Figure 19 shows the installation of this tile using PVC flyscreen as an envelope material on the eight inch agricultural tile. This flyscreen envelope prevents soil entry into the slits of the tile. The tile was laid at a depth of five feet in behind a trencher and backfilled with the material that came out of the trench. The natural soil was used as backfill rather than a sand envelope.

One of the primary problems with injection recharge is answering the questions of the EPA Water Quality Standards. A sump was used to simulate the recharge well. This sump was pumped so changes in water quality could be observed. Chemically, the water is of extremely high quality (Table 2). Bacteriologically, the canal water had a range of "total counts" in the neighborhood of 200 to 300 times 104 and chloriform counts were greater than 200 per hundred mils. By the time the water went through the soil filter it cleaned up to drinking water standards. Along with the filtration through the soil, algae and other biological life in the water associated with ponds and incoming canal water was removed.

It was necessary to pump develop the tile collector because of sediment associated with the soil directly around the tile line plus that sediment which developed in the transmission of the water through the soil caused a high concentration of suspended solids in the discharge (Figure 20). When the lines were fully developed, a residual turbidity still existed in the system (Figure 21). Clay particles which continue to be developed out of the surface soil are actually delivered into the water table during the spreading operations.

These particles are extremely mobile, so small they are subject to Brownian motion yet, have the potential of clogging aquifer sands. Figure 22 is a down-hole photograph of the deep sub-surface layering that is associated with the geologic fan materials into which the water is being injected. The most important point here is that clay and silt layers exist separating the sand aquifers, and these sand aquifers are mobile. This is an extremely important criteria in the development of the Fresno injection well.

We took heed of the experience in the Texas High Plains and in Los Angeles Barrier studies on their success in the utilization of standard well construction techniques in construction of injection wells. It has been the experience in the high plains that wells which are sanders are used for recharge. Those wells that produced sand seemed to redevelop better than the ones that didn't, and so we took an extreme view of this and designed a sanding well (Figure 23). This required an extremely coarse (1/4 inch) louvered well screen mesh or 1/4 inch slots. A round rock (1 1/4 inch to 1 1/2 inch) well pack was used in Fresno with the idea that if the system clogged, the sand aquifer could be mined as well as the clogging material to regenerate the well's recharge capacity.

The first thing that happened during the experiment was a blow-through of soil occurred into the well (Figure 24) and the well did clog. Redevelopement of the well (Figure 25) pumped considerable amounts of sand (Figure 26), some 28 yards, and it was replaced with 18 yards of gravel. Figure 27 indicates the response of this redevelopment in the specific recharge capacity of the well. The well after it was unclogged, has maintained a specific capacity between 40 to 45 gallons per minute/foot. Redevelopment brought the specific recharge capacity up to 45 gallons per minute/foot where it has remained essentially constant into the 1978 season. We have injected some 1,000 acre feet and approximately 27 tons of those particles without clogging the well. Therefore, we feel that this is a valid injection technique.

Figure 28 summarizes the Fresno System. Tiles are placed in the surface sandy soil where perching occurs from the 40 foot sub-layer. Water gravitates down the injection well taking advantage of the diminished pressure head in the deeper sand aquifers. The water then flows out laterally into these deeper aquifers.

Systems can be developed for artificial recharge through manipulation of both the surface hydrology, conditions in the soils, and the aquifer geology to its best advantage to accomplish this task.

Physical, Environmental, and Management Influences on Water Spreading at Leaky Acres.

Delivery			Delivery Cut Back Losses by Source			Evaporation Loss
Year	Metered Delivery (Ac.ft.)	Potential Delivery 1/ (Ac.ft.)	Water Quality (Ac.ft.)	Environmental Control (Ac.ft.)	Delivery Fluxuations (Ac.ft.)	Evaporation (Ac.ft.)
1972	9772 (79.0%)	12370	117 (0.9%)	1134 (9.2%)	860 (7.0%)	487 (3.9%) (4.98%) 3/
1973	14365 (73.3%) 2/	19607	3215 (16.4%) 2/	1222 (6.2%) 2/	351 (1.8%) 2/	454 (2.3%) 2/ (3.16%) 3/

1/ Based on the proration end of season rate for individual ponds over the total delivery period.

2/ Based on potential delivery.

3/ Based on metered delivery.

TABLE 1

BACTERIAL ASSAY OF DRAIN COLLECTOR EFFLUENT AND CANAL WATER

SAMPLE DATE	MEAN TOTAL COUNT COLONIES/ML	COLIFORM COLONIES/100 ML
DRAIN EFFLUENT		
1973, OCT. 15	62	< 2.2
1973, OCT. 15	36	< 2.2
1975, APRIL 1	91	< 2.2
JUNE 12	11	< 2.2
AUG. 5	20	< 2.2
AUG. 19	18	< 2.2
SEPT. 4	43	< 2.2
SEPT. 17	17	< 2.2
OCT. 7	6	< 2.2
OCT. 29	1	< 2.2
CANAL WATER		
1975	RANGE $2\text{-}300 \times 10^4$	< 200/100 ML

TABLE 2

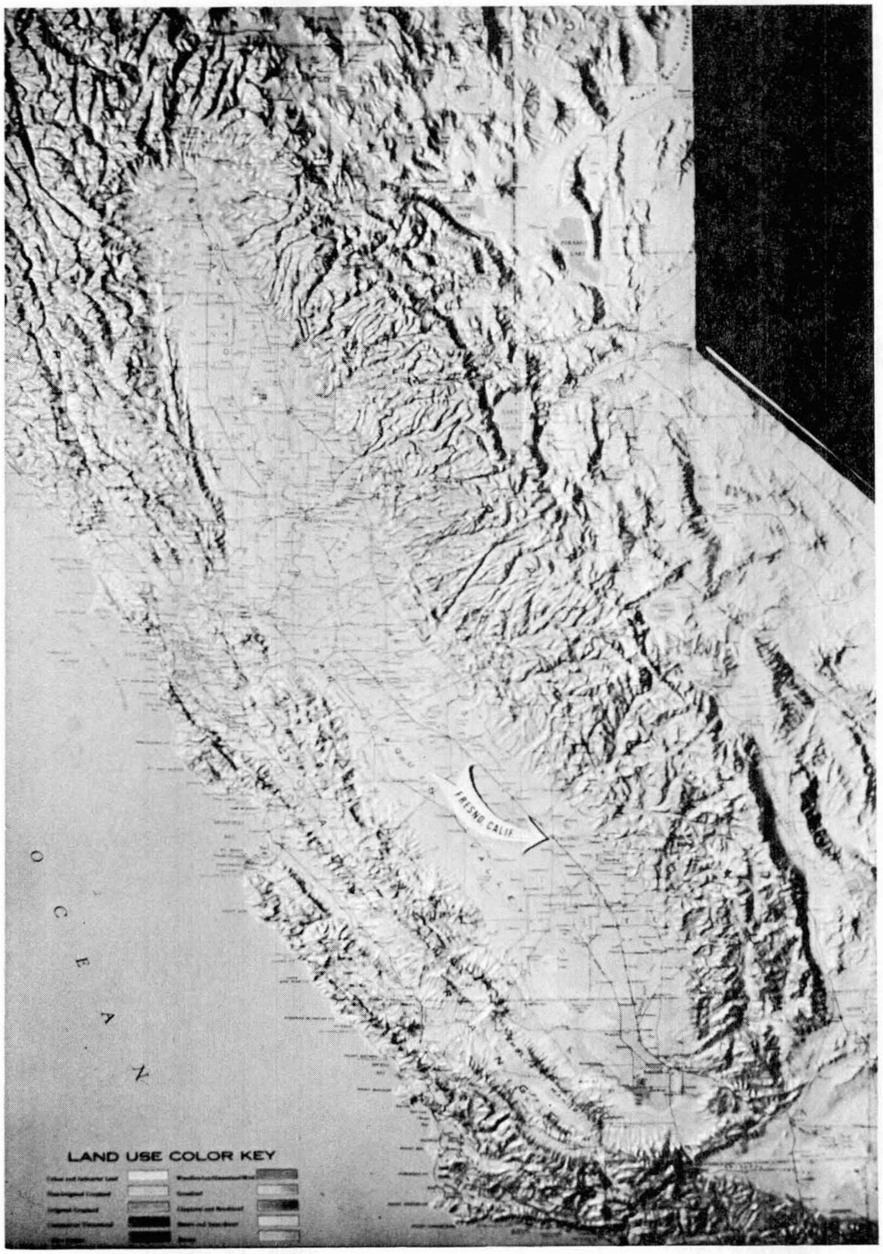


FIGURE 1 - PHYSOGRAPHIC AND GEOLOGIC SETTING OF FRESNO, CALIFORNIA

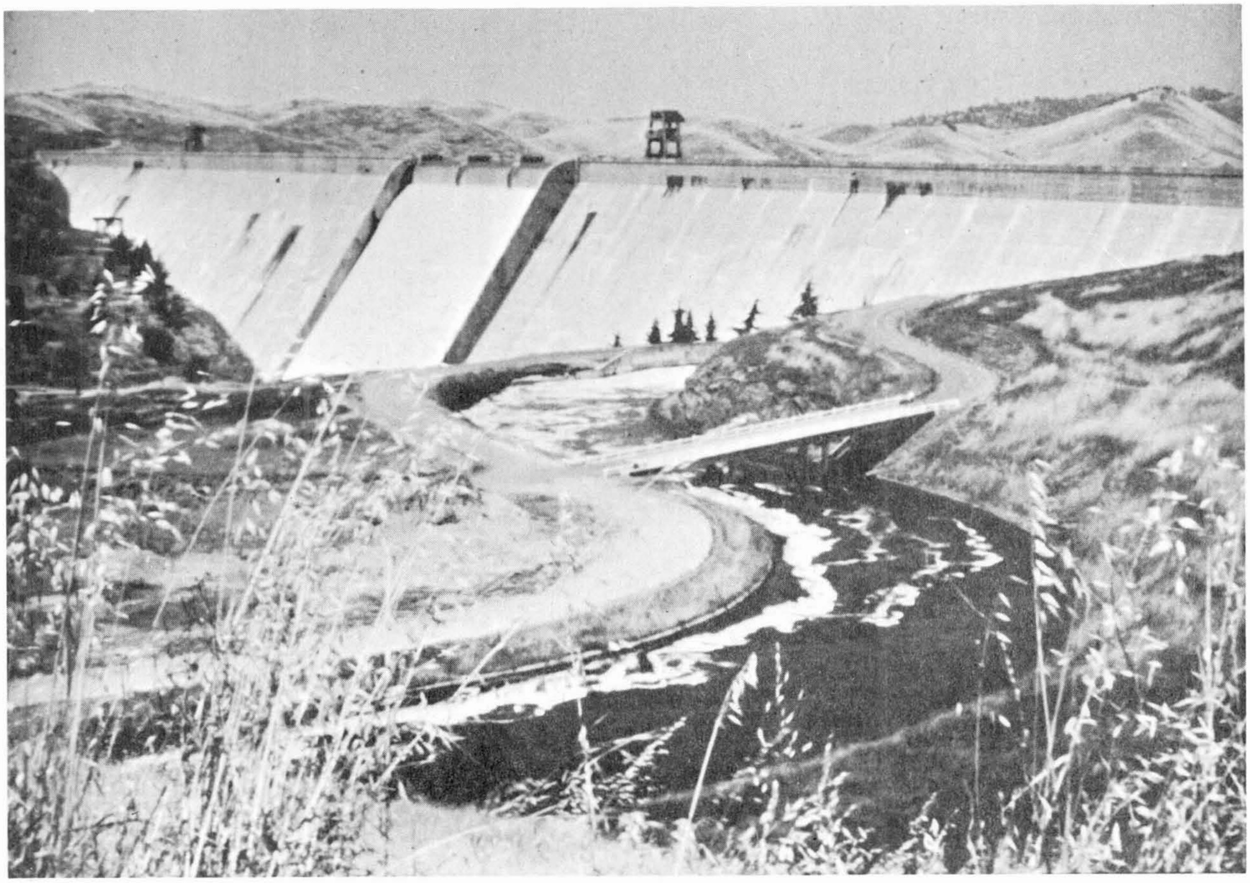


FIGURE 2 - FRIANT DAM ON THE SAN JOAQUIN RIVER. STORAGE 520,000 ACRE FEET. FRIANT-KERN CANAL IN FOREGROUND

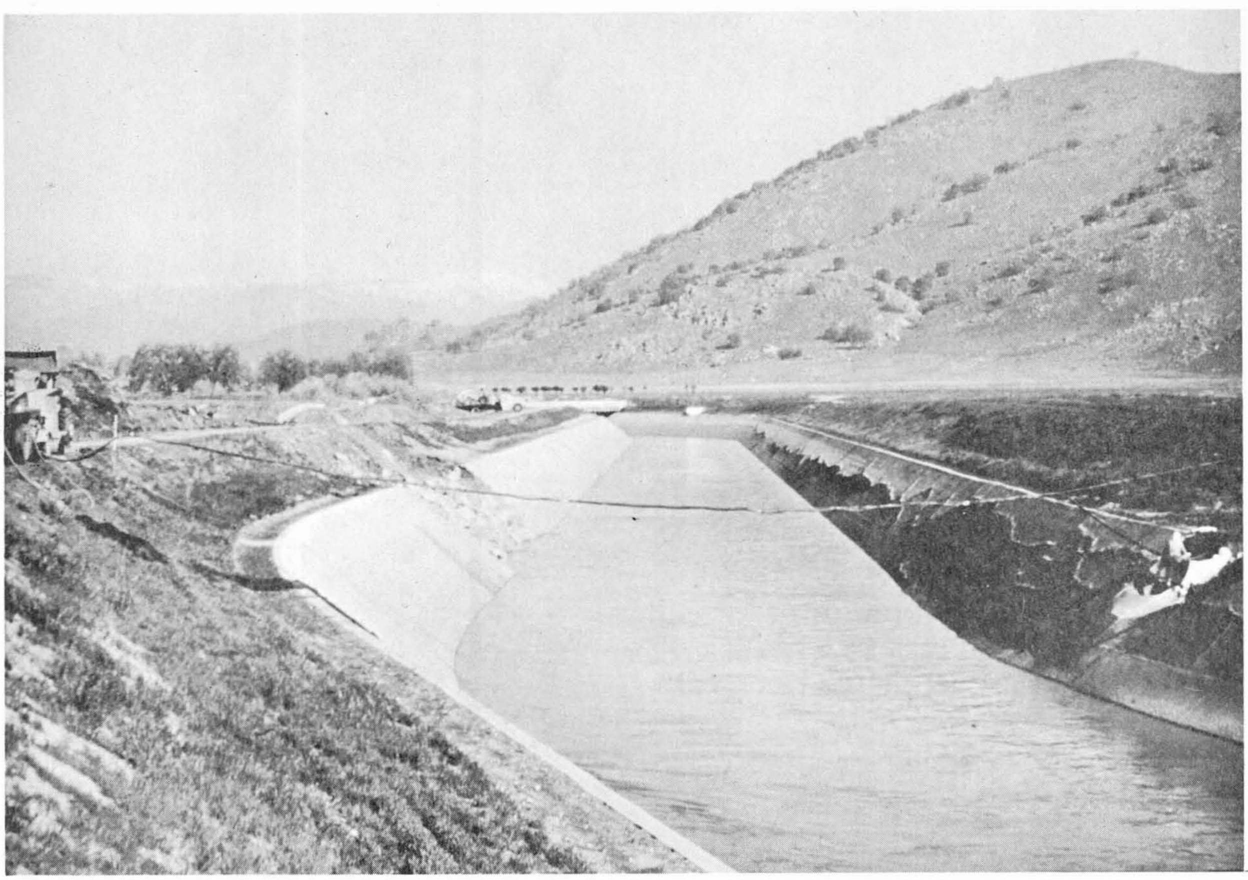


FIGURE 3 - FRIANT-KERN CANAL EAST OF SANGER

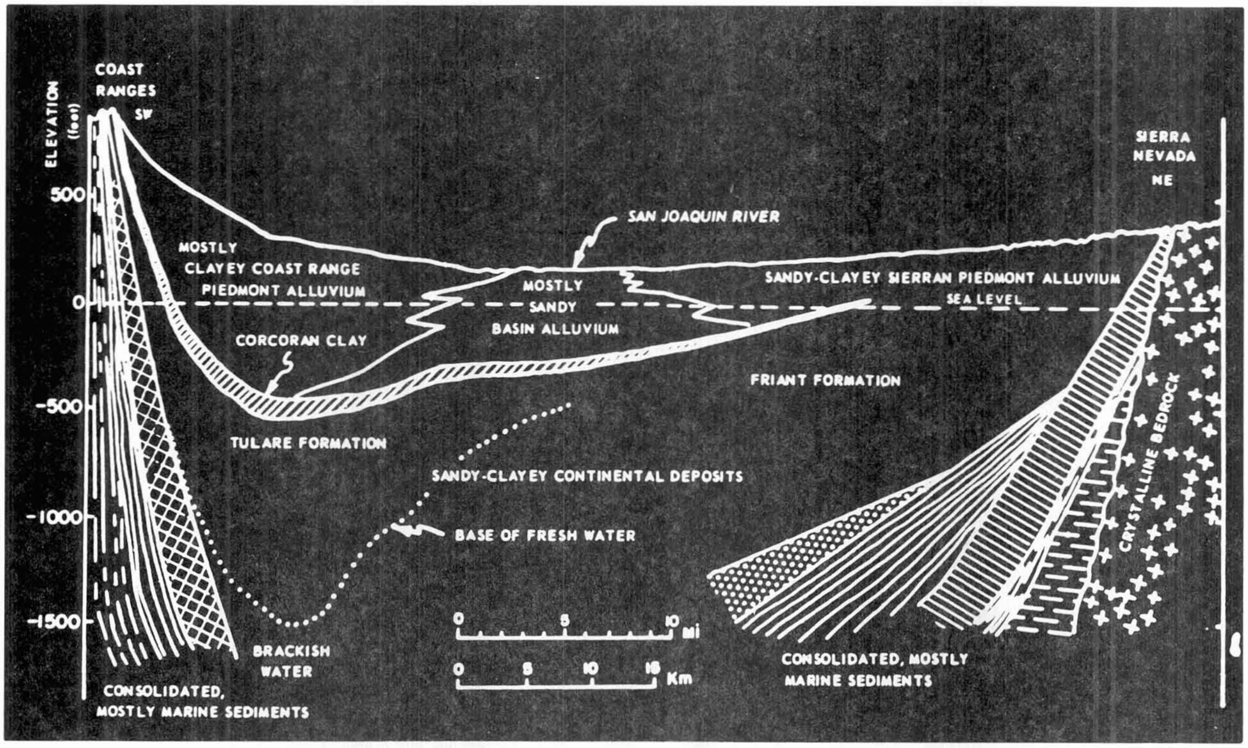


FIGURE 4 - DIAGRAMMATIC GEOLOGIC SECTION ACROSS THE SAN JOAQUIN VALLEY, CALIFORNIA, SHOWING CORCORAN CLAY. VERTICAL EXAGGERATION IS APPROXIMATELY 55X

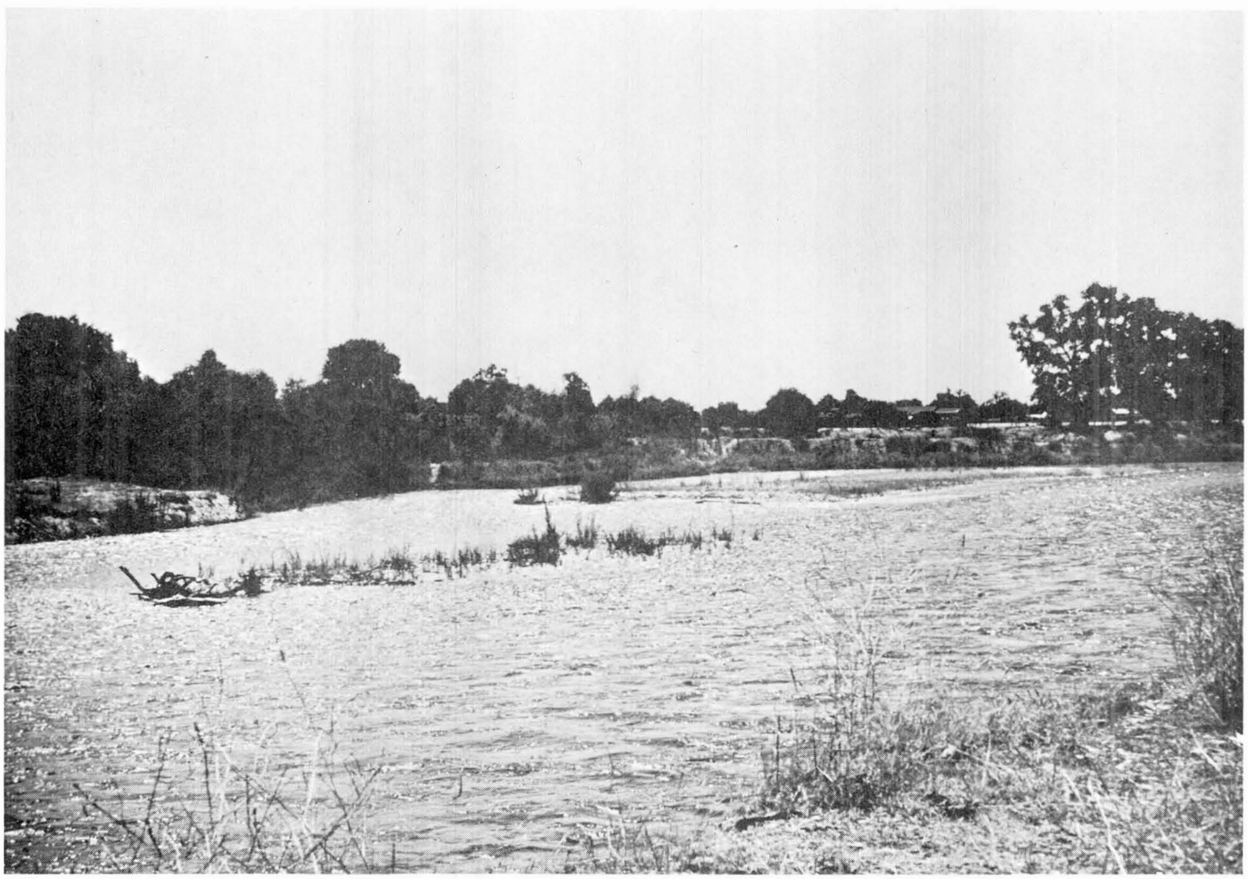


FIGURE 5 - KINGS RIVER AT CENTERVILLE

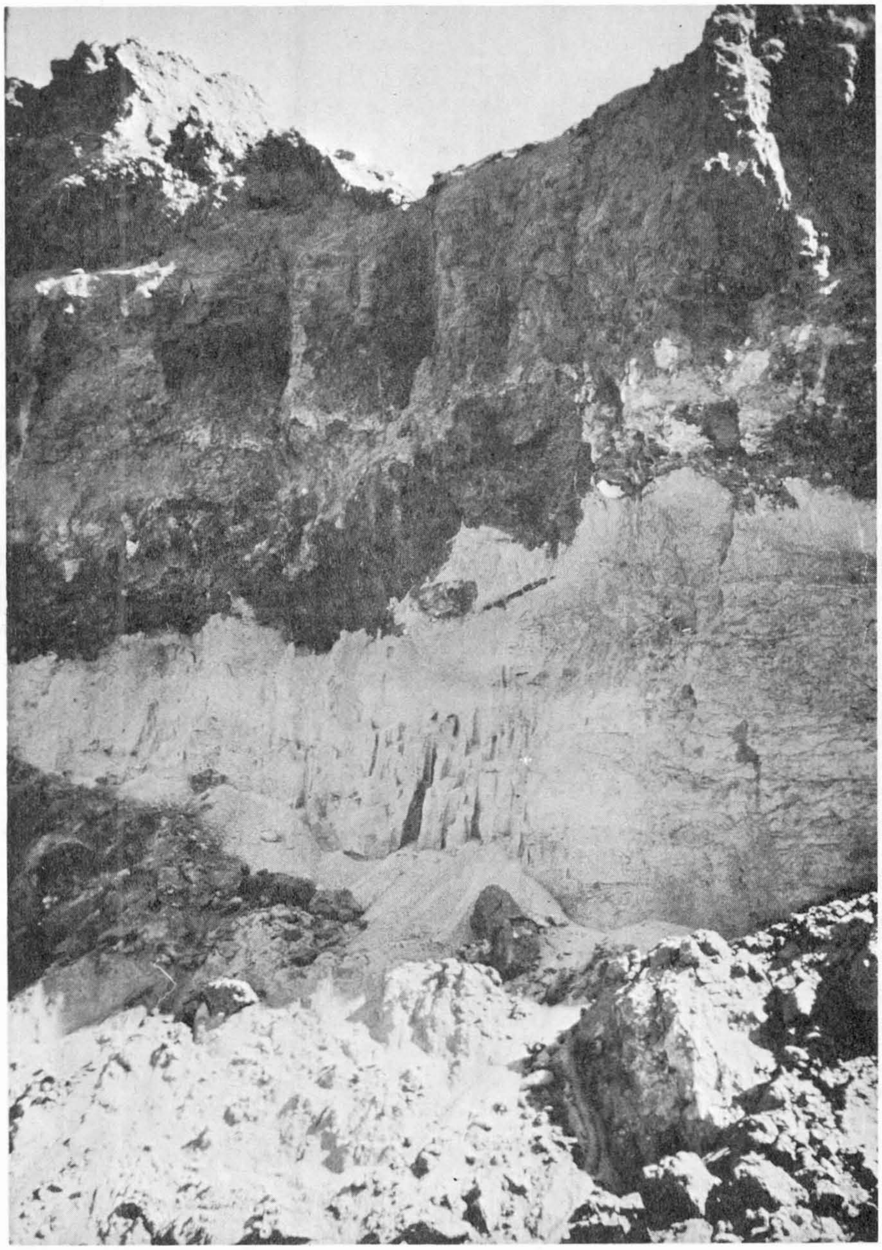


FIGURE 6 - CONTACT BETWEEN SURFACE HARDPAN SOIL PROFILE AND CLEAN SAND.

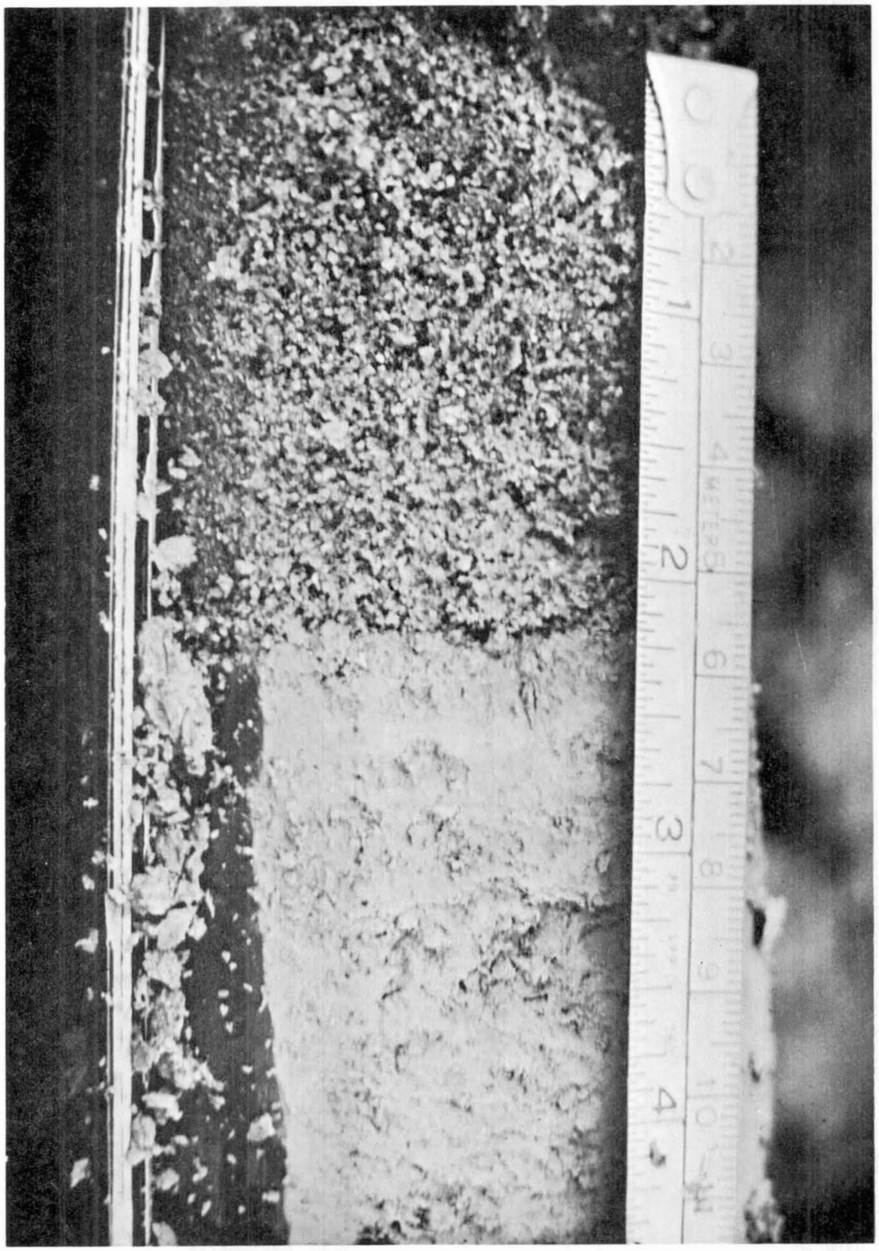


FIGURE 7 - CONTACT DEPTH IN VADOSE ZONE - CLEAN SAND ON SILT

FIGURE 8 - GRAVEL-SAND PROFILE IN SALT RIVER ALLUVIAL FAN NEAR PHOENIX.

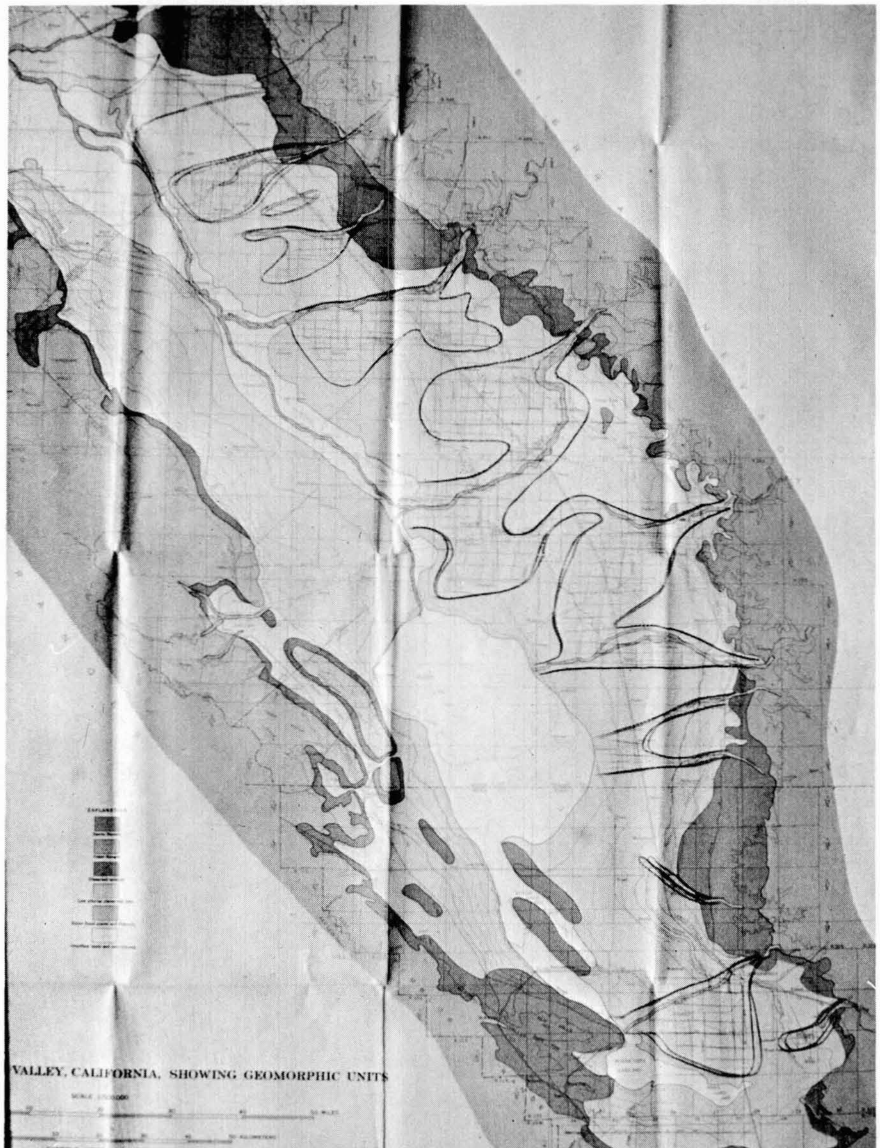


FIGURE 9 - DISPOSITION OF MAJOR ALLUVIAL FANS ALONG EAST SIDE OF SAN JOAQUIN VALLEY

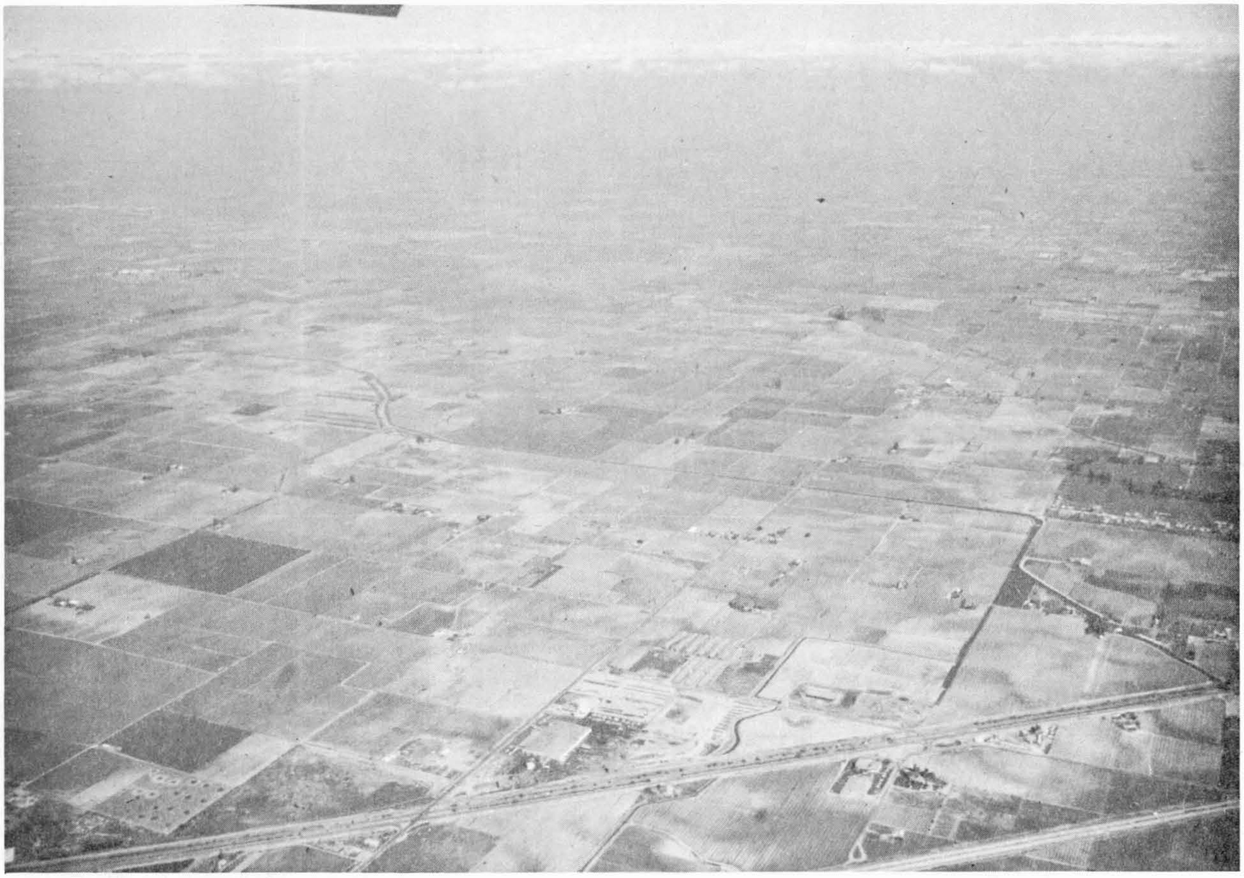


FIGURE 10 - OLD CHANNEL OF KINGS RIVER NORTH OF SELMA, CALIFORNIA

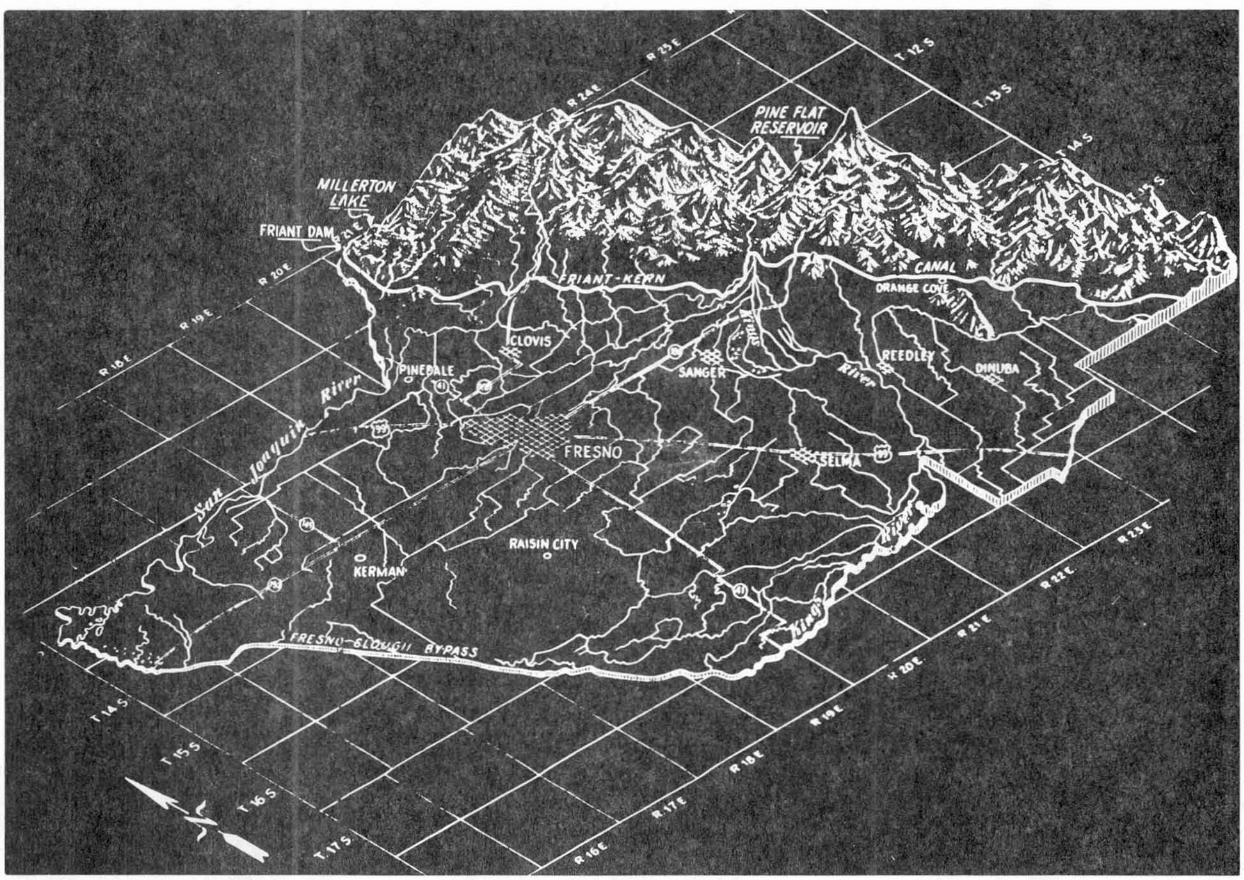


FIGURE 11 - LOCATION OF THE CITY OF FRESNO ON THE KINGS

FIGURE 12 - "LEAKY ACRES" PROJECT

FIGURE 13 - SITUATION OF LEAKY ACRES WITHIN THE URBAN AREA AND ITS WELL FIELD

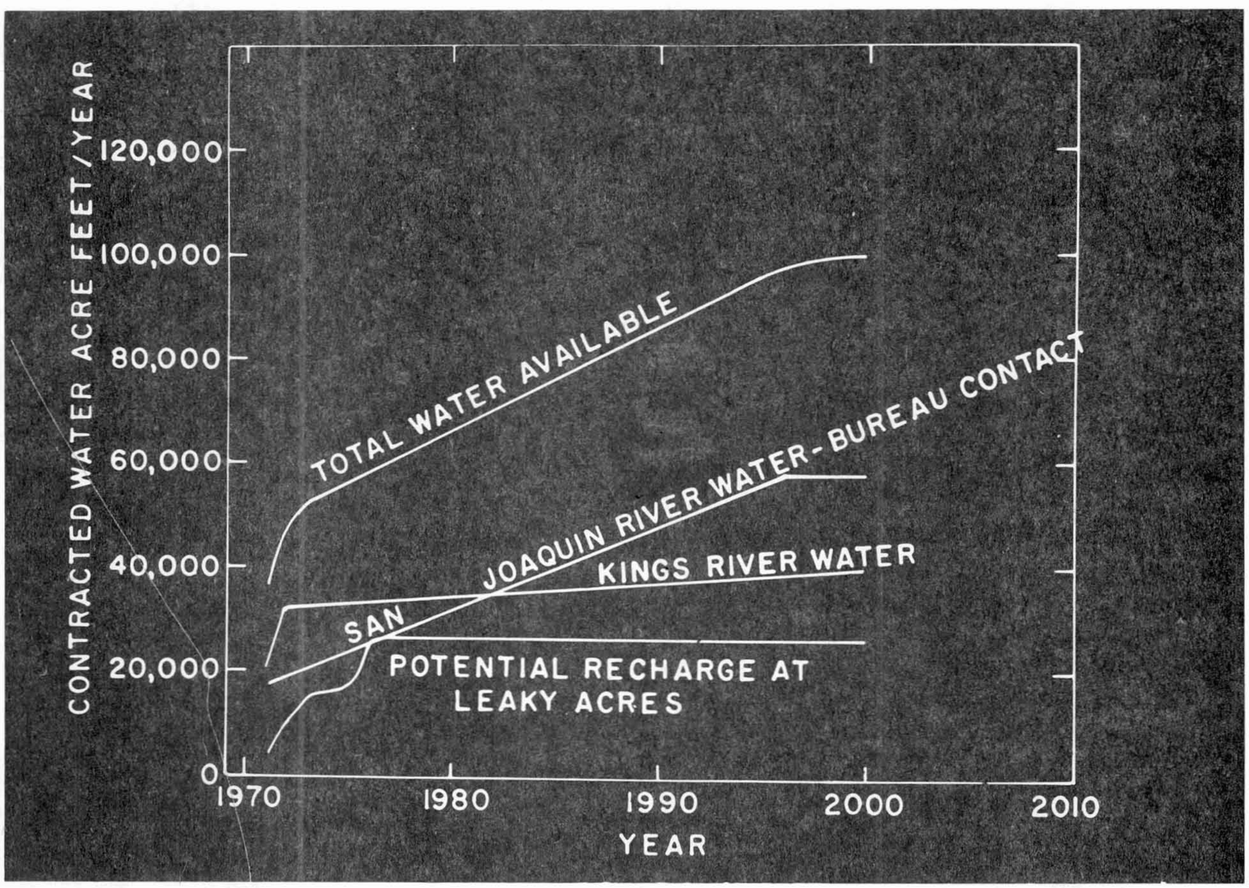


FIGURE 14 - CITY OF FRESNO WATER SOURCES AND LEAKY ACRES RECHARGE POTENTIAL

FIGURE 15 - CONTACT BETWEEN TUJUNGA SOIL AND FIRST PERCHING HORIZON

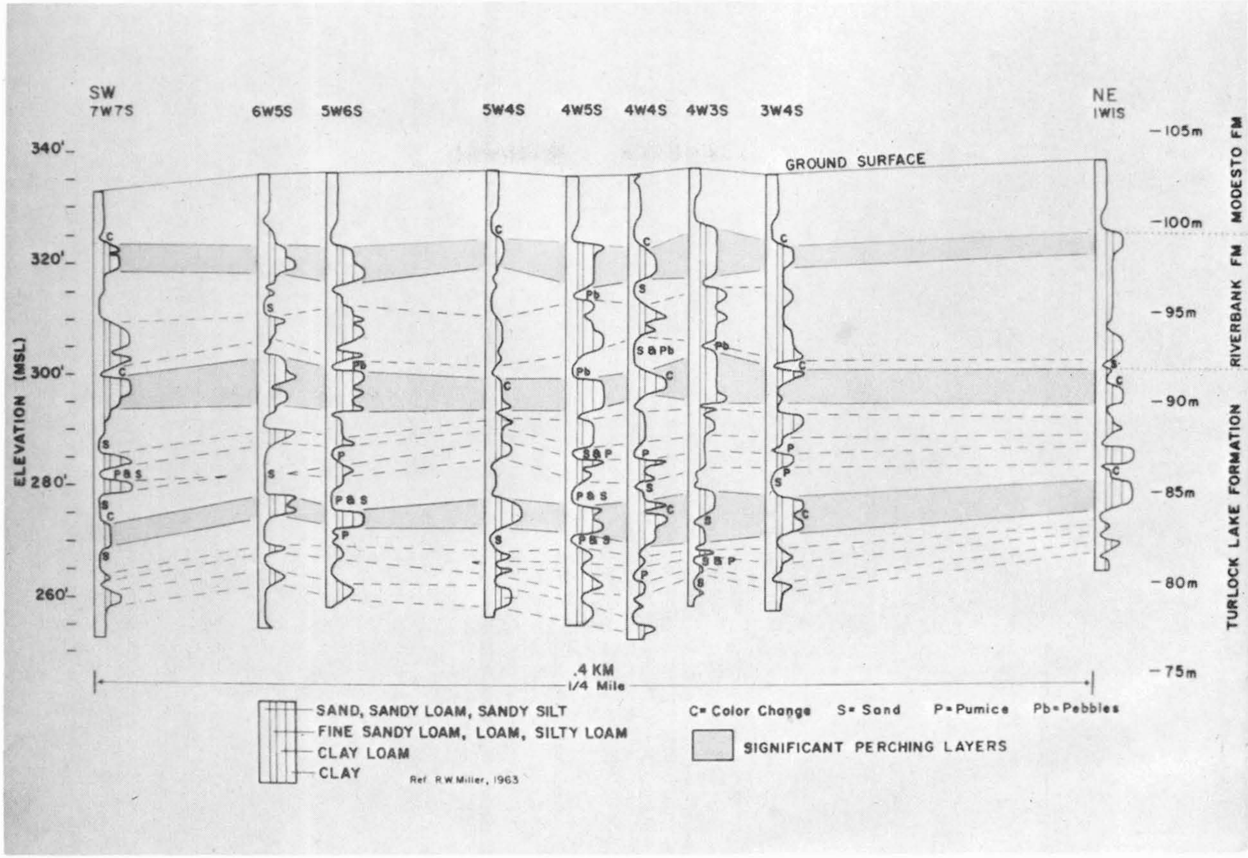


FIGURE 16 - NATURE OF SUBLAYERS BENEATH LEAKY ACRES

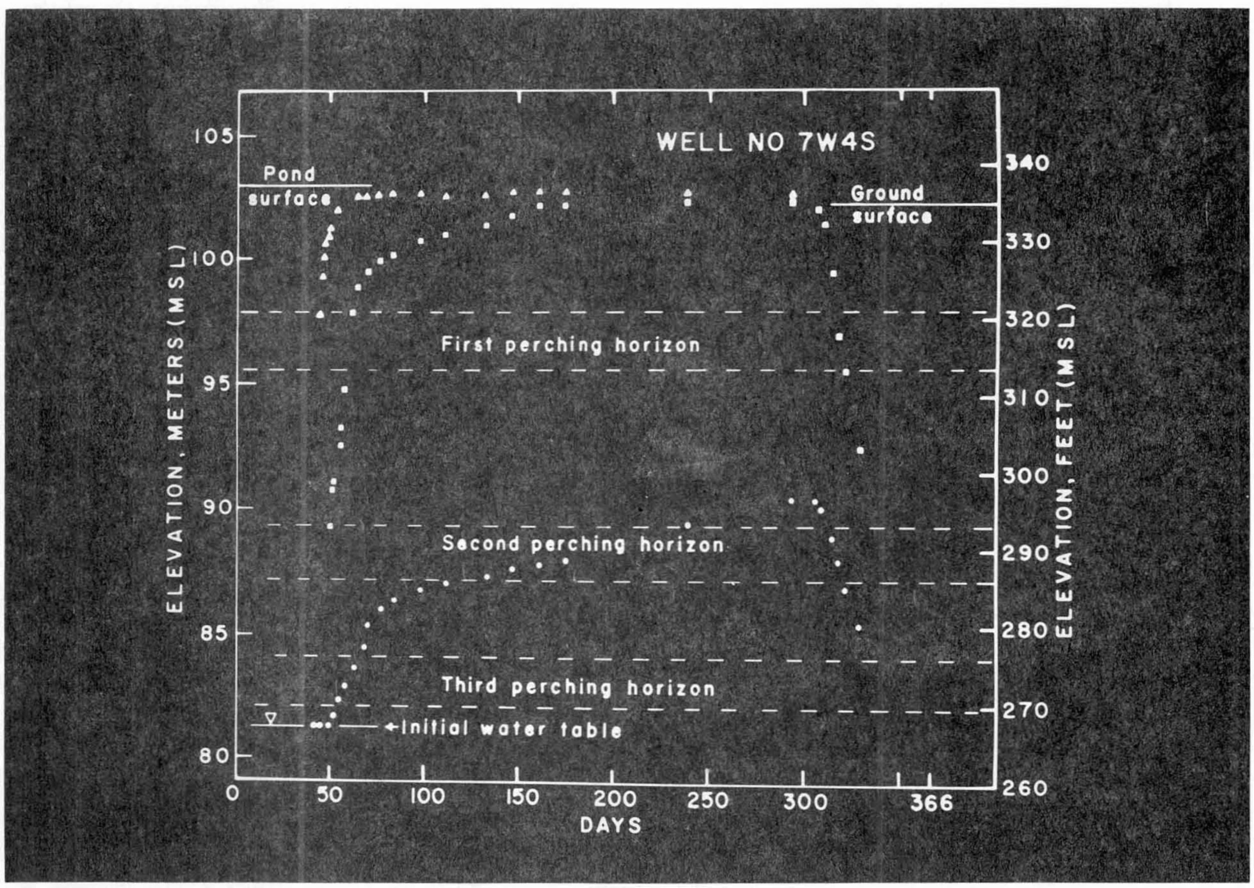


FIGURE 17 - THE DEVELOPMENT OF PERCHED WATER TABLES BENEATH LEAKY ACRES THAT CONTROL RECHARGE

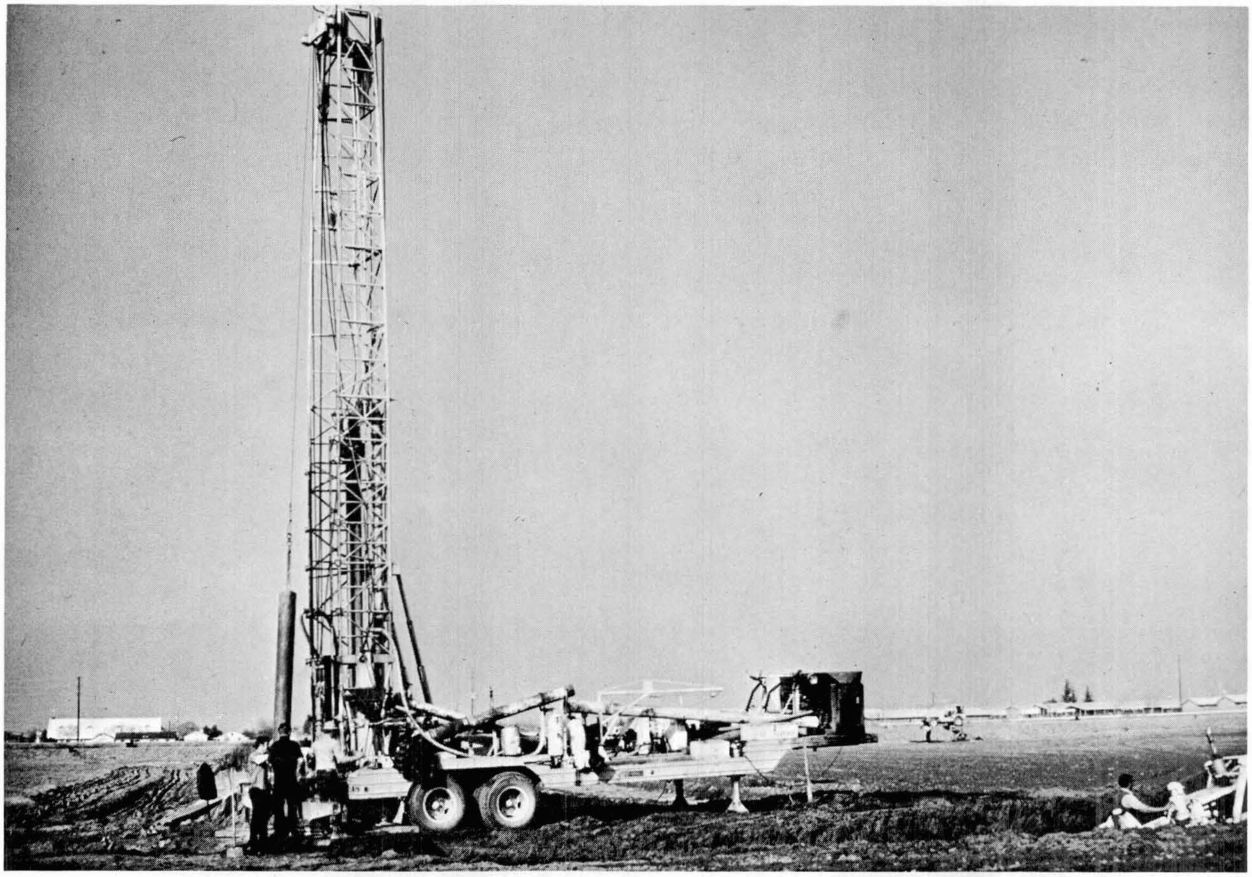


FIGURE 18 - DRILLING 250 FOOT RECHARGE WELL

FIGURE 19 - INSTALLATION OF COLLECTOR IN TUNJUNGA SOIL

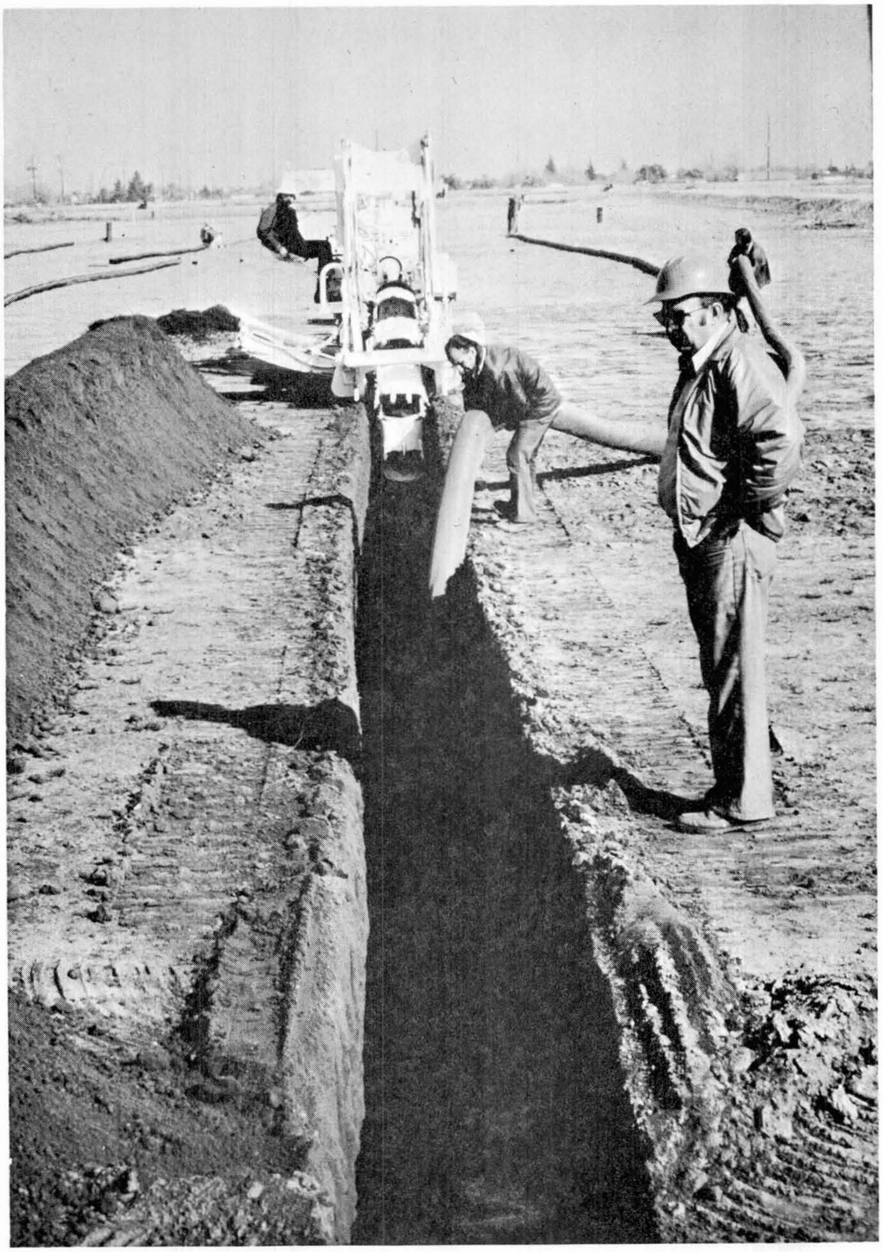


FIGURE 19A - INSTALLATION OF COLLECTOR IN TUNJUNGA SOIL

FIGURE 20 - SUSPENDED SOLIDS BEING DISCHARGED DURING DEVELOPMENT PROCESS ON TILE COLLECTOR SYSTEM

FIGURE 21 - CLAY PARTICLES ORIGINATING IN THE SOIL PROFILE AND DELIVERED TO TILE IN PERCOLATING WATER

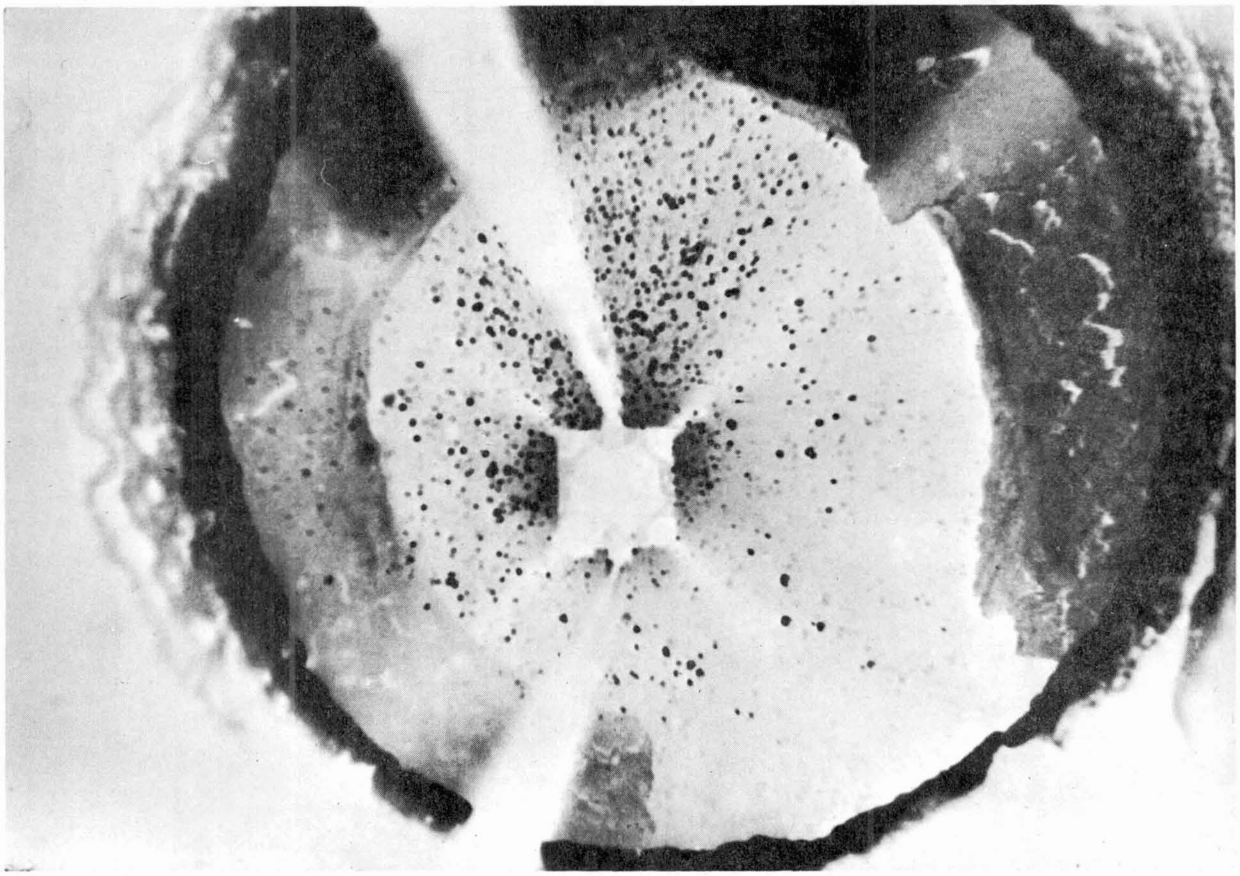


FIGURE 22 - DOWNHOLE PHOTO OF AQUIFER - SILT LAYER STRATIFICATION SHOWING MINING OF SANDS FROM DEVELOPMENT OF THIS "OPEN BOTTOM WELL"

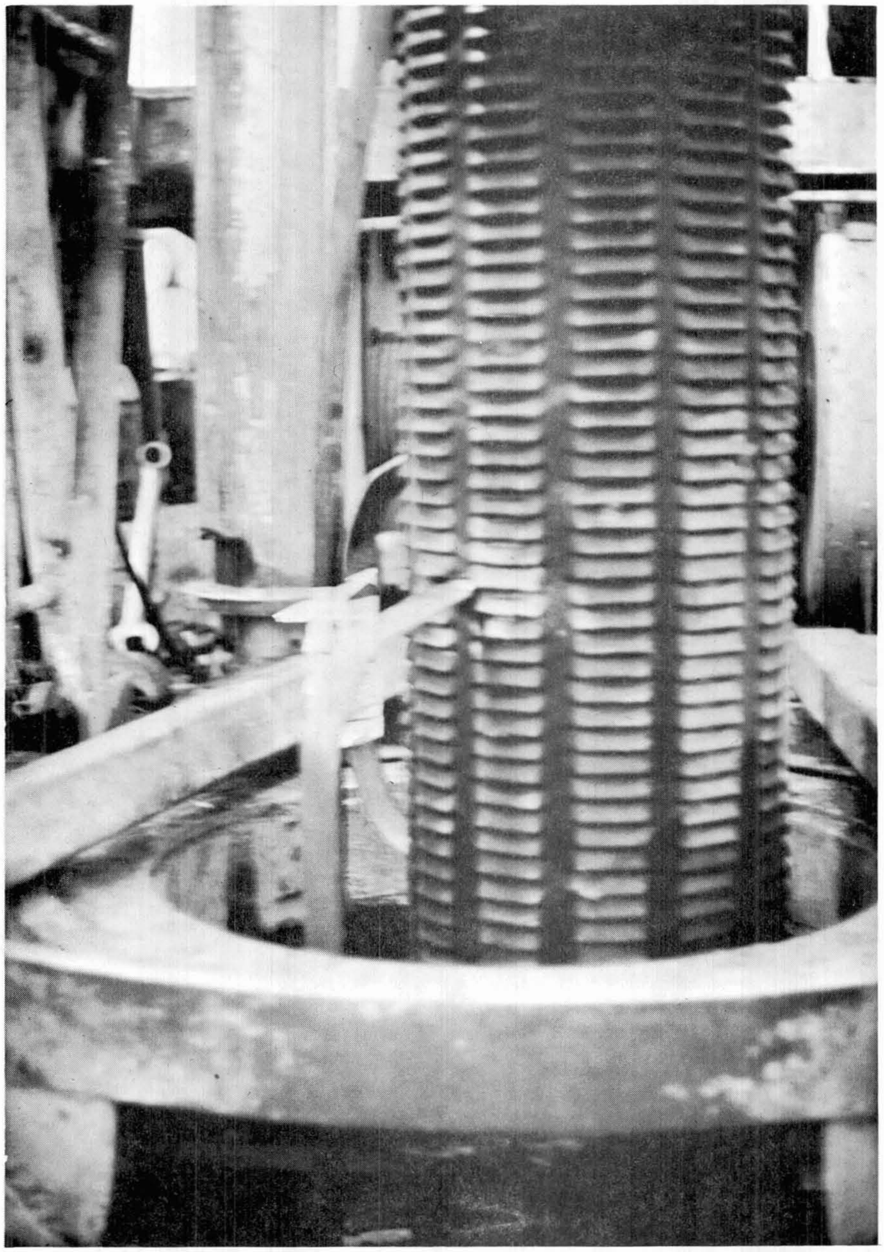


FIGURE 23 - WELL SCREEN USE ON 34-INCH BOREHOLE TO ACHIEVE "SANDER" WELL REQUIREMENTS FOR RECHARGE WELL

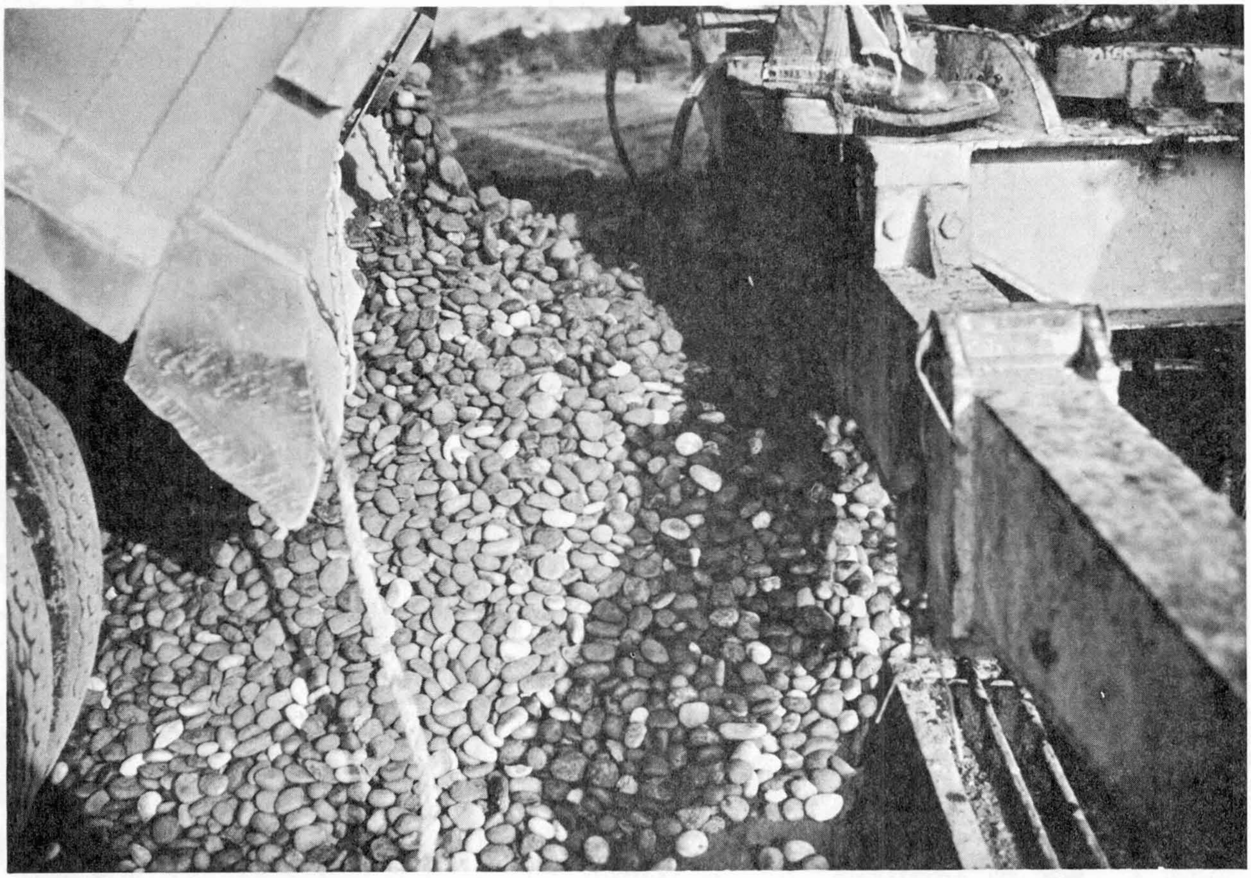


FIGURE 23A - GRAVEL PACK USE ON 34-INCH BOREHOLE TO ACHIEVE "SANDER" WELL REQUIREMENTS FOR RECHARGE WELL

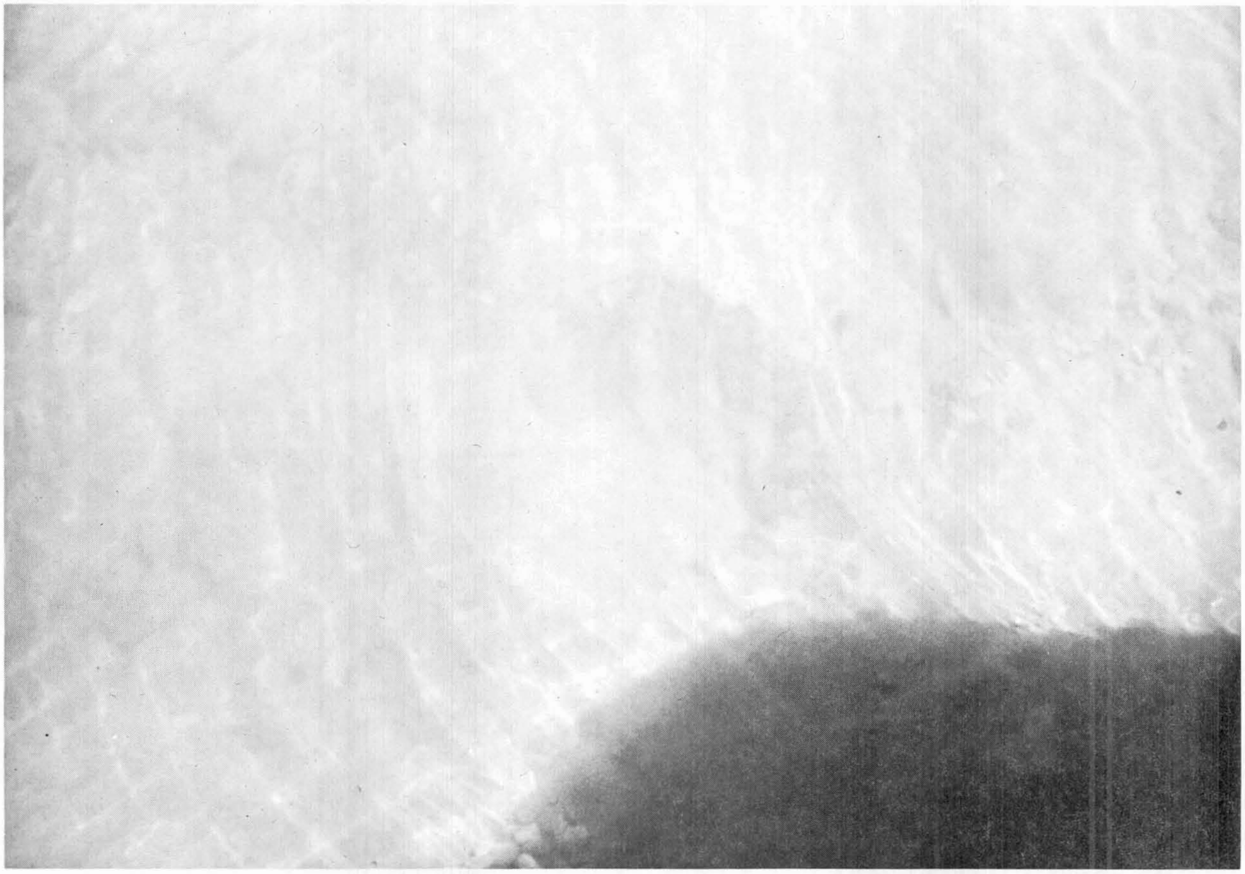


FIGURE 24 - DEPRESSION IN SOIL BENEATH PONDED SURFACE INDICATING DOWN WELLING OF SOIL INTO RECHARGE WELL

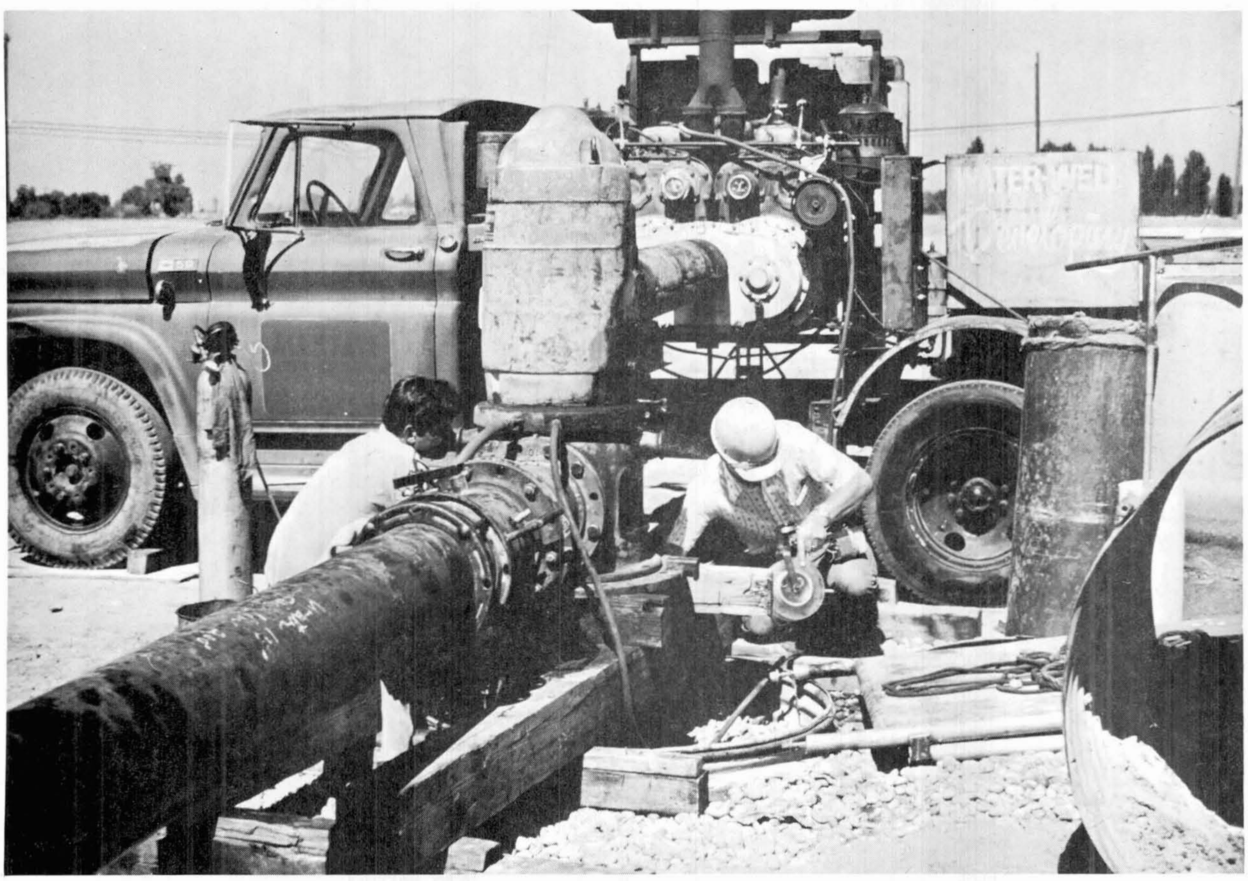


FIGURE 25 - REDEVELOPMENT OF SOIL CLOGGED WELL

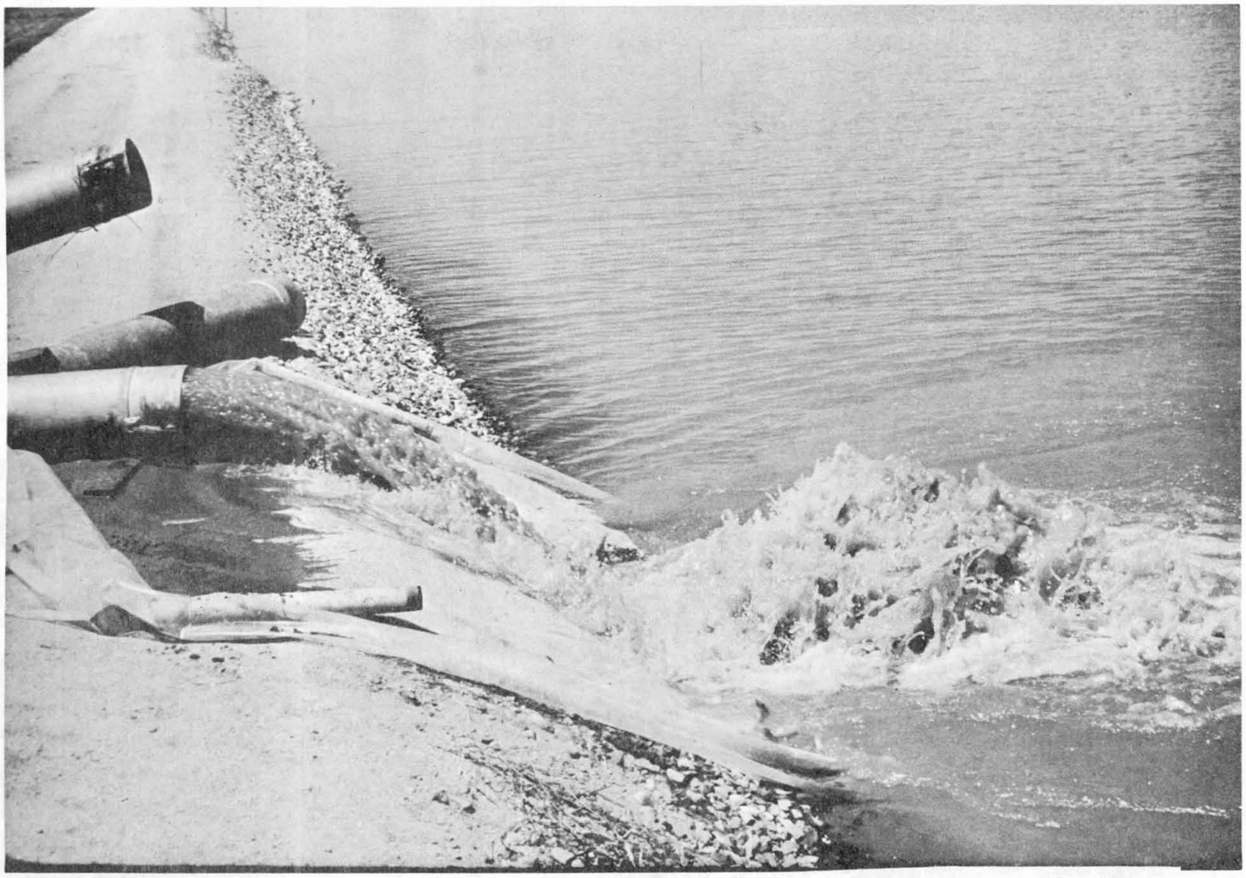


FIGURE 26 - DISCHARGE OF SAND LADDEN WATER DURING DEVELOPMENT OF RECHARGE WELL

FIGURE 26A - SAND REMAINS AFTER REDEVELOPMENT

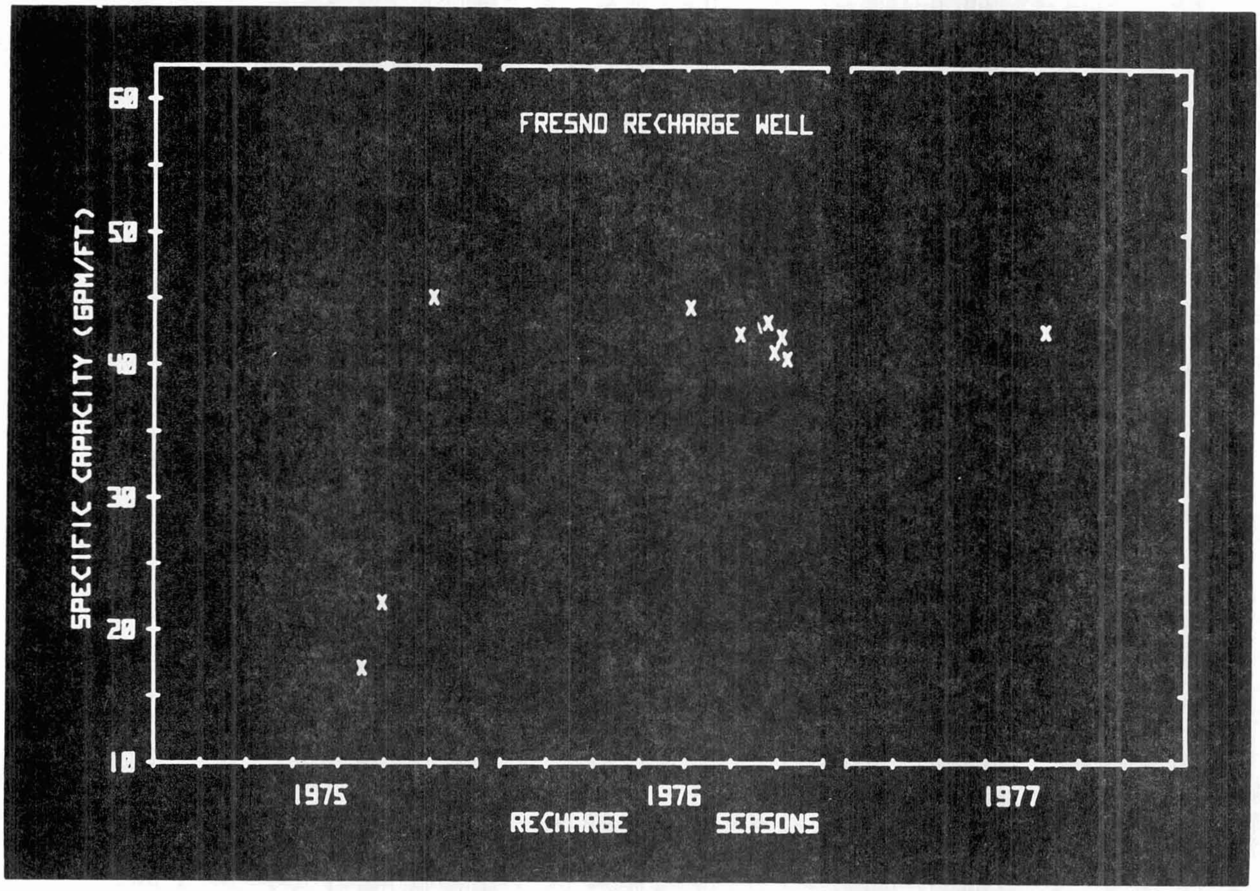


FIGURE 27 - RESPONSE OF RECHARGE WELL TO REDEVELOPMENT AND CONTINUED MAINTENANCE OF RECHARGE CAPACITY

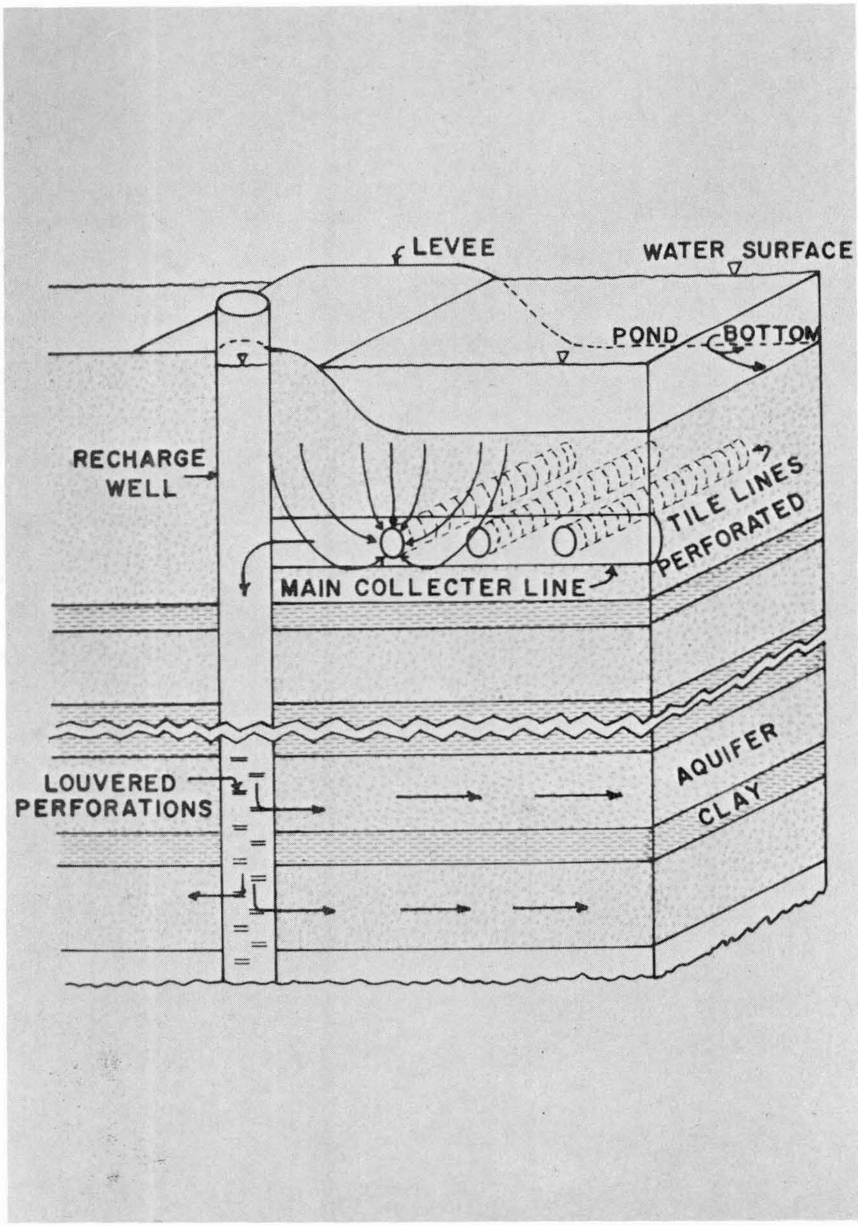


FIGURE 28 - TOTAL PICTURE OF FUNCTION OF "FRESNO COLLECTOR - INSPECTION WELL SYSTEM"

AUTHOR'S BIOGRAPHICAL SKETCH

NAME: Joe Dixon

EDUCATION: B.S. Degree in Geographical Engineering from the University of Arizona

M.S. Degree in Civil Engineering from Long Beach University in California

JOB POSITION: Project Manager for U.S. Army Corps of Engineers Artificial Groundwater Recharge Study

EXPERIENCE: Involved in water resource planning efforts including flood control, water supply and wastewater treatment systems

FEASIBILITY OF ARTIFICIAL GROUNDWATER RECHARGE

IN THE SALT RIVER VALLEY (PART 1)

by

JOE DIXON

What we would like to do today is give you a little history of the U.S. Army Corps of Engineer's experiences in the Salt River Valley in the way of artificial groundwater recharge. The first talk will discuss what we call an overview (Phase I), and the second talk will develop some of the details of the report (Phase II).

Looking at the program, the title of our talk seems a little presumptuous. I am not sure we can tell you whether artificial groundwater recharge is feasible or infeasible in the Salt River Valley. As you have heard, in the last day and a half, it is an extremely complex topic. It is complex not only from the engineering and technical standpoint, which we have heard a great deal about, but also the legal and institutional aspects. We will have to address all these issues before we can seriously analyze the kind of program that we are discussing.

The Corps of Engineers began its work on this study in 1974-1975, through the Phoenix Urban Study Program. The Urban Study Program is a national program which provides that the Corps of Engineers, when directed by Congress, work with a community to solve their urban water resource problems. The Phoenix Urban Study, which was initiated in 1974, consisted of five study areas including: Flood Control, Waste Water Treatment, Fish and Wildlife Enhancement, Recreation, and Water Conservation. The full title for Water Conservation is Flood Water Conservation.

The setting for the Phase I Report is keyed to those events which happened just prior to the initiation of the Phoenix Urban Study. Several major water events took place during 1973 which were tied to the January through May releases of 1.2 million acre feet of water by the Salt River Project. A portion of that water percolated into the ground, but a portion didn't. The controlled release of that water triggered a string of events which was to extend all the way to Mexico.

The water created a flooding problem as it went through Phoenix. Although it wasn't a severe flooding problem, it did disrupt travel from Tempe and South Phoenix into Phoenix. The water continued downstream to Buckeye where a portion of the water percolated. The water table in Buckeye tends to be high. In fact, the water table is so high that they must pump to dewater. Also, the water quality in the Buckeye area is poor. It is obviously undesirable to have any more water percolating into the groundwater table at Buckeye.

The water continued on down the Gila River, and it ended up eventually in Painted Rock Dam, which is a flood control structure near Gila Bend. The Corps of Engineers captured about a half a million acre feet of water at Painted Rock Dam where it was detained and released at a controlled rate.

People usually assume that the problem stops at Painted Rock thinking that the water has been controlled, but the problem continues on downstream. It happened to be in the spring when they were planting crops in the Welton-Mohawk, and the farmers downstream said, "Please don't release that water," so the Corps of Engineers kept the water in the reservoir and it caused a different problem. The quality deteriorated as it evaporated, but eventually the water was released and went on to Mexico where we have a salinity agreement. By the time the water got to Mexico, it was of such poor quality they didn't want the water.

So, as you can see, this story has many facets and goes on and on and on. The point I would like to make is, we should have kept the water in this basin. With that initial setting, the Corps of Engineers looked at the opportunities to conserve floodwaters. What would it take to put that water into the groundwater system in the Phoenix Metropolitan Area, and to begin to recharge some of the depleted aquifers, in what is called the East Basin located between Granite Reef and Tempe Buttes. Overdraft has lowered the water level in East Basin anywhere from 200 to 300 feet.

There were other considerations besides the physical setting of overdraft and quantity and quality issues, and that was a severe drought was beginning in the western United States. This being the setting, our concern was that we should begin to look at the opportunities to conserve some of these waters. Also, institutionally, people were becoming very aware of water resources. There was much impetus to begin to study water conservation.

Further, President Carter at this time was beginning to review national water policy. The President has stated that the key to implementing his water policy is water conservation. So, when I, as a planner for the Corps of Engineers or for the Federal Government, do any type of water resource planning, I have to look at the opportunities for water conservation. In order to implement a water conservation program, one needs to be able to conjunctively manage the water. To conjunctively manage water totally, one needs to understand surface process, (surface hydrology), one also needs to be able to understand groundwater and the way the groundwater hydro-dynamics work. Once these processes are understood, we can begin to manipulate both the surface and ground sources.

The fact is, we have a good handle on our surface hydrology. The Salt River Project does an excellent job of managing the surface waters. They also do a very good job in managing the groundwaters.

The problem comes in, in trying to relate surface and groundwaters. As mentioned, the state of the art of artificial groundwater recharge is fairly well understood from a technical standpoint. The theories seem to work. Leaky Acres near Fresno works - it works in the High Plains of Texas - it works in Los Angeles County. But the question is, is it going to work in Phoenix? We have talked to a lot of people and there seems to be two sides to the story. Neither side has any facts, but they both have extremely strong opinions.

We have talked to both sides. One side will tell you, "Well, we have got to do recharge, it's the panacea." And then the other side says, "The economics of this will never work, we can never get the water back in the ground and be able to take it back out." But, you ask them to give you some facts, and nobody has any facts to back it up.

Therefore, the purpose of the Corps of Engineers' work to date was to begin to determine what facts are available so that we can make some valid decisions on groundwater recharge, and we need to make some decisions pretty quick. In order to make these decisions, we need to get out and do some work and develop the data necessary to make those decisions.

The Corps of Engineers' Phase I Report was looking at the opportunity to recharge floodwater. In order to recharge floodwater, or in order to recharge in general, one needs to have a source of water, but one must have a method to control the source.

There are only a few drainages that have or will have control structures. They include New River, Skunk Creek and Cave Creek, on which the Corps is building flood control structures. We looked at the opportunity for controlling floodwaters on these drainages, and then releasing the water at a controlled rate.

We looked at the opportunity at these Corps of Engineers' Dams, and the fact is that we found it hydrologically infeasible. The quantities of water available on an annual average were not sufficient to warrant any further investigation. We also examined, at the same time, the Salt River. One must understand that the study took place in 1974-75, and the Orme Dam was still a funded, authorized project.

An important assumption of the Phase I study was that there would be a control structure on the Salt River, and the fact was, it could detail floodwaters, and it could release those waters at some controlled rate. The facts at that time were that given a certain volume of water behind a now hypothetical Orme Dam, one could put a certain volume of water back into the ground. What is important is one needs to have a structure in order to control the source of water. Whether it be Orme Dam, whether it be the existing Salt River Project dams, I am not sure that that is critical at this time. What is critical is that one needs to have a control structure in order to artificially augment groundwater recharge.

The findings of the Phase I study as they related to recharge on the Salt River, which dealt with floodwaters as the source was, in fact, that one could expect on an annual average, floodwaters would be available for recharge. The flows would be typical to the 1973 release and 1978 release. If one could control this water, then one could recharge them.

The study, although it was a feasibility study, was very conceptual. A tremendous number of assumptions were made. But we feel that the topic did warrant further study. Therefore, we developed a second, third and fourth phase for artificial groundwater study in the basin.

Those phases included a second phase that would be a plan of study for a demonstration project. The third phase would be implementation of the demonstration project, and the fourth phase would be a full scale project.

The first two phases would be paid for and done by the Corps of Engineers through the Phoenix Urban study. The third and the fourth phases are as yet unauthorized and unfunded.

Some of the problems that we came up with in writing up the Phase I study were in having to deal with the high number of technical assumptions. We had assumed an infiltration rate of two feet per day. We don't know what the long-term infiltration rate is. A major question is, is there sufficient storage available in the east basin? One would assume so, because extent of overdrafting that has been reported. An additional problem is we don't have a good handle on the geology in the basin

The recent work by Bob Laney of the U.S. Geological Survey has taken great strides to help us begin to delinieate some of the geological problems that are going to be involved in the investigations. Also, during the Phase I study, we ignored, if you will, the institutional questions and problems. As an engineer, the first thing that happens when one gets into a study as controversial as this could be, is that the attorneys tell you "that you can't do it." Well, we tried to take the study out of that position and concentrate more on the technical problems that needed to be solved.

As we began Phase II, the logic was this: We needed to begin to develop the answers to the engineering questions, the technical questions, the environmental questions, the economic questions, and also the institutional and legal questions involved which we had not addressed in Phase I. We were also concerned how those six fields relate to the planning, the design, the construction, and operation and maintenance, also monitoring of an artificial groundwater recharge study.

The Corps of Engineers has worked very closely with the University of Arizona in developing the Phase II report which is undergoing its final in-house review. The report outlines the task to be accomplished, Phase III, the duration of those tasks that would have to be accomplished, how those would fit into an overall time scale, and the approximate cost of a demonstration project.

An additional finding of our Phase I report was that artificial groundwater recharge does not have to be limited to floodwaters. As was pointed out by Mr. Sid Wilson, Salt River Project, one can only count on floodwaters as a source of water for a very small percentage of the time. But the fact is that there are other potential sources of water that could be recharged. There are institutional problems and considerations associated with all of them. But, if one is looking at the opportunities and potential of a groundwater recharge project, one only needs to look at Southern California and Los Angeles County where they recharge from all available sources of water.

We too, have multiple sources of water potentially available. Those include water from the Salt River, and water from the Colorado River. When we talk about the Colorado River as a source, we can talk about deliveries through the Central Arizona Project (CAP), and it could be either CAP water or it could be excess water in the Colorado River system itself. As we know, in the spring of 1976, if we had not had a drought, the Bureau of Reclamation was expecting to release water from both Lake Powell and Lake Meade. So the fact is, there is potential for excess water in the Colorado system. If we have the ability to take delivery of that water and utilize it, we may be able as a state, as a community to be able to artificially recharge it.

A third source of water could be treated effluent. At the time the Phase II study was taking place, the Corps was involved in an area-wide waste water treatment study which was looking at the potential of locating pilot satellite treatment systems throughout the basin. This highly treated effluent would be a potential source of recharge water. Essentially, that is an overview of the Corps' involvement in artificial groundwater recharge in the Phoenix metropolitan area.

AUTHOR'S BIOGRAPHICAL SKETCH

NAME: Michael Mooradian

EDUCATION: B.A. Degree in Psychology from University of California at Los Angeles

JOB POSITION: Staff member of the U.S. Corps of Engineers, Phoenix, Arizona

EXPERIENCE: Working on artificial recharge study by the University of Arizona for the U.S. Corps of Engineers

Working on both a M.S. degree in Environmental Health at California State University in Fresno, California and a PhD degree in Hydrology at the University of Arizona in Tucson, Arizona

FEASIBILITY OF ARTIFICIAL GROUNDWATER RECHARGE IN THE SALT RIVER VALLEY (PART 2)

by

MICHAEL M. MOORADIAN

Phase II of the U.S. Army Corps of Engineers' study on artificial recharge is a plan for a demonstration project. It is not a feasibility study of artificial recharge. Phase II was developed on two levels:

First, as a general plan that can be used by any community wishing to initiate recharge studies. The purpose of the plan at this level is to gather the available information on recharge in technical, environmental, economic, institutional, and legal study areas, identify the gaps in the knowledge, and to formulate techniques to obtain the information needed.

Second, Phase II was also developed as a site specific plan in the East Basin of the Salt River Valley for a demonstration project. The study was limited to a twelve mile reach of the Salt River between Granite Reef Diversion dam and the Tempe bridges. Objectives of Phase II at this level include identifying potential sites for a demonstration recharge project, sources of water for recharge, and budgetary and time estimates for this type of project based on the information gathered in each of the five study areas.

Five possible sites were selected during Phase II for the demonstration recharge project in the east basin. Four are located in the Salt River channel and one north of the Arizona canal near the Evergreen washway on the Salt River Pima Indian Reservation. Sources of water for these potential sites played an important part in location determination. While Central Arizona Project water will not be available until 1985, other sources are available to implement the demonstration project. Floodwater, irrigation tailwater, sewage effluent, groundwater, as well as releases from the Salt and Verde rivers are all potential sources that can be used to help determine the feasibility of recharge in the Salt River Valley.

Because quality and quantity concerns as well as economic and legal problems may exist with different sources of water, and each site has specific benefits and constraints in each of the five study areas, Phase II recommends that a more detailed investigation be conducted for each site to determine the final location for the demonstration project.

Information regarding each of the five study areas was obtained through an extensive literature search and personal interviews. All known information was compiled and questions were formulated regarding the five areas. Techniques were formulated that could be used during a demonstration project to answer these questions while no actual attempt to answer them was made at this time. While much of the technical aspects of recharge have been developed in the past, three site specific questions that emerged immediately were in regards to infiltration rates, storage capacity, and recapturability of recharged water. Answers to these questions are essential for a successful recharge program. A demonstration project is recommended to answer these important questions that will help determine the feasibility of artificial recharge. Preliminary studies can recommend the optimum site for recharge studies while extensive monitoring during the demonstration project can reveal the long-term effects recharge has on infiltration, storage and recapturability.

Again, through a literature review and personal interviews, questions and methods were developed to assess the environmental impact that a recharge program would have on the surrounding area. An environmental impact statement was not made during Phase II of the Corps of Engineers' study. Environmental impacts made by a demonstration project will be minimal because of its small size; however, during the demonstration program, an environmental assessment can be formulated for a full scale recharge program from the information received from environmental monitoring. The only current concern is a possible vector propagation in the recharge area. This may be controlled by alternating the flow of water into recharge basins (if this method is used) to break the chain of insect propagation. This method, known as the wet/dry cycle method, has been extensively used in California.

Institutional matters may be the greatest problems facing a recharge program in the Salt River Valley. Phase II did not attempt to solve these problems but instead took a different approach. All institutions related to water resources were inventoried on federal, state, local, and private levels. The constraints and incentives for each institution was assessed in regards to managing or operating a recharge program. The information gathered revealed that a strong centralized institution was necessary to implement this type of program. It not only has to have the technical and financial capability, but also public acceptance to operate such a facility. Because of the important role public acceptance plays in the successful management of a recharge program, Phase II further investigated various methods of public involvement and education programs with regards to artificial recharge and groundwater.

Legal problems also become apparent when investigating the possibility of recharge facilities in the east basin. The lack of groundwater laws in Arizona makes it difficult to identify beneficiaries of recharged water. Legal problems also occur in land ownership for facility locations as well as in procuring water for recharge. Phase II discusses legislation in regards to groundwater in neighboring states, various methods for legal decisions, as well as those areas in which legislation is needed to insure a successful recharge program

Equally as important, economic problems are also present in recharging the groundwater system. The economic benefits of a demonstration project cannot be quantified because of the size of the proposed facility and its purpose as a research tool to help formulate the question presented by all of the study areas and to evaluate the feasibility of recharge. Once a site location for a recharge project is established, benefit cost studies can begin for a full-scale recharge program. At this time benefits and beneficiaries can begin to be quantified.

To reiterate, the demonstration project is not only a technical project to test the feasibility of recharge in the Salt River Valley, but it is also a method to look at each of the study areas and evaluate the impact they have on artificial recharge. With the completion of Phase II, there has been no conclusion regarding the feasibility of recharge in the east basin. Instead, it is the conclusion of Phase II that a demonstration project is needed to finally assess the feasibility of artificial recharge in this region.

AUTHOR'S BIOGRAPHICAL SKETCH

NAME: Donald Signor

EDUCATION:

B.S. Degree in Agricultural Engineering from Kansas State University

M.S. Degree in Agricultural Engineering from the University of Nebraska

M.S. Degree in Civil Engineering from Colorado State University

JOB POSITION: Research scientist for the U.S. Geological Survey in Lubbock, Texas

EXPERIENCE:

Spent the last ten years doing research in Artificial Recharge for the U.S. Geological Survey

Presently taking additional Hydrology course work at the University of Arizona

ARTIFICIAL GROUNDWATER RECHARGE CASE HISTORIES IN THE TEXAS SOUTHERN HIGH PLAINS

by

D. C. Signor

Three artificial recharge research projects conducted or participated in by the U.S. Geological Survey's Artificial Recharge Research Center, Lubbock, Texas are briefly described. Information obtained from other sources about recharge operations in the area are also discussed. They are presented to illustrate problems encountered in artificial recharge and emphasize considerations which must be made in the site evaluation process. The recharge operations usually have been of an experimental nature and have been conducted by individual farmers, cities and water districts.

In the case of one institution, the Colorado River Municipal Water District, Big Spring, Texas, a successful recharge operation from 1963 to 1970 was maintained after their initial experimentation in the late 1950's. At this time (1978), no recharge operations discussed except those of individual farmers are being conducted due to a lack of water.

The Southern High Plains

The Southern High Plains lies in West Texas and Eastern New Mexico (Figure 1). They cover a land area of 35,000 square miles or about 22,000,000 acres. The region is a plateau bounded on the north by the Canadian River Valley, on the east and west by escarpments and on the south by the Edwards Plateau. The topography of the area appears generally flat, and slopes at a rate of 8 to 10 feet per mile from an altitude of 4,300 feet above sea level in the northwest to 2,600 feet above sea level in the southeast (Cronin, 1964).

The climate is semi-arid and the only renewable water resource in the area is rainfall (Figure 2). Rainfall varies from about 20 inches in the eastern part declining to about 16 inches in the west and to 14 inches in the southwest. Rainfall is seasonally distributed so that approximately 50 percent falls just prior and during the growing season, but is frequently insufficient to insure successful crop production. The annual evaporation rate for the Southern High Plains (Figure 3) greatly exceeds the rainfall amount (Kane, 1967).

Irrigation on the Southern High Plains developed rapidly after World War II. Of the total 8.9 million acres irrigated in the state of Texas, 6.4 million or 72% are located in the High Plains (Texas Water Development Board, 1977). This irrigation is accomplished by an annual withdrawal of approximately 6 million acre feet of water from the Ogallala Formation. The Ogallala, the principal aquifer underlying the area, is hydrologically isolated. Under recent climatic conditions, less than 0.08 inch (2 mm) of water per year is naturally recharged to the aquifer from rainfall (Theis, 1937; Brown and Signor, 1973). Irrigation thus has caused a decline of the water level in the aquifer averaging about two feet per year, as shown in Figure 4. These data are from a well at Plainview, Texas, about fifty miles north of Lubbock, Texas.

Since it was established that natural recharge is insignificant in relation to withdrawals, farmers may take a depletion allowance from their income tax based on water level declines. The right to do so was determined in a court case Marvin Shurbet, et ux., vs. United States of America, January, 1963 (White, 1963). To this writer's knowledge, the Southern High Plains is the only location in the United States where a depletion allowance for water can be taken.

Presently, the source of water for artificial recharge is rainfall. Rain storms in the area, particularly in the spring and summer, are usually of high intensity and short duration, and produce significant runoff. Runoff into playa lakes in relation to rainfall is shown in Figure 5. Even in dry years, there is usually some runoff. In years of below average rainfall, the few points showing high runoff are probably from rainfall on fields already wet from irrigation. The cluster of points in the lower left portion of Figure 5 show that significant runoff occurs even in years of below normal precipitation. One-half inch of runoff annually would produce approximately 900,000 acre-feet of water from the 22 million acres of the area. In years of above average precipitation, runoff would increase from hundreds of thousand acre feet to some millions. Based on the data presented here, the annual amount of total surface runoff is probably between one to two million acre feet, but estimates have ranged up to a maximum of 5.7 million acre feet (Hauser and Lotspeich, 1968).

After a storm in which runoff occurs, water accumulates in thousands of playa lakes (Figure 6), which represent low points in closed basins. There are few developed streams on the High Plains, and approximately 95 percent of the drainage occurs to playas. The lakes range in size from a few acres to hundreds of acres. Ordinarily, the lakes are a few feet deep and with the prevailing high evaporation rate, most of the water returns to the atmosphere and the lakes become dry. Some water is used directly from the lakes for irrigation, but it usually is available at a time when there is sufficient water on the fields. The playa bottoms consist of nearly impermeable clay and there is little infiltration.

The Ogallala aquifer is a suitable reservoir for storing and thus conserving this water if it can be recharged and withdrawn at an acceptable cost. Rayner (1967) estimated subsurface storage space within a 21-county area of the Southern High Plains is sufficient to store nearly three times as much water as can be stored in all major surface reservoirs in Texas.

Research Projects

Spreading Basin - Lubbock, Texas

A study of recharge through a spreading basin located in a city well field near the Lubbock, Texas Regional Airport (Figure 7) was conducted in 1972-73. The research site is located near a water supply conduit that conducts water to the Lubbock water treatment plant from Lake Meredith, an impoundment of the Canadian River north of Amarillo, Texas. The city of Lubbock provided water for the experiment from their allotment.

Two one-acre basins were constructed (Figure 8). The soil zone from one basin was scraped and the soil was used to build berms around both basins. Thus, one basin had approximately 1.5 feet of the surface soil removed, and the other basin surface was left in its natural state (Figure 9).

Recharge through the scraped basin started on April 12, 1972. Water was supplied continuously, except for a supply line break, for fourteen months (Figure 10), which allowed the effects of long term inundation to be studied. The infiltration rate reached its maximum of about three feet per day about four months after the experiment commenced (Figure 11). The data show a sharp decline and recovery in the infiltration rate the last of June, 1972, which occurred after a supply line break caused the basin to become dewatered for a six-hour period.

The infiltration rate was initially high as the basin soil was wetting and then declined to a minimum one month after start.

As entrapped air was dissolved from the soil, the infiltration rate increased. After the supply line break and basin dewatering, the length of time required to achieve the infiltration rate equal to that just before the dewatering was about 1.5 months, the same time originally required. This is attributed to reintroduction of air into the basin bottom material.

A sharp decline in infiltration rate occurred after the rate reached its maximum four months after the the test started. At that point, the basin bottom material was clogging. The recharge water supply was essentially sediment-free and clogging was due to bacterial growth. Anaerobic bacteria developed at a depth of about four to six inches, and the infiltration rate was reduced because of their activity (Wood and Bassett, 1975). A core sample collected below the basin surface (Figure 12) shows the color associated with the bacterial growth condition that reduced the infiltration rate. The dark color shown in the push core rapidly oxidized to a light brown when exposed to air. Recharge continued, however, at a uniform rate of about 0.5 feet per day through openings in the basin bottom that are assumed to be old animal burrows enlarged by water flow.

The experiment did not include management techniques other than scraping the bottom. The recharge rate might have been increased by sequential use of two or more basins, thus allowing for a drying and oxidizing cycle in each basin when clogging began. A total of 580 acre feet were recharged in the fourteen month duration of the test but appoximately 80 percent of the recharge occurred during the first seven months.

<u>Well Recharge</u> - <u>Stewart Site</u>

A well situated near a playa lake at Dawn, Texas, a small community fourteen miles west of Canyon, Texas, was recharged with untreated lake water in 1971. The well, which is used also as an irrigation well, is still operational and had received recharge as recently as June, 1978. This well is typical of installations used for recharge from playas and is illustrated by Figure 13. An inlet placed in the lake connects by pipe through valving to the well casing. Simply opening the valve allows water from the lake to enter the well, which then cascades down between the pump column and the casing. The lake inlet is enclosed by a hail screen, which removes large floating debris and aquatic life (Figures 14 and 15). The arrangement illustrated in Figures 13-15 permits untreated water to enter a well directly and usually proves unsuccessful because the sediment and biological material in the water result in rapid clogging of the aquifer at the bore hole face.

There are exceptions to the usual lack of success, as in the case of the Stewart well. A few other recharge wells in the Southern High Plains that use this general type of inlet arrangement have been functioning for over twenty years. A characteristic of these successful wells is that they pump sand when they are used as irrigation wells. This indicates that injected material retained near the well bore by aquifer filter action is removed during pumping, and the ability of the aquifer to accept recharge water is renewed (Brown and Signor, 1973). A second and probably more important characteristic of such successful wells is the presence of secondary porosity within the aquifer (Brown and others, 1978). Aquifer materials at the Stewart recharge well site possess significant large secondary porosity.

Water was turned into the well September 30, 1971 at a flow rate of 600 gallons per minute (Figure 16). Recharge continued for thirteen days, at which time the lake had been drained. There was no indication of clogging, and a total of 35 acre feet were recharged.

The water quality of this playa was not typical of that for playa lakes in the Southern High Plains. It was relatively clear, whereas playa lake water ordinarily is heavily laden with suspended clay and silt. The lake bed was covered with a growth of grass and weeds, and the runoff event resulted from rainfall of moderate intensity. The sediment content of the recharge water is illustrated in Figure 17. The variation in sediment content over the recharge period is attributed to differences in wind conditions. The maximum sediment input shown of about 340 kilograms per day is equivalent to a sediment content of about 100 milligrams per liter (mg/l) (parts per million by weight). Typical playa lake water frequently contains from 500 mg/l to a few thousand mg/l of suspended sediment. The Stewart lake was populated with large numbers of ducks along with the usual aquatic life that appears when water gathers after a storm. The water, therefore, had a high total bacteria count which was monitored during the test (Figure 18).

The farmer considers this recharge well to be successful, as it readily accepted untreated playa lake water with no apparent detriment to its production or acceptance of water. Preliminary evaluation of the aquifer by coring and geophysical logging at the site showed a fine grained unconsolidated sand section which gave little encouragement to the probability of success. The presence of a very permeable section in the aquifer was not detected from the cores or logs. The high permeability was identified during recharge by the use of temperature logs (Keys and Brown, 1973, 1978).

A series of temperature logs (Figure 19) made in an observation well during the first week of the 1971 test shows water movement through a thin section of the aquifer (Keys and Brown, 1978). An observation well located 38 feet from the recharge well, was constructed of 2-inch steel pipe sealed at the bottom, and filled with water, was used for temperature logging (Keys and Brown, 1978). The bulge at a depth of 160 feet in the first log on September 30, 1971 (Figure 19), indicates the arrival at that level of the recharge playa-lake water, which was warmer than the ground water, less than four hours after the start of recharge. The subsequent upward expansion of this bulge indicates continuing arrival of recharge water and its movement upward toward the rising water table. Permeability at other depths was lower than that located at 160 feet. The first arrival of recharge water at a depth of 180 feet was not detected until October 3, three days after beginning recharge, and arrival at other depths could not be positively identifed. Temperature at the bottom of the observation well fluctuated less than 0.01 C during the entire test, suggesting little if any water movement at that depth.

Temperature fluctuations at the inlet of the recharge well and at the 160 foot depth in the observation well were plotted (Figure 20), from which time lags between temperature peaks in the injection well and in the observation well were obtained (Keys and Brown, 1978). The time lags indicated the travel time from the recharge well to the observation well. Travel time decreased as the test proceeded, due to a head build up in the recharge well resulting from clogging of the less permeable materials. The reduction in travel time showed that the highly permeable material transmitted water at a higher velocity later in the test under the higher head conditions. Travel time analysis is treated in detail by Keys and Brown (1978). The passage of a cold front in which the temperature of the lake water is below that of the groundwater shows up dramatically in Figure 20, three days after the start of the test.

Since the initial site evaluation did not provide information indicating the presence of the highly permeable section, new techniques of coring were utilized. Prior to the test, the aquifer was sampled by drive-coring, which destroyed the secondary-porosity features within the permeable layer. A new rotary coring system provided samples of the permeable layer (Figure 21) showing the open structure of the material that allowed the recharge well to perform successfully.

Hufstedler Recharge Well

A recharge well was installed near a playa lake about twenty miles northwest of Lubbock, Texas at the Hufstedler site (Figure 22). Construction of this well is similar to that illustrated in Figure 13. The initial site evaluation indicated that recharge at this site might be successful because of a gravel layer present near the base of the aquifer.

Turbid playa lake water containing 550 to 600 mg/l of suspended sediment, primarily clay, was recharged at an average rate of 150 gallons per minute for 21 hours. Immediately after shutoff, the well was pumped to remove the suspended material that had been recharged. The specific capacity of the well after recharge was determined to be 61 percent of the specific capacity prior to recharge. With a reduction of that magnitude, the farmer decided not to continue the test and the experiment was terminated. The experiment is presented in more detail by Schneider and others (1971).

The two recharge well experiments contrast in that the evaluation of the Stewart well led to the conclusion that the site probably was not suitable for recharge, but it was a success; in the Hufstedler well case, there was indication that recharge would be successful and it was not. These results emphasize that site specific characteristics of the hydrologic environment must be adequately determined and evaluated at a potential recharge site. It also illustrates the difficulty associated with accomplishing such an evaluation.

Recharge Operations

Individual Farmers

Farmers in the Southern High Plains area have installed recharge wells or dual-purpose wells used for both recharge and irrigation. These wells are enumerated by an annual Irrigation survey conductecd by the Agriculture Extension Service, Texas A&M University, without comment as to their frequency of use, success, or failure. It is known that some wells in this category have been operated for many years, but few operational data are available. The number of recharge wells listed for the Southern High Plains averaged 139 in the years 1973 to 1977, ranging from 136 to 145 (New, 1973, 1974, 1975, 1976, 1977). It is assumed that these operations recharge some locally significant quantity of water to the Ogallala Formation.

City of Lubbock, Texas

The City of Lubbock, Texas recharged the Ogallala aquifer through municipal wells with water from Lake Meredith, an impoundment of the Canadian River north of Amarillo. The municipal wells were modified for recharge to permit water flow into the wells through the discharge line. Thirty-nine wells received 920 acre feet in 1968 and 1,840 acre feet in 1969 at a maximum rate of 2 million gallons per day (mgd). The water was treated in the city's water treatment plant by filtration and chlorination prior to recharge. No problems were reported. However, recharge has not been conducted since the two reported years because of a lack of surplus water.

City of Midland, Texas

Wells in the McMillen well field, a part of the water supply system for the city of Midland, were used for artificial recharge on three occasions. Prior to recharge, the potentiometric surface contained several drawdown cones in an elongated trough (Figure 23) and from 1953 to 1959 water levels declined as much as 34 feet (Reed, 1959). The first test, in 1957-58, was designed to obtain information on feasibility of recharging the well field. In the test, 335 acre feet were recharged over a 107 day period through wells in the central part of the field and from wells in the northwest corner of the field. The configuration of the resulting mound, computed as the difference between normal recovery and actual recovery with injection is shown on Figure 24. Recharge of 1,391 acre feet in 1965-66 resulted in a more extensive mound (Figure 25). In the latter test, water was obtained from another city well field located thirty miles northwest of the McMillen field (data was furnished by E. L. Reed, Midland, Texas). The McMillen field was also successfully recharged in 1966-67 and 1967-68. No problems were reported, and it was concluded that 1,500 acre feet a year could be stored in the 2 square mile area of the McMillen field and recovered by the city. Water has not been available subsequently, and no further recharge has been conducted (Personal communication, E. L. Reed, Midland, Texas, 1978).

Colorado River Municipal Water District (CRMWD), Big Spring, Texas (Data furnished by W. P. Odom, P.E., Assistant Manager, Colorado River Municipal Water District, Big Spring, Texas, 1978).

The CRMWD experimented in the late 1950's with recharging surface water during winter or off-season months into the Ogallala Formation in Martin County, Texas. Water has been produced from that well field from early in the 1950's until present (1978). Since surface water supplies were developed in the mid-1950's, the well field has been used only to meet summertime peak demands. The recharge experiment proved satisfactory and a recharge operation was started during the fall of 1963.

Surface water was recharged during the winter months, when demand was low and excess pipeline capacity from the city's surface-water supply was available. During summer months, when demand exceeded surface-water supply capacity, the stored water was pumped from the well field. The project continued from 1963 through the winter of 1969-70. At that time, additional surface water supplies and pipeline capacity were developed and the recharge operaiton was discontinued. Over the recharge-operation period, almost 4,900 acre feet of water were recharged.

Chlorination was the only treatment used for the surface water prior to recharge, and water entering the wells had a 1 mg/l residual chlorine content. The water contained suspended solids with a turbidity of 15 to 30 Jackson units. Initially, back wash operations were performed twice a week to remove suspended solids from the face of the well bore. Later, the wells were pumped once a week by operating the pump and surging the well until the water cleared. The only well modification to allow recharge was removal of the check valve in the discharge line to allow recharge water to enter the well through the column pipe and pump.

The recharge operation was considered a success. The indicated recovery rate of the recharged water was between 90 and 95 percent. The wells took approximately the same rate of recharge as they yielded initially from pumping.

Conclusion

Artificial recharge on the Southern High Plains is currently (1978) practiced to a limited extent. Successful recharge operations have been carried out but discontinued because of change in water demands and availability. Generally, water of high quality introduced into the aquifer through wells which initially yielded satisfactorily was accomplished without problems and the water was recovered.

Recharge through wells of untreated playa lake water has generally been unsuccessful. The untreated water contains material which rapidly clogs the aquifer. Wells that have operated for years as both recharge and production wells are those which produce sand, thus allowing for the removal of injected sediment. The presence of large secondary porosity is an important factor in successful recharge when suspended sediment is present in significant quantities.

Recharge by use of spreading basins may be more feasible than recharge by use of wells. The most serious problem confronting spreading-basin recharge is the presence of low permeability between the land surface and the water table. However, the spreading technique is more amenable to management, particularly when the water supply is of poor quality.

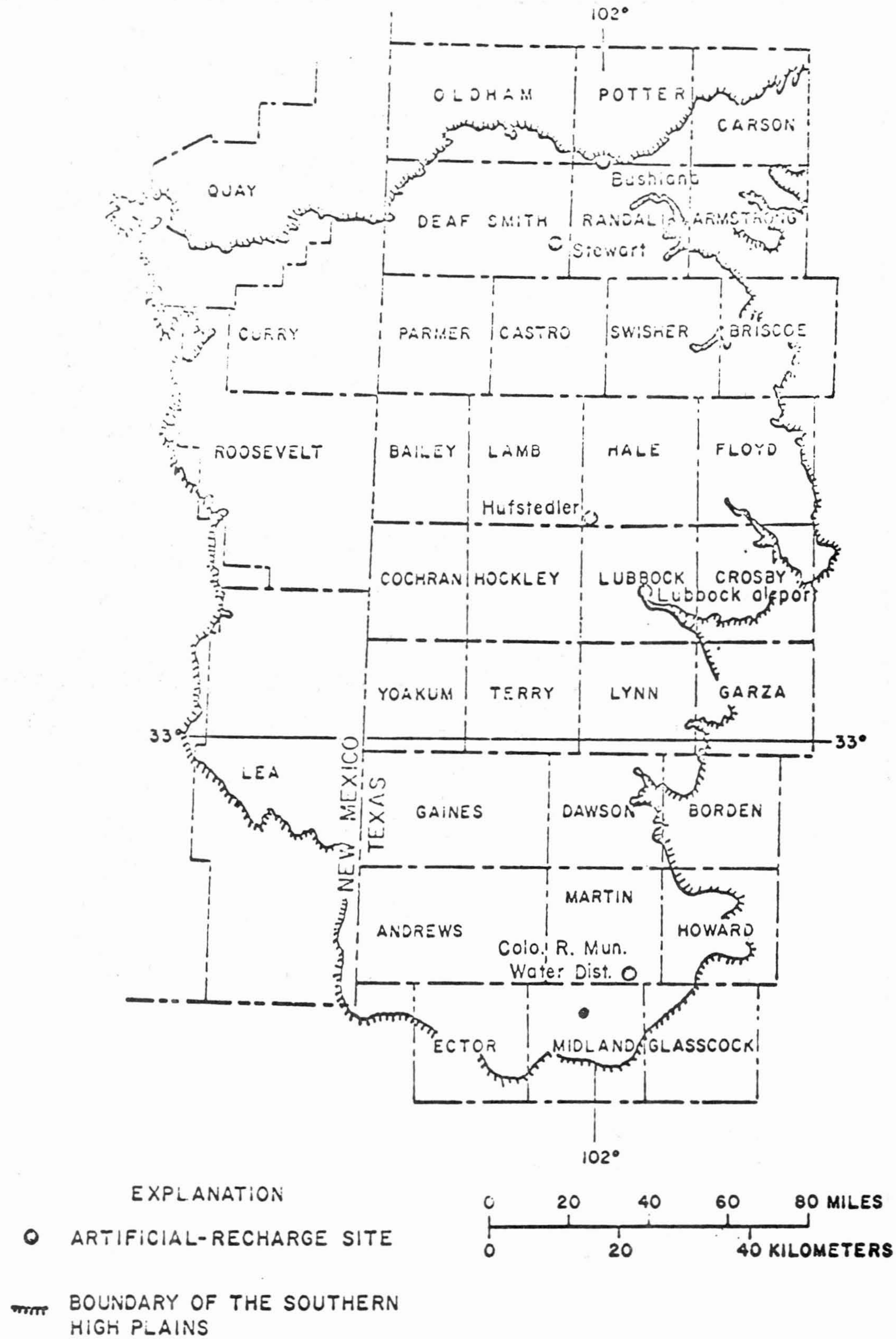


Figure 1.

Locations of Artificial-Recharge Sites

Base from U.S. Geological Survey State base map, 1: 1,000,000

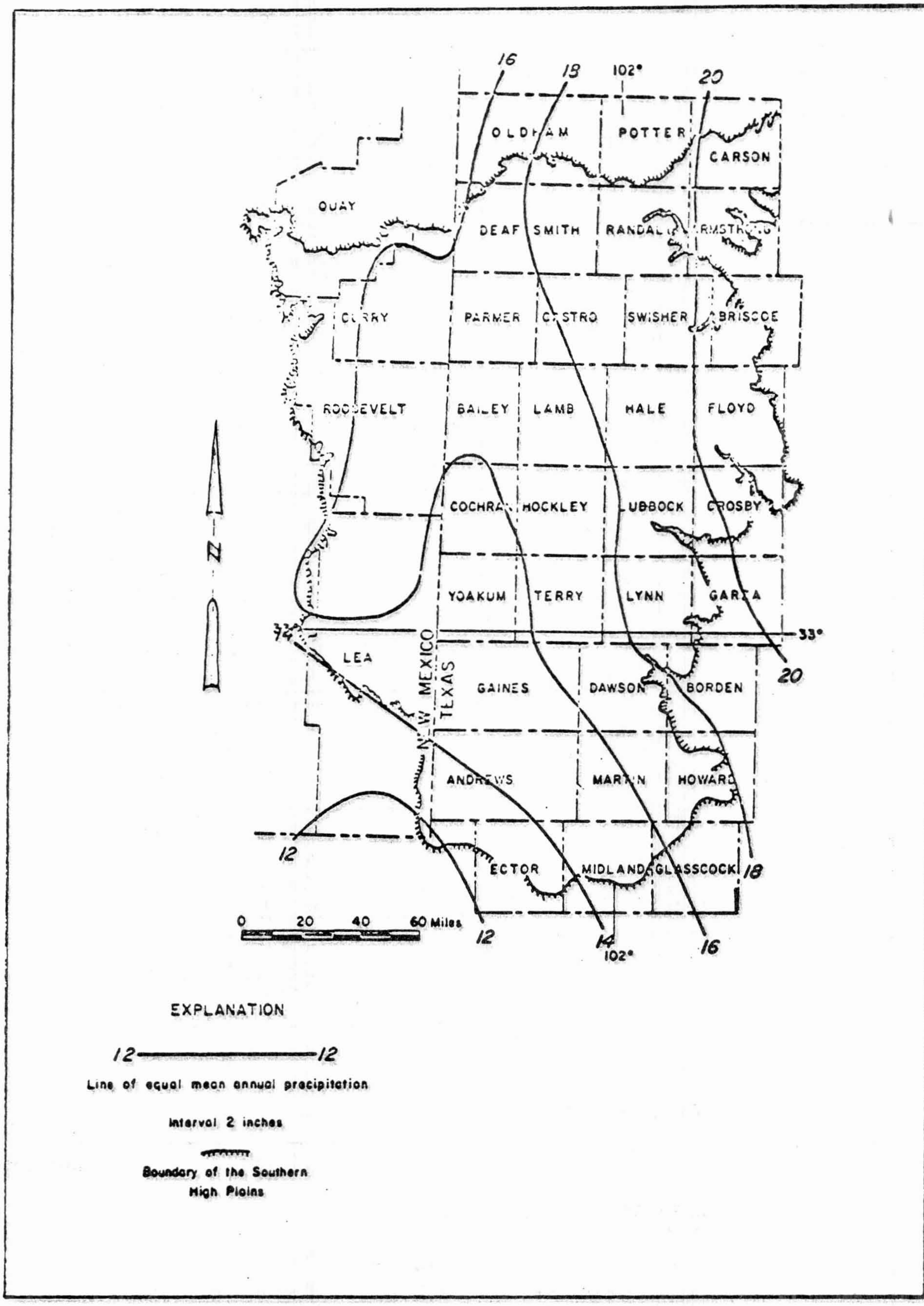


Figure 2. Mean annual precipitation on the Southern High Plains of Texas and New Mexico, 1931-1960.

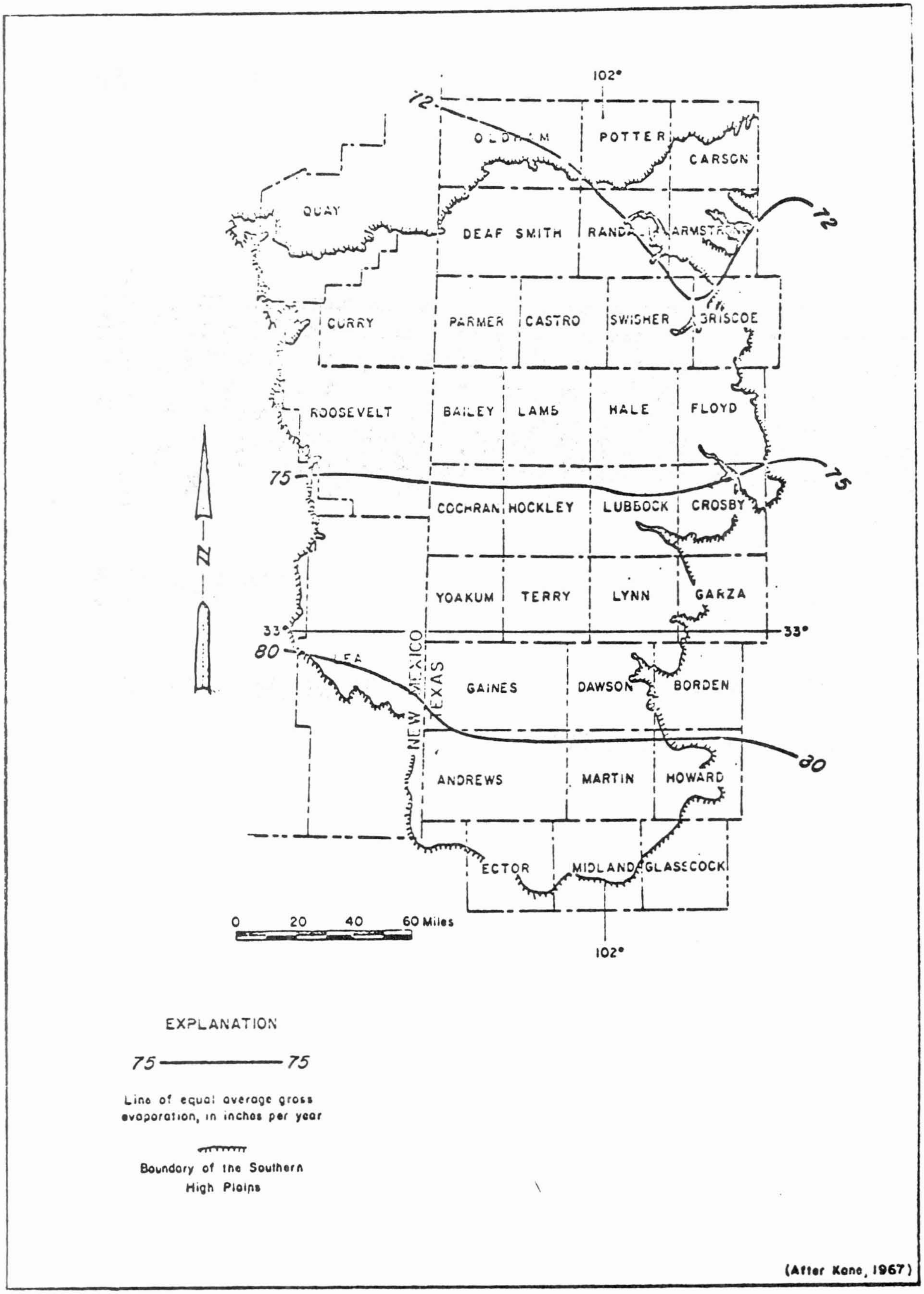
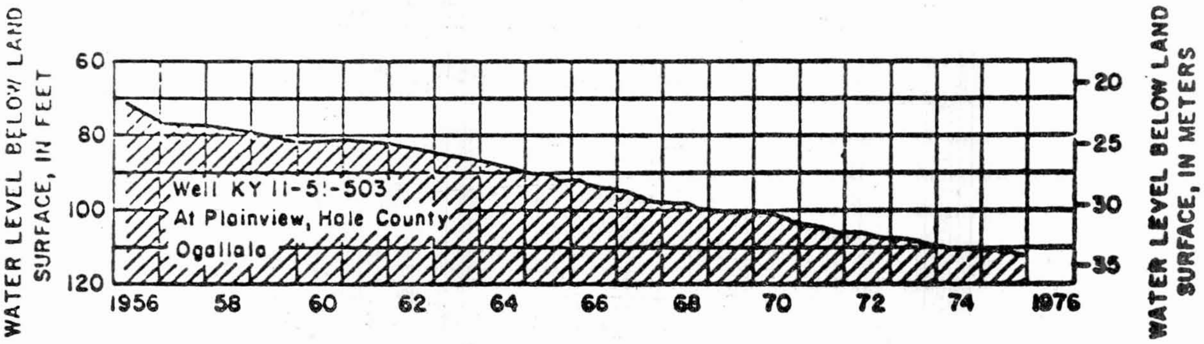


Figure 3. Average annual gross lake-surface evaporation, 1940-1965.



Texas Water Development Board, 1975 p.23

Figure 4. Historical decline of the water level in the Ogallala Formation at Plainview, Hale County, Texas.

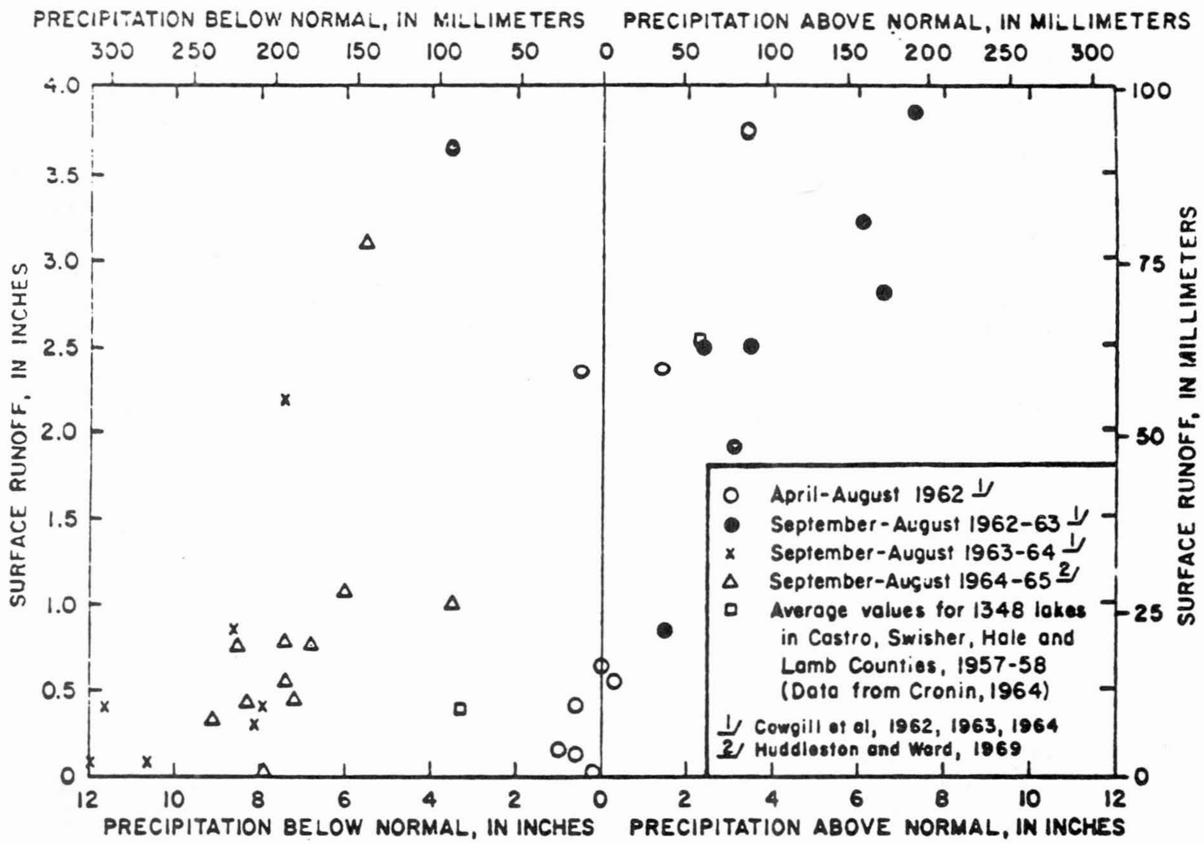


Figure 5. Runoff into playa lakes in relation to rainfall. Data are for Lubbock County, except as noted.

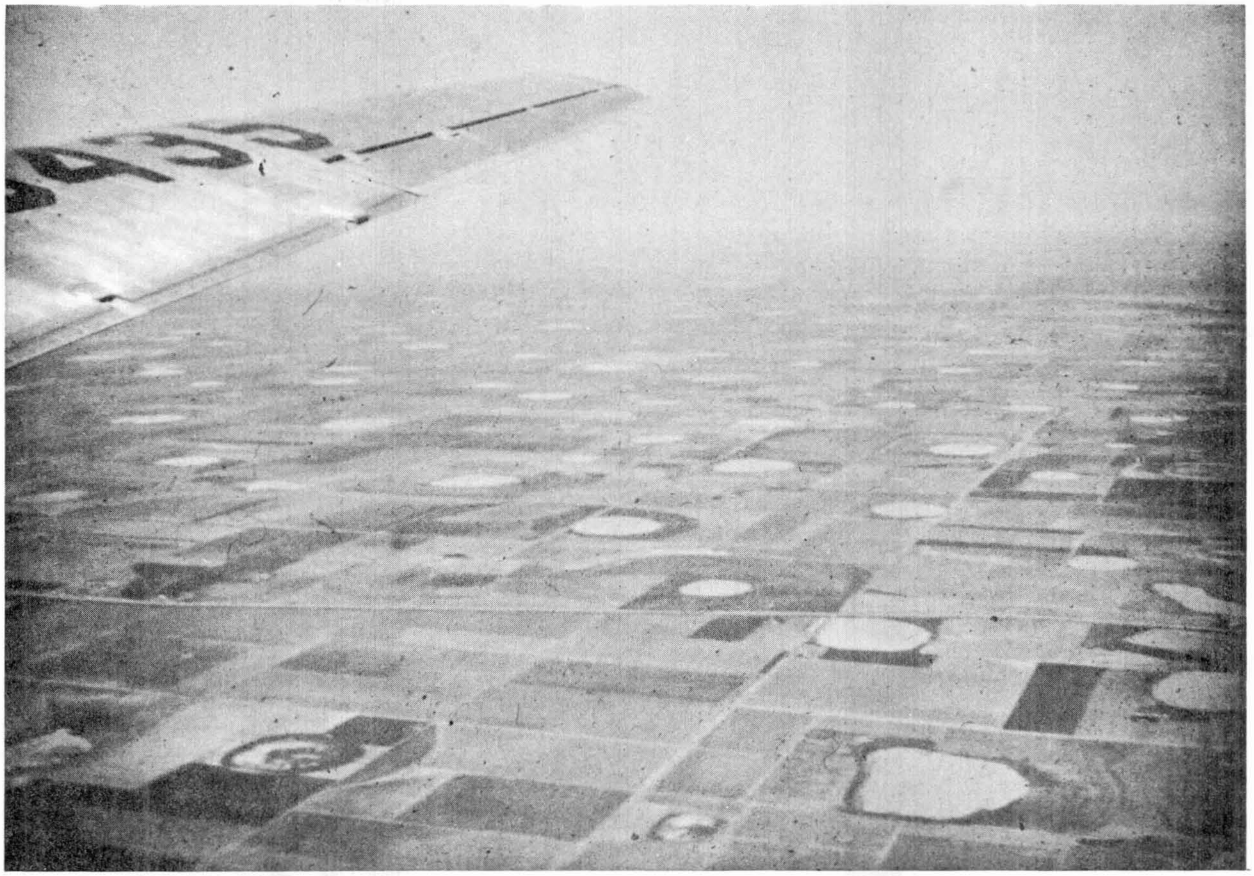


FIGURE 6 - AERIAL VIEW OF PLAYA LAKES AFTER RAINFALL AND RUNOFF

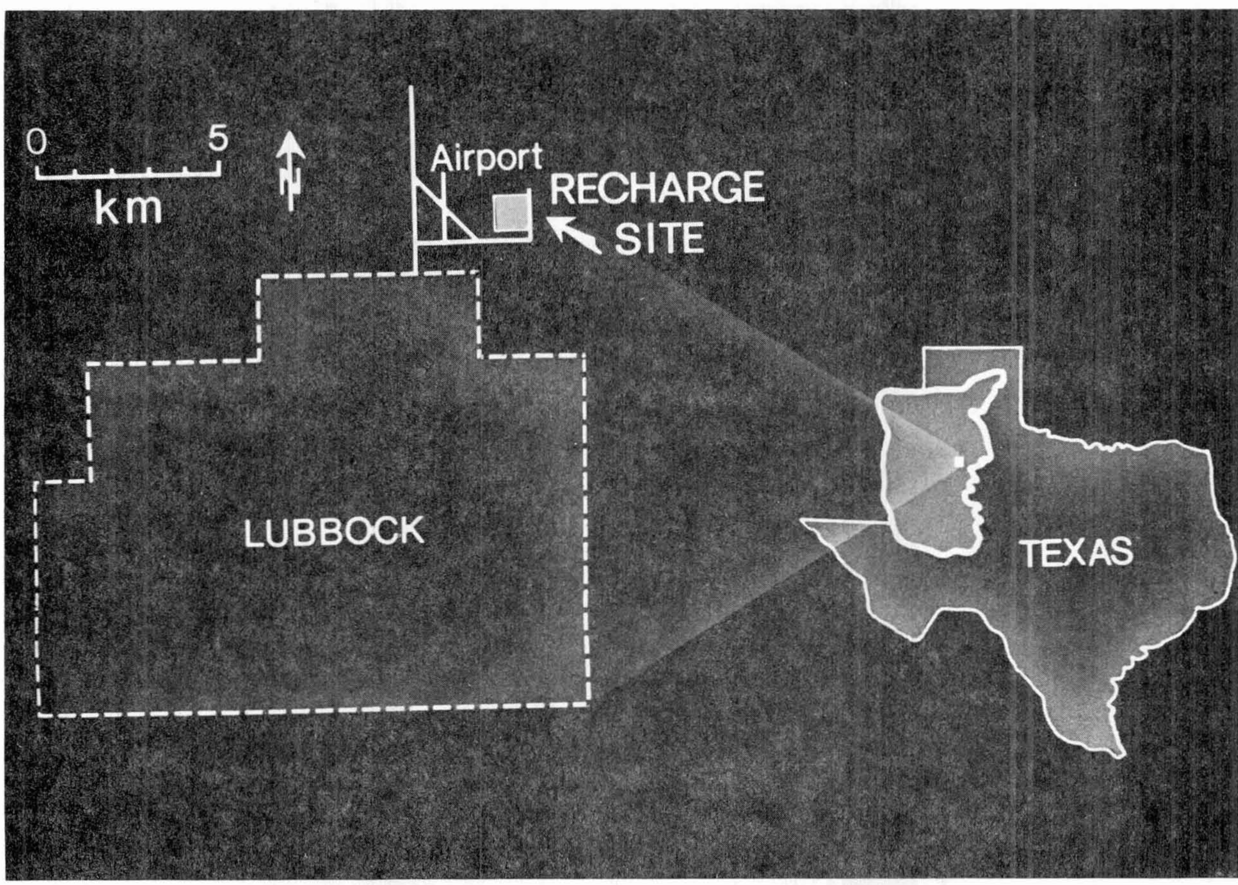


FIGURE 7 - LOCATION OF AIRPORT SPREADING SITE

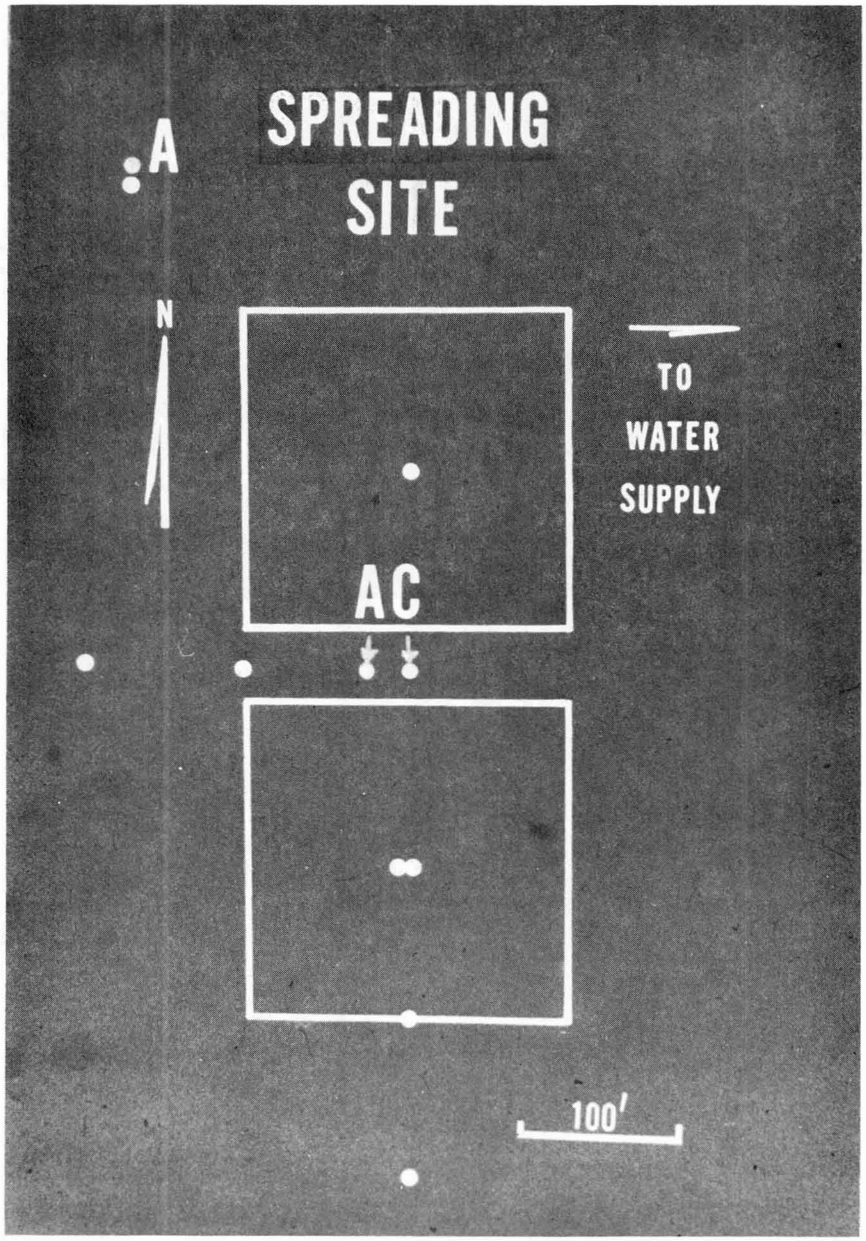


FIGURE 8 - AIRPORT SPREADING SITE PLAN, LUBBOCK, TEXAS

FIGURE 9 - VIEW OF AIRPORT SPREADING SITE, NORTH BASIN, LUBBOCK, TEXAS

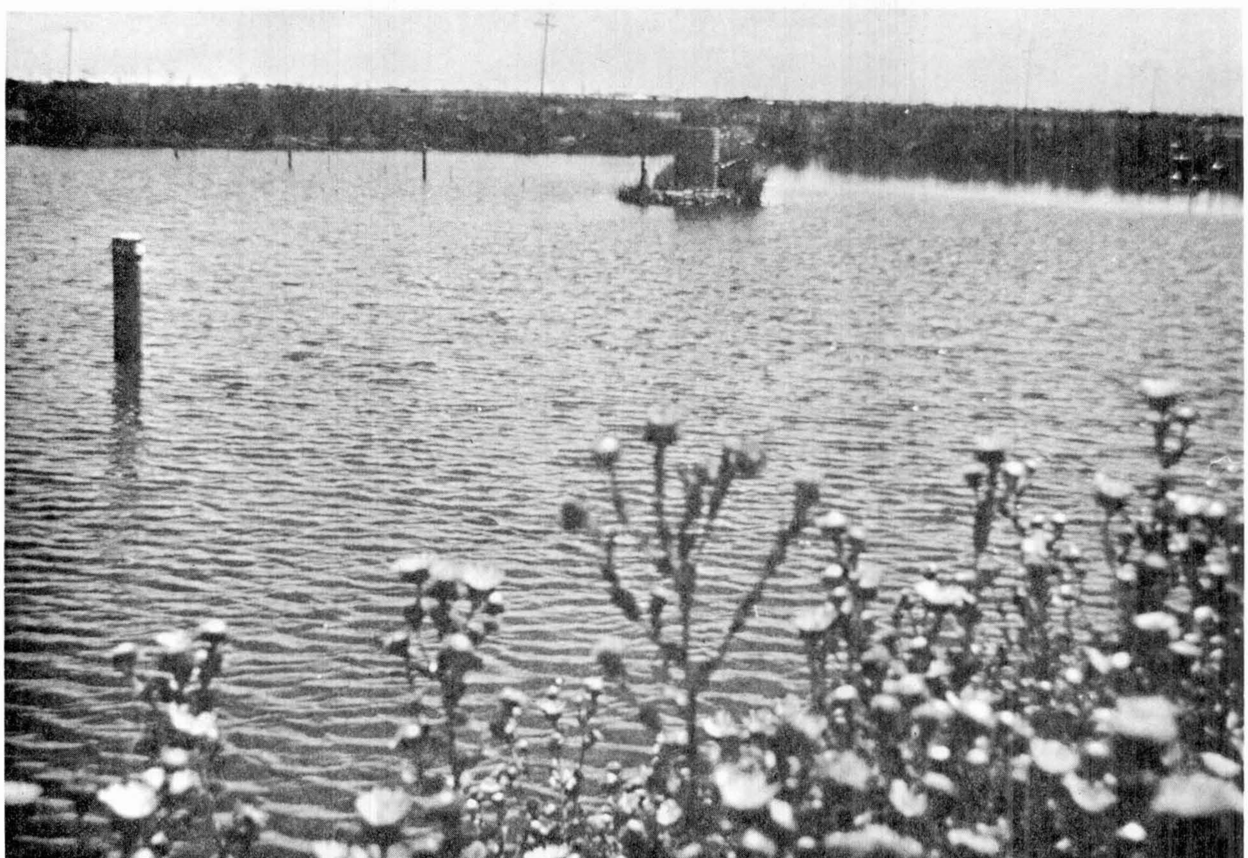


FIGURE 10 - AIRPORT SPREADING SITE IN OPERATION, SOUTH BASIN, LUBBOCK, TEXAS

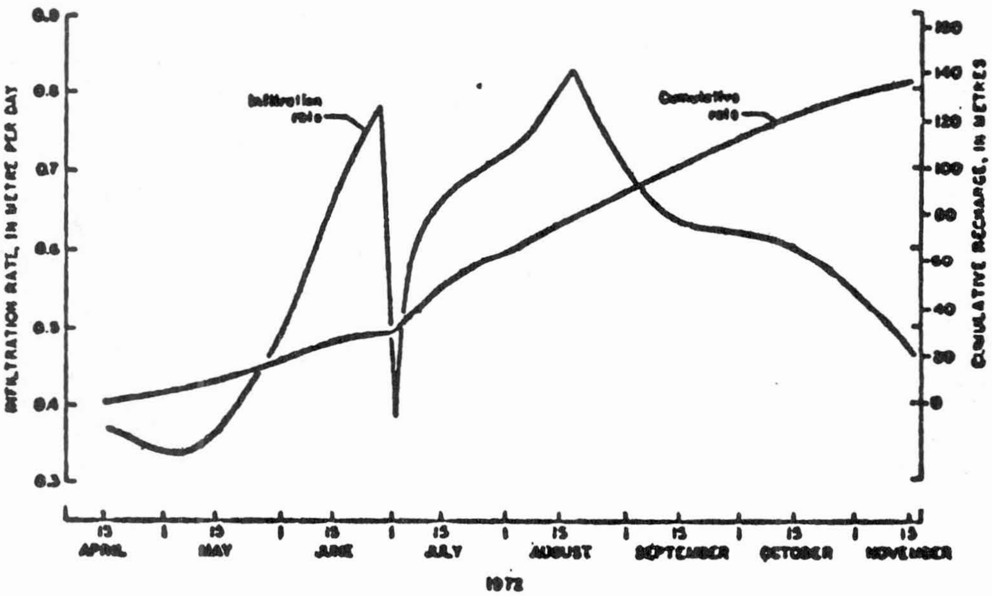


Figure 11. Infiltration rate and cumulative infiltration, airport spreading site, south basin, Lubbock, Texas.

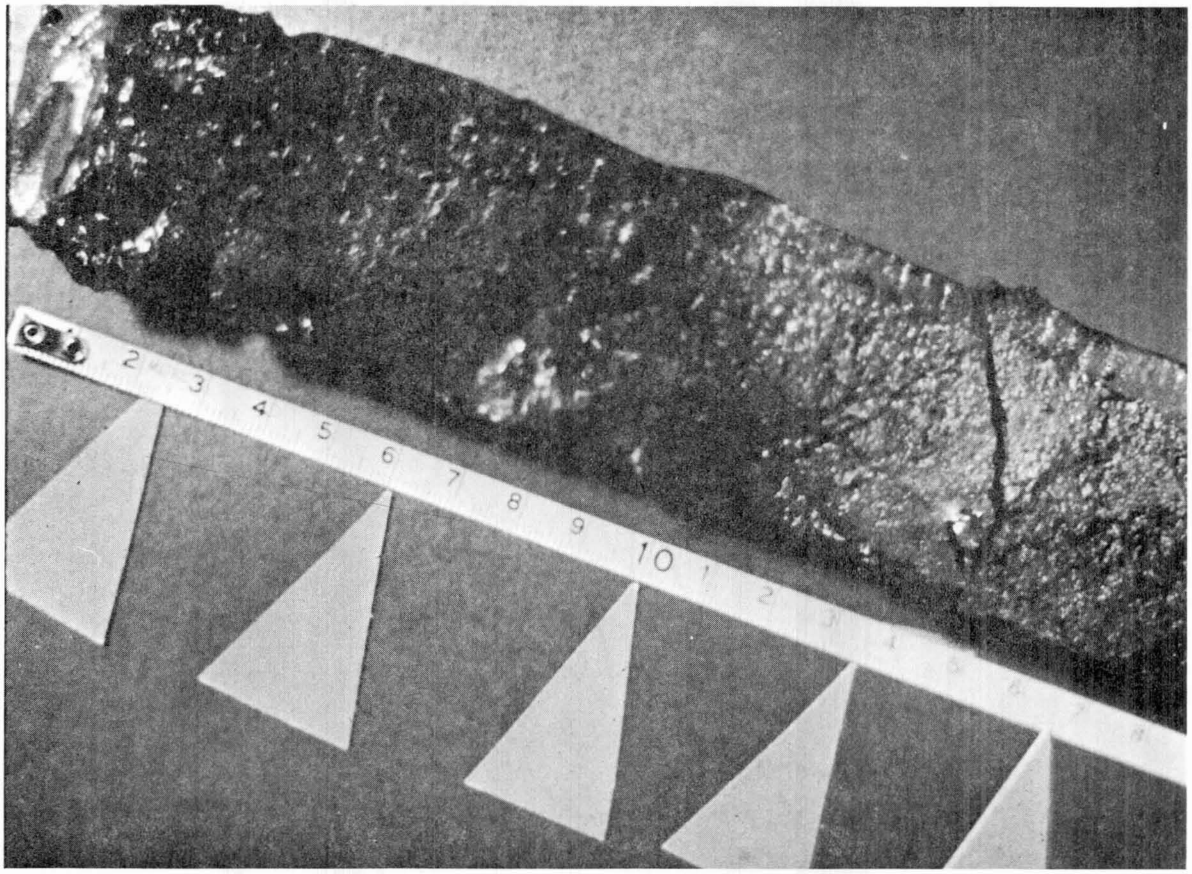


FIGURE 12 - SOIL CORE FROM BOTTOM OF SPREADING BASIN SHOWING ANAEROBIC BACTERIA GROWTH, AIRPORT SPREADING SITE, LUBBOCK, TEXAS

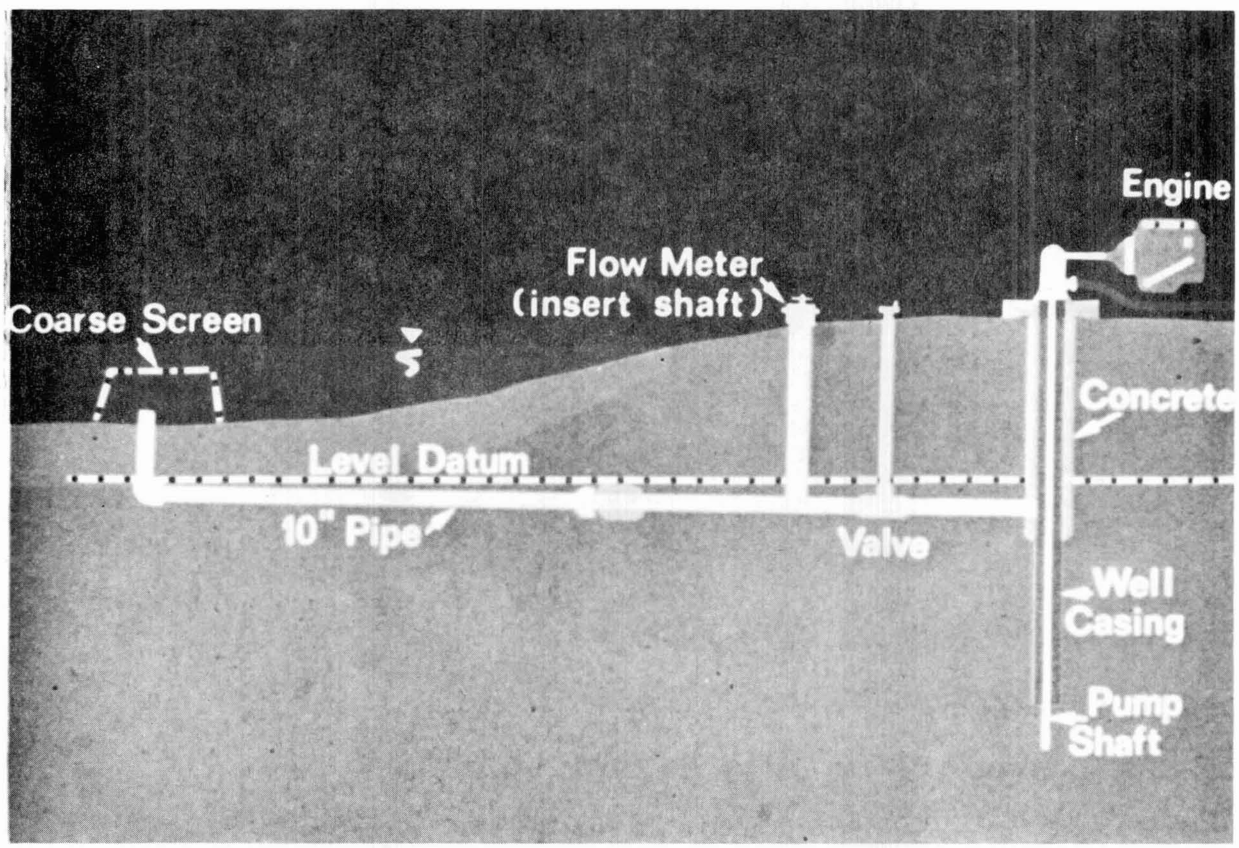


FIGURE 13 - TYPICAL WELL RECHARGE INSTALLATION FOR RECHARGE FROM A PLAYA LAKE

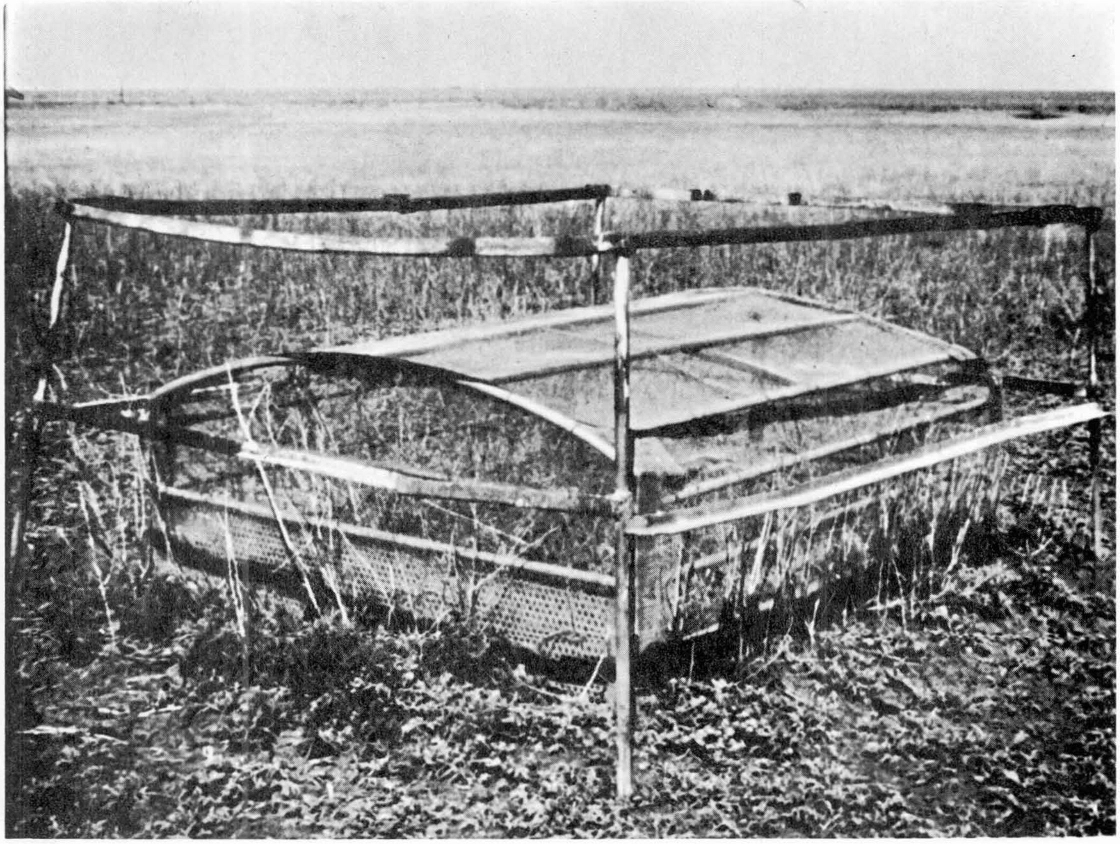


FIGURE 14 - SCREENED INLET TO RECHARGE WELL, STEWART SITE NEAR DAWN, TEXAS

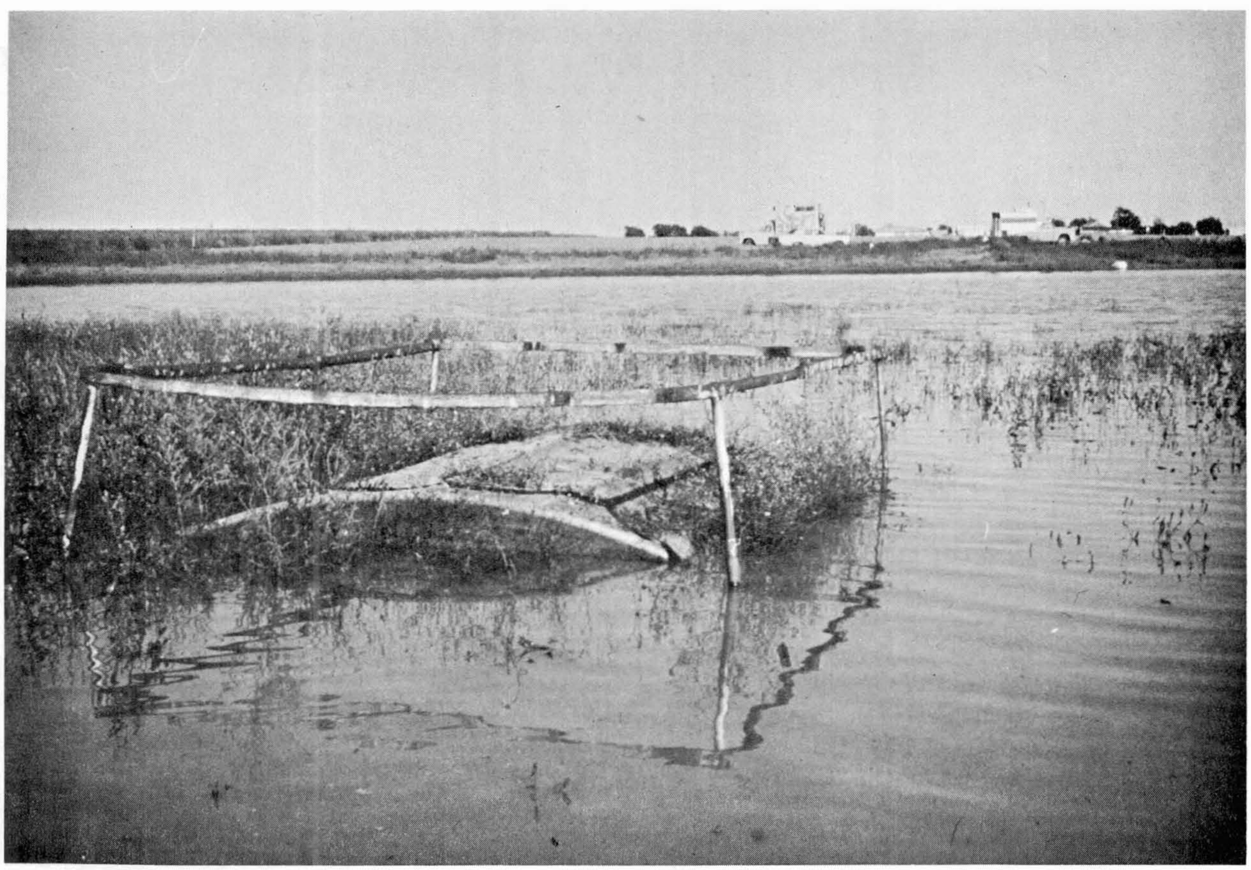


FIGURE 15 - SCREENED INLET TO THE RECHARGE WELL IN THE PLAYA LAKE, STEWART SITE NEAR DAWN, TEXAS

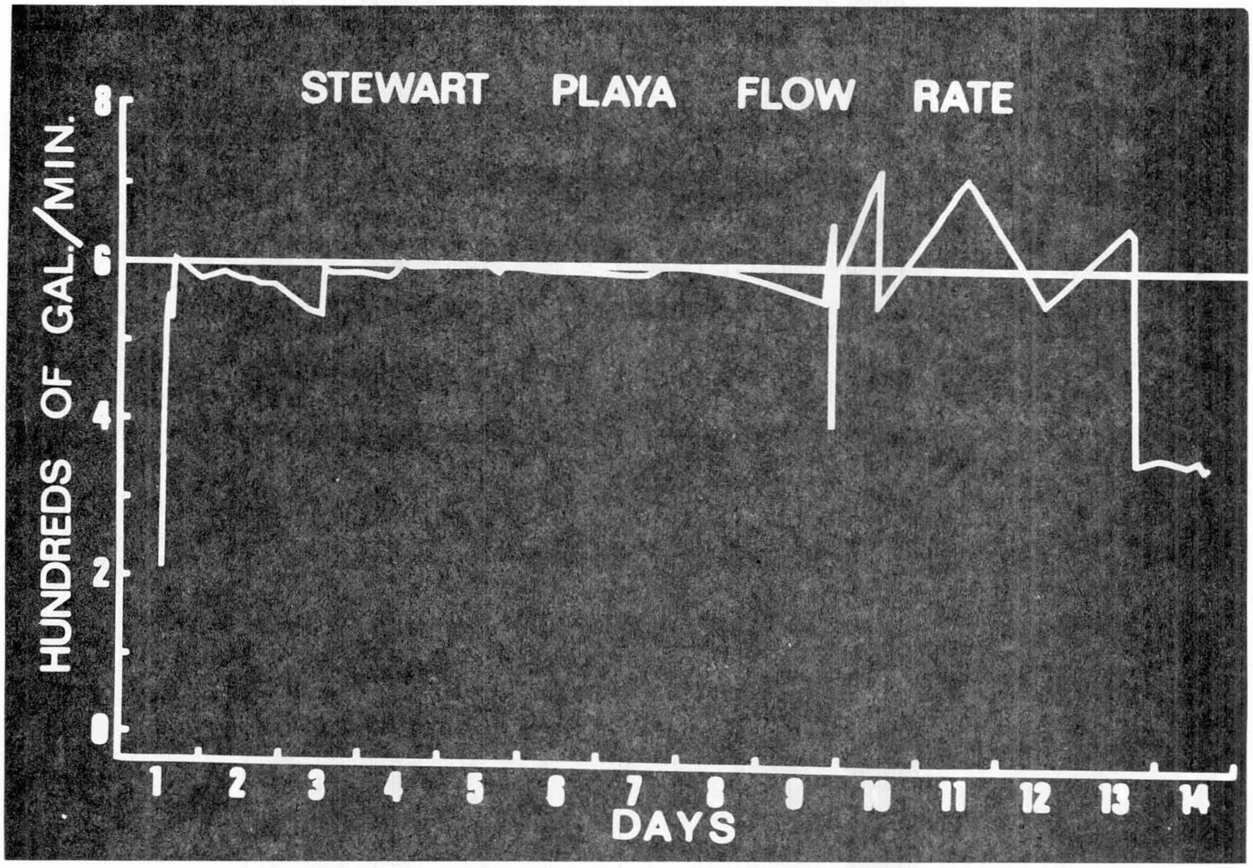


FIGURE 16 - INFLOW RATE, PLAYA LAKE RECHARGE THROUGH STEWART WELL NEAR DAWN, TEXAS

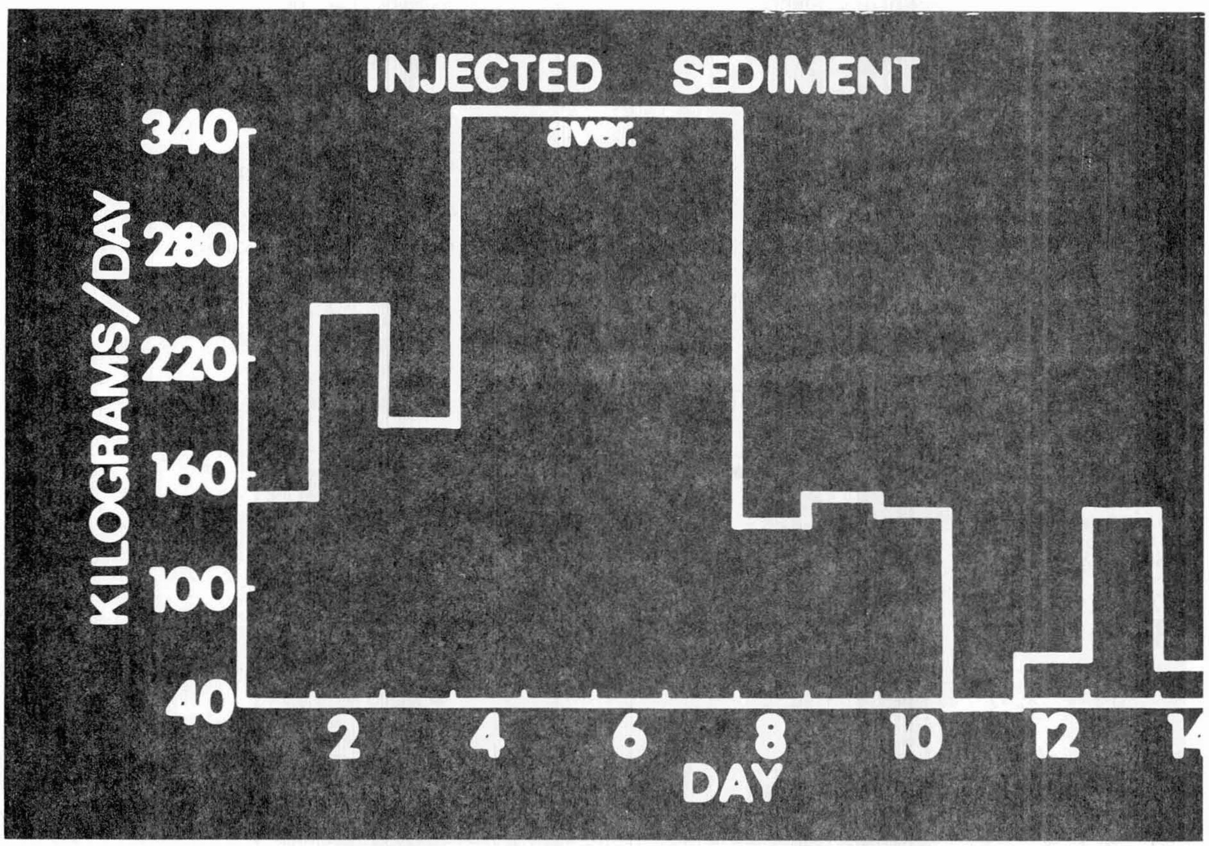


FIGURE 17 - SEDIMENT INJECTION RATE WITH PLAYA LAKE RECHARGE WATER, STEWART SITE NEAR DAWN, TEXAS

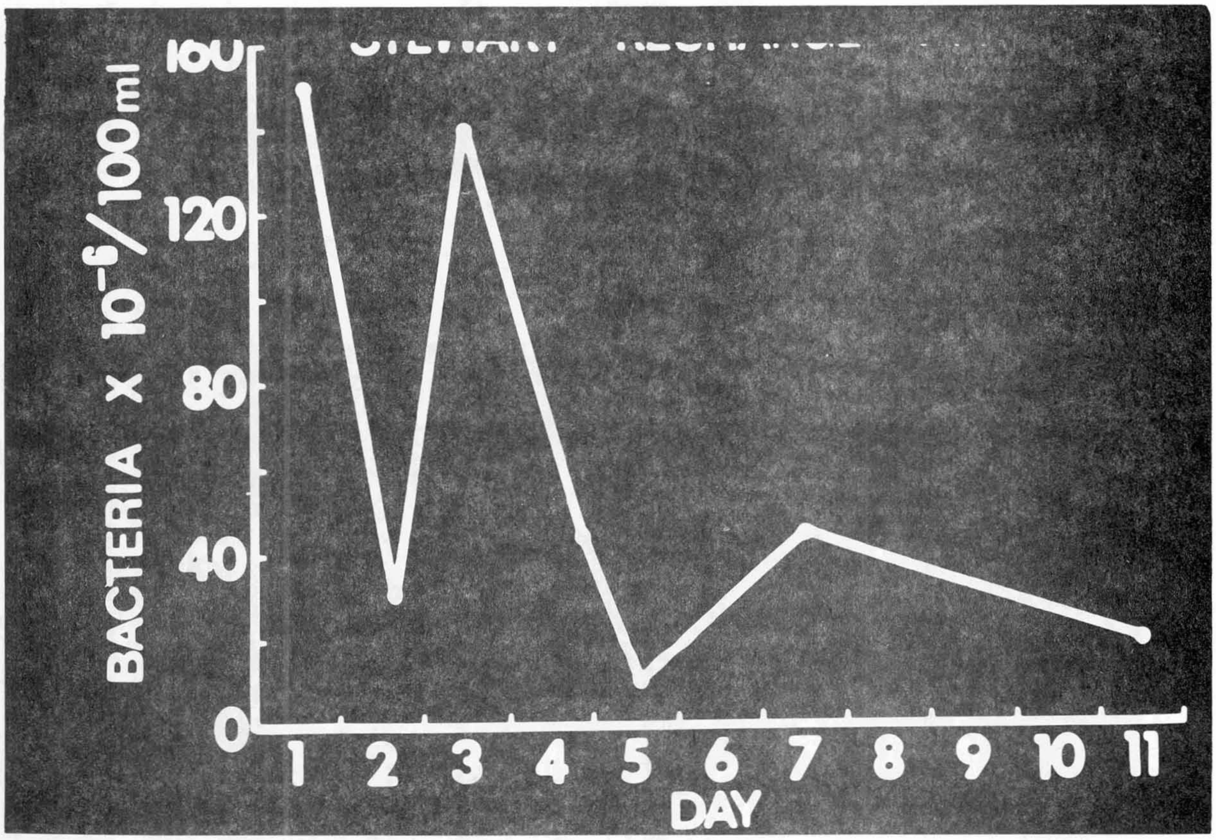


FIGURE 18 - BACTERIA COUNT OF WATER SAMPLED FROM INFLOW DURING PLAYA LAKE WATER RECHARGE THROUGH A WELL, STEWART SITE NEAR DAWN, TEXAS

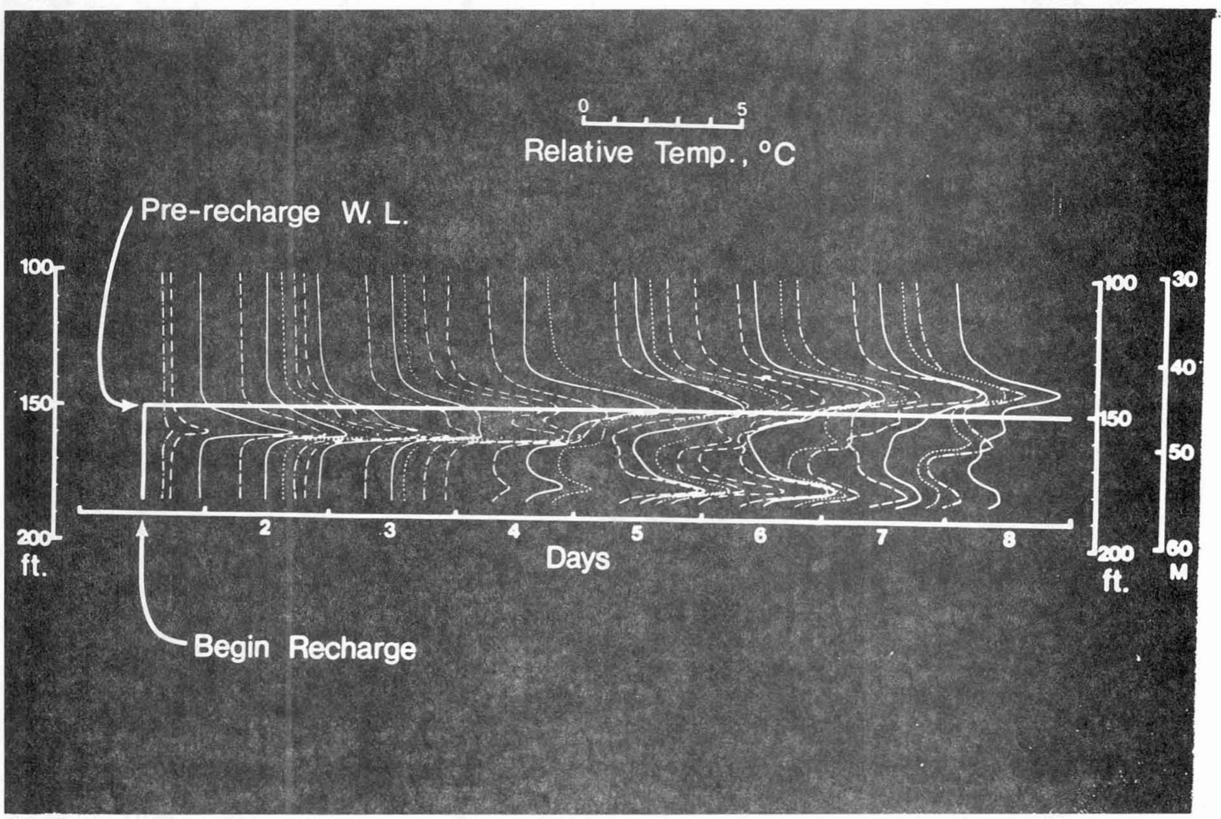


FIGURE 19 - TEMPERATURE LOGS ON AN OBSERVATION WELL, STEWART SITE. RELATIVE TEMPERATURE SCALE IS THE SAME FOR EACH LOG BUT DISPLACED TO SHOW TIME. BOTTOM HOLE TEMPERATURE APPROXIMATELY 15°C on each log (KEYS AND BROWN, 1978)

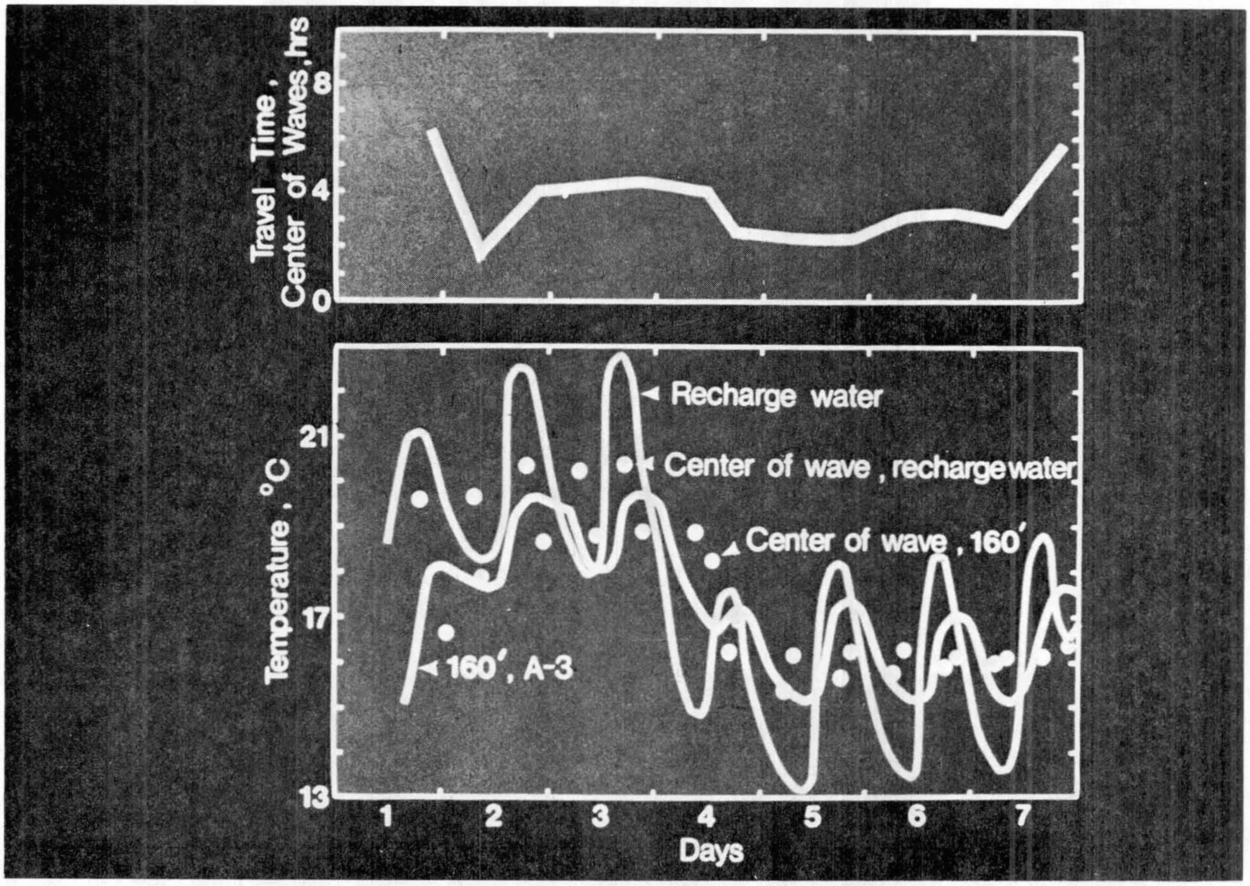


FIGURE 20 - LOWER HALF - TEMPERATURE FLUCTUATION OF RECHARGE WATER AND WATER IN AN OBSERVATION WELL AT A DISTANCE OF 38 FEET AND DEPTH OF 160 FEET; UPPER HALF - TRAVEL TIME OF THE DIURNAL TEMPERATURE WAVES AS MEASURED BETWEEN THE CENTERS OF WARM AND COLD PULSES (KEYS AND BROWN, 1978)

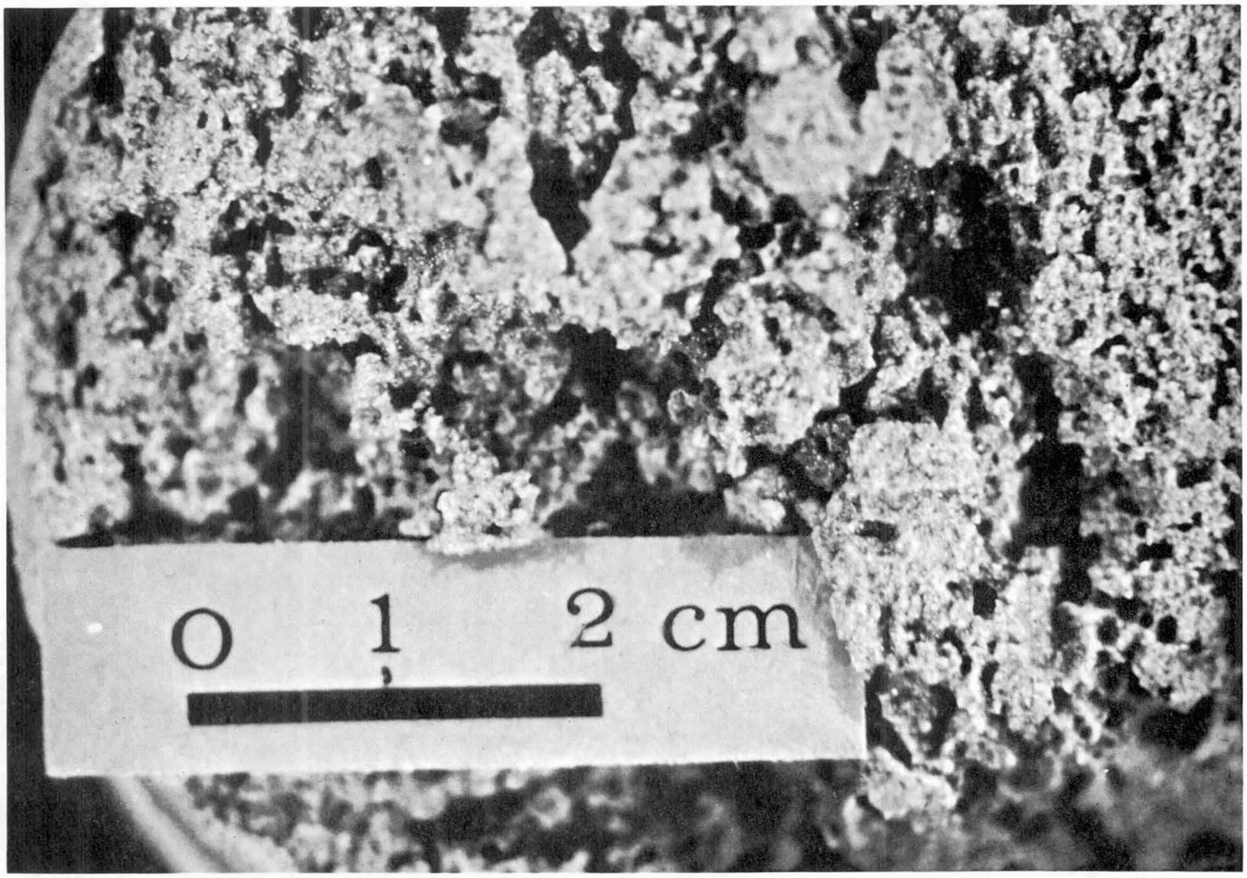


FIGURE 21 - CORE SAMPLE FROM PERMEABLE SECTION AT 160 FEET DEPTH SHOWING LARGE SECONDARY POROSITY, STEWART SITE NEAR DAWN, TEXAS

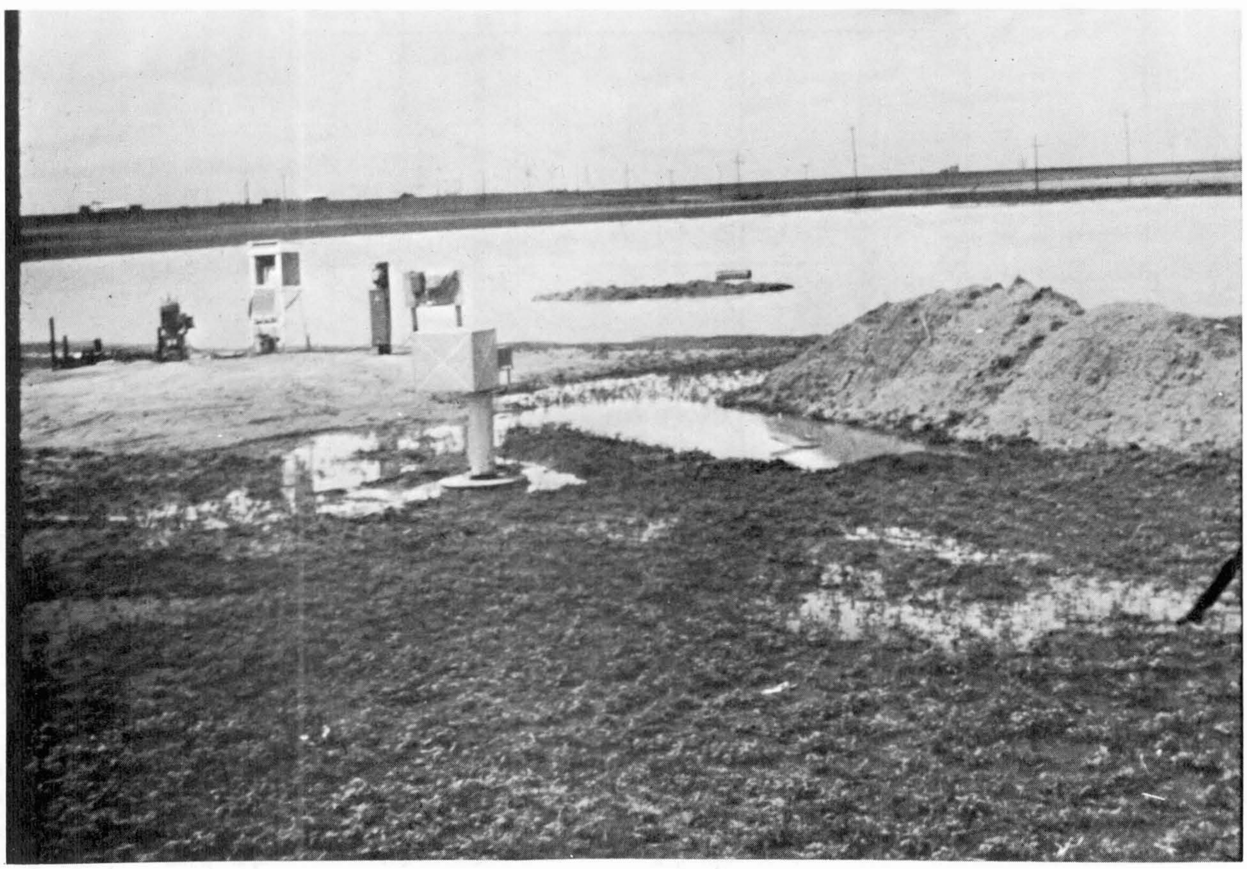


FIGURE 22 - VIEW OF HUFSTEDLER WELL RECHARGE SITE NORTHWEST OF LUBBOCK, TEXAS

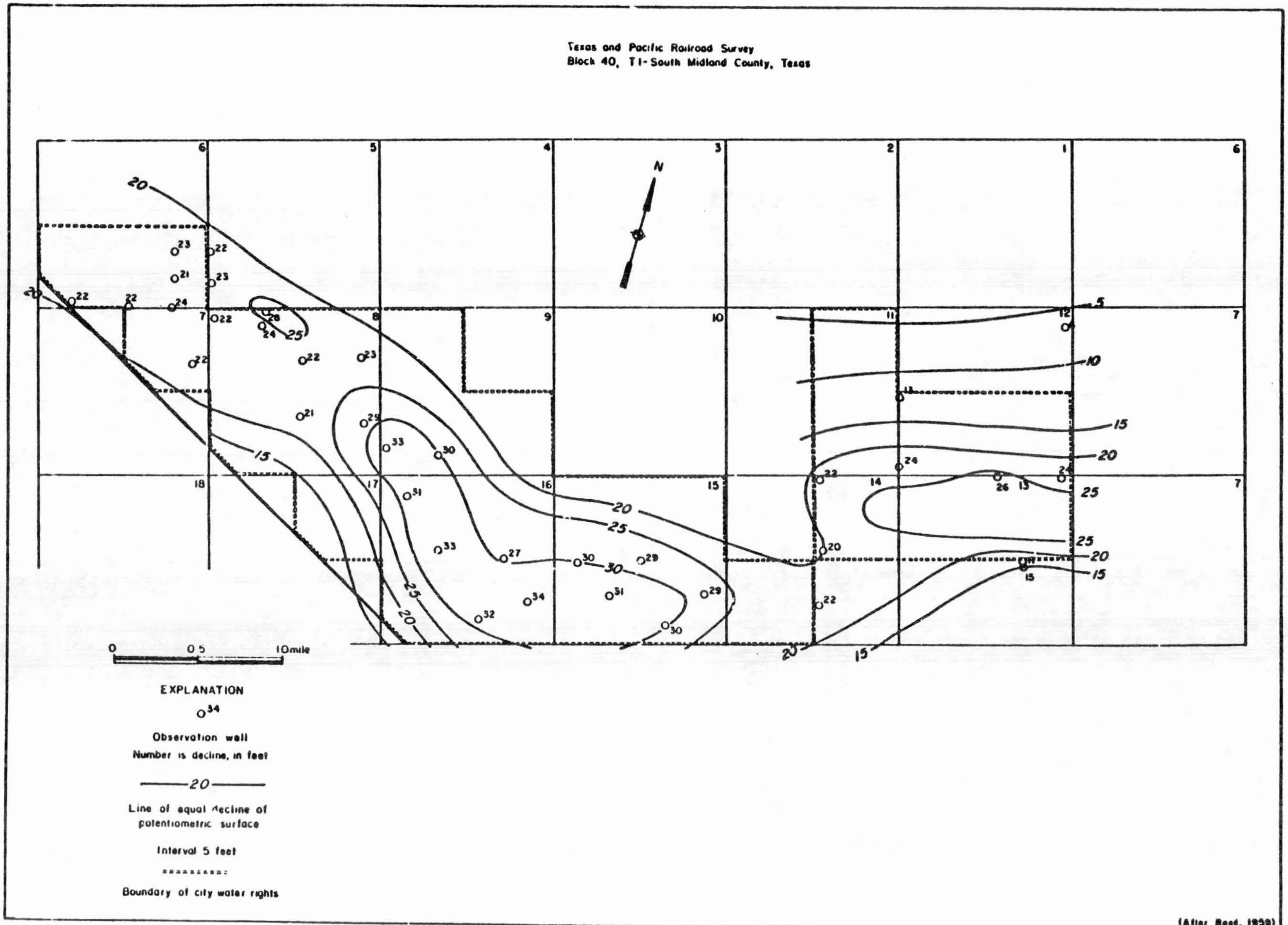


FIGURE 23 -Decline of the potentiometric surface in the McMillen well field, Midland, Texas, 1953-59

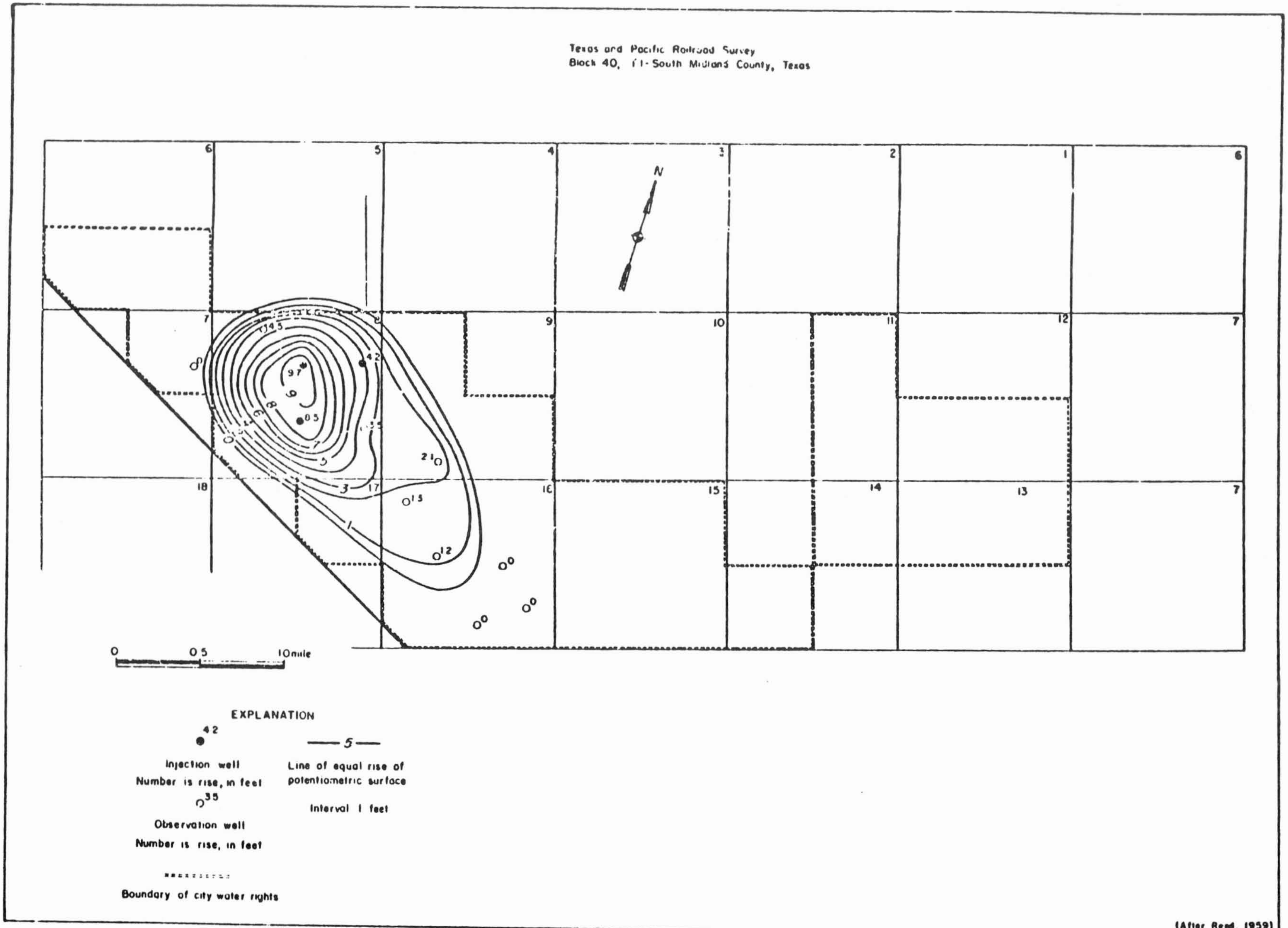


FIGURE 24 -Potentiometric surface of a recharge mound in the McMillen well field, Midland, Texas, 1957-58

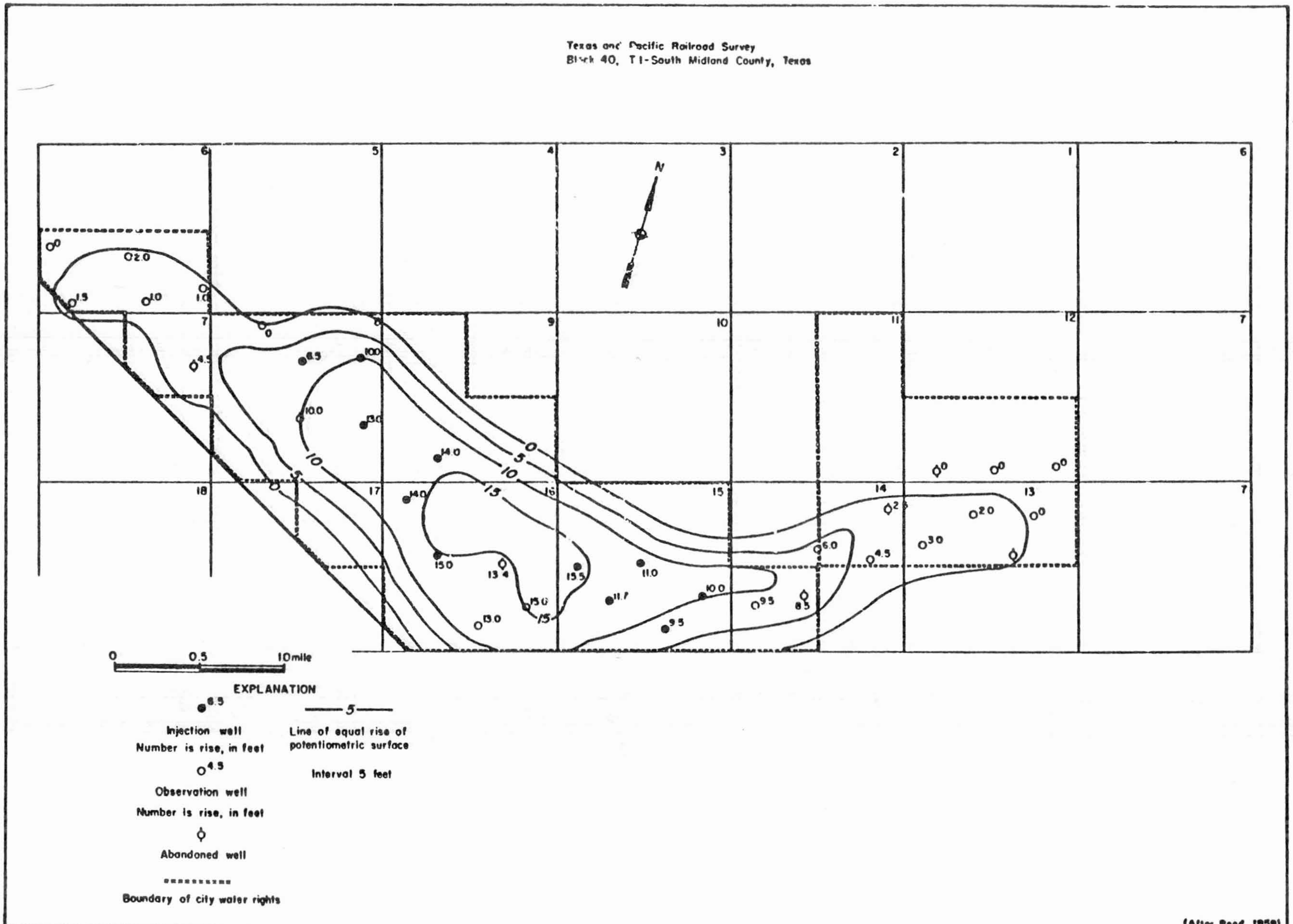


FIGURE 25 -Potentiometric surface of a recharge mound in the McMillen well field, Midland, Texas, 1965-66

AUTHOR'S BIOGRAPHICAL SKETCH

NAME: L. G. Wilson

EDUCATION:

B.S. Degree in Agriculture from the University of British Columbia

M.S. Degree in Irrigation Science from the University of California at Davis

PhD Degree in Soil Science from the University of California at Davis

JOB POSITION: Hydrologist for the Water Resources Research Center at the University of Arizona, Tucson, Arizona

EXPERIENCE:

Irrigation specialist at the University of California at Davis conducting drainage-salinity studies

Responsible for conducting research on artificial groundwater recharge and groundwater quality monitoring at the University of Arizona

CASE HISTORY - GROUNDWATER RECHARGE IN ARIZONA

by

L. G. WILSON

The recent drought in the western states highlighted the importance of groundwater for mitigating deficiencies in surface water supplies. In Southern Arizona where drought conditions are quite common, the economy is heavily based on the mining of groundwater. Groundwater usage is particularly significant in the Tucson area where there are no reliable surface water supplies.

In response to an explosive population growth in Arizona, the stress on groundwater resources is increasing. Inasmuch as pumping exceeds natural recharge, groundwater levels are steadily decreasing with recession rates ranging from 2 feet per year in the Salt River Valley to 14 feet per year in the Harquahala Valley. In light of heavy mining of groundwater, considerable effort has been expended by various local, state, and federal agencies to quantify natural recharge and to evaluate the potential of artificial recharge.

The main focus of my presentation will be on three case histories of artificial recharge. I do not mean to imply by this that studies on natural recharge are not of equal or greater significance. In fact, I could be accused of remissiveness, and if I did not acknowledge the valuable studies of the Geological Survey; for example, those of Briggs, Warho and Shummann in characterizing recharge in the Salt River Valley, or by Sebenick of the State Land Department in examining recharge in the Gila River downstream of Gillespie Dam. The studies by the U.S. Geological Survey and the University of Arizona in characterizing recharge in the Santa Cruz River and its tributaries of the Tucson basin should also be mentioned. Similarly before discussing specific cases of artifical recharge, we should briefly inventory significant recharge mechanisms taking place at the present time.

Artificial recharge (or alternatively, culturally-modified recharge) in the state occurs primarily as a result of return flow to groundwater from irrigation. This may account for as much as 40% of the applied water in certain areas. Canal seepage is another primary source of artificial recharge. Seepage of municipal waste water during disposal in ephemeral stream channels in Phoenix and Tucson should be mentioned, as well as seepage from septic tank, leaching fields, and seepage from pits, ponds and lagoons.

The first example of artificial recharge presented relates to the disposal of urban runoff. In both the Phoenix and Tucson metropolitan areas, urban runoff constitutes both a nuisance and a valuable resource. Studies have been conducted by Sal Resnick and his students at the University of Arizona to determine techniques for improving the quality of urban runoff for alternative uses such as park irrigation. Concurrently, McGuckin Drilling, Incorporated, has developed and installed a number of dry wells, or recharge shafts for draining runoff from paved and grassed areas.

Figure 1 is a cross section through one of the dry wells. It constitutes two basic components; an upper region, which is essentially a catch basin and a lower dry well section. Water spills into the catchment where sediment settles out. The water then overspills into a connecting pipe down into the lower region which is actually a dry well or a recharge shaft. These shafts may be as much as 100 feet deep, but normally they are less than 85, and mostly around 35 feet deep. During construction, the well is excavated until very coarse sediments, primarily sands and gravels, are encountered. Generally, five to twenty feet of these materials are uncovered to ensure rapid drainage from the lower region.

Precast concrete lines, with perforations in the permeable region and in the catchment basin, allow drainage into a gravel pack around the outside. The well is usually constructed with a bucket auger, four foot in diameter, and then reamed out to about six feet in diameter. The annulus between the liner and the wall of the hole is filled with washed gravel.

Figure 2 is a picture of the drill rig in operation during installation of a well near the Arizona State Senate Building.

Figure 3 shows the reaming tool used to ream out the diameter of the hole to a six-foot diameter.

Figure 4 is a down-hole picture showing the kind of materials encountered during drilling. Occasionally tight regions favoring perching are encountered. The holes are drilled below such regions.

Figure 5 is a view of a perforated section of the liner being lowered in the cavity.

Figure 6 shows the installation of the catchment basin liner and the connector pipe.

Figure 7 is a final view of the assembly looking down the catch basin, showing the screen which filters out larger materials during overflow. As indicated above, the exterior of the annulus is backfilled with washed gravel.

Figure 8 is a completed installation within a retention basin in a housing development. For such developments, it is frequently required that water be drained within 36 hours so several of these units may be installed to ensure drainage.

With these units the sediment is probably effectively removed by the catch basin. However, the fate of organics and bacteria has not been examined.

The second case history of artificial recharge briefly reviewed relates to the studies of Dr. Herman Bouwer and his associates on land treatment of sewage effluent. In both the Phoenix and Tucson areas, sewage effluent is a very valuable resource for reuse purposes.

In the past, this effluent has been drained into dry channels, the Salt River and the Santa Cruz River. Recharge occurs during flow in the channels but a large volume flows out of the region where it could be reused effectively. One problem with reuse of effluent, of course, is that the quality needs to be upgraded to expand the number of potential uses. Land treatment such as conducted at the Flushing Meadows Project, is a very effective and relatively economical technique for upgrading effluent quality.

Figure 9 is an aerial view of the Flushing Meadows Project, operated by Dr. Bouwer and his associates at the Water Conservation Laboratory in cooperation with the Salt River Project. The facility is located downstream of the 91st Avenue Treatment Plant. Water is diverted into the project area and spread in recharge basins which are 20' by 700' long. The basins are well instrumented with a number of monitoring facilities which we will describe briefly.

Figure 10 shows one of the basins, including a critical depth meter and water stage recorder.

Figure 11 represents a cross-section of soils underlying the Flushing Meadows Project. The water table is about 10 feet at the site. As shown on the picture, the overlying materials are sandy loam, underlain by a very coarse gravel. For such conditions, clogging will occur primarily at the surface where clogging substances can be readily removed in order to sustain favorable intake rates. This is a more desirable situation than if the layers were reversed, in which case it would be very difficult to reclaim or renovate the gravels.

Another view of one of the spreading basins is shown on Figure 12. The tensiometer networks shown here measure the head loss across the surface. The worker is inserting a neutron moisture logger in an access well to obtain a water content in the soils beneath the basin.

One of the prime objectives of Dr. Bouwer's experiments was to arrive at optimal wetting and drying cycles to effect treatment. Treatment considerations involve reduction in nitrates, which are a severe problem and removal of micro-organisims and organics.

To maximize efficiency, a facility should be operated as continuously as possible. At the same time, intake rate should be sustained to the maximum extent. By experimenting with a number of cycles on these field studies, supplemented with laboratory column studies (see Figure 13), Bouwer and his associates determined that a loading rate of 200 feet per year reduced about 60% of the nitrogen in applied effluent compared to a loading of 400 feet per year which resulted only in 30% removal of nitrogen.

They also found that B.O.D. and suspendedd solids were effectively reduced. For example, fecal bacteria were essentially eliminated after 200 feet of travel. Virus removal was very effective as was phosphate removal. A certain amount of residual organics remained, however, in the form of total organic carbon which indicated that water should be recovered before mixing extensively with potable groundwater supplies.

Based on the results of these experiements, Dr. Bouwer in a cooperative study with the City of Phoenix, constructed a larger facility downstream of the 23rd Avenue Sewage Treatment Plant. The facility comprised an 80-acre oxidation pond and four spreading areas. Figure 14 is a diagramatic representation of the facility.

Because of the need to recapture this water rather than allowing it to mix with groundwater and move beyond the system, a series of wells will be installed between the second and third basin. At the present time, one of the wells has been installed. The operation of these wells would produce a groundwater gradient towards the wells. By monitoring water levels in observation wells on the edges of the facility, pumping would be adjusted to ensure a gradient toward the recovery well.

Flow patterns are shown on Figure 15. In operation, two of the basins are operated at one time. The checks are 10 acres in size.

Figure 16 is an aerial view of the facility with all four basins in operation. Figure 17 is another view showing the discharge well. The water table at this location is about 80 to 100 feet - the well is 200' deep. The large capacity of the pumping plant is favorable for recovery purposes. Figure 18 is a geologic cross-section near the Salt River showing the kind of materials underlying both Flushing Meadows and the 23rd Avenue facility. Very permeable materials are interlayered with finer material.

A larger high-rate renovation operation is envisioned by the Rio Salado Project where water would be recharged in a series of basins and recaptured and then diverted into a series of lakes for recreation. The water quality, of course, is suitable also for unrestricted irrigation, as well as some industrial purposes. Figure 19 is a model of the proposed operation.

The third case study of recharge in Arizona comprises recharge studies by the University of Arizona in Tucson. Some of the original studies conducted by the Center, by Resnick, Maddox and others, were in the Phoenix area. Figure 20 is an example of a recharge pit operated by the Center in cooperation with the Beardsley Irrigation District. The purpose of this pit was to recharge water collected behind McMikin Dam. The source of the water is flood runoff from the White Tank mountains.

The pit was constructed in the early 1960's. The depth to the water table at this particular location is about 400 feet. Consequently, a pit is not the most desirable method of recharge. However, underlying the pit, there is a coarse region from 20 feet to 60 feet. The hypothesis was that water would percolate through the overburden and encounter this coarse region. Lateral flow in this region would be intercepted by a number of nearby wells and subsequently cascade down these wells to the groundwater system. Filtration through the overburden would be an effective way of removing sediment and micro-organisims.

The blue coloration of the pit water is due to copper sulphate used for the control of algae. One of the principle concerns with recharge is entrained sediment in floodwater. A number of techniques for sediment reduction have been examined. Earlier studies at the Center concentrated on use of flocculents, for example. Polyelectrolyte flocculents have been used very effectively in the high plains of Texas for removing sediment.

Researchers at the Water Resources Research Center also looked into the possibility of using grass filters as an economical way of settling out sediments. Figure 21 shows grass strips that were installed at the Safford Experiment Station. Gila River water was passed through these grass bays, and water samples were collected at different intervals to determine the concentration of sediment. In Figure 22, the water sample on the right was collected at the head and at the checks, and the sample on the left was obtained at the discharge end. The discharge sample is very clear. However, there is still a lot of colloidal size material and flocculents would also be required. The important feature is that the concentration of flocculent would be reduced by this preliminary filtering technique.

The Center also examined the possibility of recharging sewage effluent in the Tucson area, concomitant with reclamation by means of a grass filter system. Grass filtration has been used very effectively in Australia by the City of Melbourne, for reclaiming effluent. Studies by the Center examined the possibility of reclaiming oxidation pond effluent by grass filters.

Three grass strips were constructed as shown in Figure 23. The strips were being renovated at the time the photograph was taken. The outer two strips were guard strips with the test strip being the center one. The water was metered into and out of the facility. Water samples were obtained at the inlet and outlet ends at the check and analyzed for chemical and biological constituants; as well as algae concentrations. A number of monitoring facilities were also constructed to determine the vertical movement of water in a vadose zone and associated quality changes. The grass filtration process was not particularly effective for reducing algae and B.O.D. levels in the oxidation pond effluent, but soil filtration was a very effective way of reclaiming effluent.

The main thrust of the Center's research effort has been at a research site near Tucson at the Water Resources Research Center Field Laboratory. The site is located about a mile from two sources of water for recharge studies; one constituting blown down water from Tucson Gas and Electric Power Plant, and the second source being cooling water discharge from a nearby power station of the Bureau of Reclamation. The two sources are discharged into a common ditch (see Figure 24 and 25). The water in the cooling towers, before it is blown down, is concentrated about two and a half times. However, the water from the power station is heated but the salinity is not changed. Consequently, the blended source is generally at reasonable quality.

Occasionally concentrations of sulphate were observed in excess of 700 milligrams per liter and the total dissolved solids (TDS) has been over 2,000 at times. Figure 25 is another view of the discharge ditch showing blowdown water and a Parshall Flume used to meter the discharge. A 4200 foot pipeline was installed to transport effluent to the research site.

Figure 26 is a schematic representation of the Center's research facilities, about a mile from the sources of water. At the outset, it should be pointed out that the objectives of the experiments at the site tied in very closely with the general objectives of conjunctive-use projects. In particular, project activities related to the infiltration characteristics of recharge facilities; to transmissive and storage properties at the vadose zone and groundwater zone, and to the eventual recovery of recharge water. As shown in Figure 26, water is brought into the area via the pipeline and either bypassed into a holding pond or into a drain line to the Santa Cruz River. The holding pond provides on-site storage. The site also houses a shop and laboratory.

The main recharge facilities are a recharge pit and a recharge well. A number of monitoring wells were installed to permit water sampling at various depths in the vadose zone and groundwater zone to determine quality changes. One hundred foot deep access wells were also installed for neutron moisture logging in the vadose zone. Three 150 foot deep observation wells were installed for monitoring water level changes in the water table.

In addition to the recharge well, a down gradient pumping well was installed for use during two well recharge studies.

The site is located near the Santa Cruz River as shown here on Figure 26. The possibility of diverting floodwaters, when they occur, for recharge was considered. Extensive works would obviously be required to remove sediment from floodwater prior to recharge.

By means of our moisture-logging monitoring program, it was found that the Santa Cruz River is a very effective natural recharge unit. Consequently, it was decided that it would be impractical and uneconomical to divert this water, treat it and recharge it. Consequently, the research effort concentrated on the other sources. Figure 27 is an aerial view of the research facility.

One of the first considerations in any recharge project is to examine the nature of the underlying materials. Consequently, extensive geological and geophysical studies were conducted at the research site prior to construction of the pit and well. For example, during drilling of the observation wells by the cable tool method, drill cuttings were obtained for grain-size analysis. The particle-size data were correlated with logs obtained by down-hole loggers, such as natural gamma and neutron loggers.

Surface geophysical methods, such as the resistivity technique, were also used to estimate the spatial distribution of sediments. A rather general picture of the lithology was thus obtained. As shown on the fence diagram on Figure 28, the upper unit comprises alluvium. At the base of this unit a coarse layer was found. This layer is hydraulically connected. Underlying the alluvium unit is a basin-fill unit consisting of coarse material, but not as coarse as the alluvium unit. The water table was 80 feet when the fence diagram was prepared and it corresponded with an underlying older unit.

Figure 29 is a view of the recharge pit. The pit was excavated into the coarse gravels at the base of the alluvium unit. Originally, the pit was constructed with zero bottom width, 50 foot top width, 100 foot top length and later, a trench was constructed in the pit to facilitate removing sediment from the base of the facility. An inlet pipe is apparent on the picture.

An access well was installed at the end of the platform, together with a stand pipe on which is mounted a water state recorder. The recorder is used to monitor changes in water levels in the pit during recharge tests. The interior of the pit was surveyed to obtain a relationship between depth of water, volume of water in storage for each depth, and wetted surface area for each depth. Water is metered into the pit via a flow meter. Intake rates are calculated from inflow rates, and the relationship between depth - surface area - wetted volume. Figure 30 is a view of the pit during a recharge test.

An intake curve obtained during a study in 1966 is shown in Figure 31. The curve is the usual type obtained when air impedence is not a problem. The intake rates compared favorably with rates obtained in other pits, reported in the literature.

During this trial, of 142 days duration, the pit was inundated continuously without any type of cycling or addition of algacides or bacteracides. Later pit recharge tests involved imposing wet-dry cycles. Cycling was found to be an effective technique for sustaining long-term intake rates.

Figure 32 shows the neutron moisture logger in operation. The logger includes a motor drive for lowering the tool in the access wells. This allows a hole to be scanned in a few minutes (generally 20 minutes or less). The water content profiles on

Figure 33 were obtained, I believe, in a well during the 1966 studies . The well is about 300 feet from the pit. The profiles show water content versus depth. The May 10th profile is essentially a drainage profile although there is some residual water above the water table of 80 feet. Two days after starting to recharge, a buldge occurred at 30 feet. The buldge in water content occurs at the interface between the very coarse sediments of the alluvium unit and the underlying gravels.

This points out that perching occurs even without the presence of an underlying tight layer. In other words, perching layers also occur at the interface between permeable formations. The requirement for perching is that the permeability at the underlying layer is less than the vertical flow rate.

Generally, these layers are ephemeral and they drain very quickly. At any rate, based on this inference of arrival of water in this location, and then the growth of a lower mound above the water table (see Figure 33), rather rapid lateral velocities are inferred, maybe in excess of 100 feet per day. This rate is in contrast to the natural groundwater movement of the area which may be a half a foot per day.

Another sequence of profiles are shown in Figure 34. These profiles again show the growth of a mound near 30 feet. This sequence was taken at various times during the 1966 test. When recharge rates were high, a complete profile developed and water moved very rapidly through the system. Later, as clogging occurred in the pit and intake rates declined, the upper mound drained until at the end of the trial, on September 30th, the upper mound was completely dissipated.

Dr. Bianchi, in some of his earlier recharge studies in California, referred to water movement and storage in the vadose zone as an "in-transit storage", a very apt description. The sequence of profiles on Figure 34 show this phenomenon very clearly. Also of interest was the observation that monitoring wells in the same area reflected a very slight rise, maybe one or two feet, in groundwater levels during recharge. Relying only on groundwater level changes, the inference might be that recharge was not very effective. Only with a device such as the neutron moisture logger, can a true picture of the amount of water in storage in the vadose zone be obtained.

Figure 35 is a break through curve showing chloride changes with time during recharge in water samples from a 100 foot deep well. This particular well terminated about 20 feet below the water table. The recharge water quality was about 300 milligrams per liter in chloride. Initial chloride in the groundwater system was 140 was milligrams per liter. The gradual increase in chloride indicates that groundwater was being displaced with recharge water.

Figure 36 is a cross-section of the recharge well. The unit is 150 feet deep and 20 inches in diameter. Based on the observations from pit tests that recharge rates are very high in the upper region, it was elected to perforate the casing via premilled slots in the region from 20 feet to 40 feet. The lower region below the water table was perforated from 80 feet to 130 feet. The upper and lower perforated regions were isolated by means of a liner and packer assembly. In a sense, the well is really a combination recharge shaft and recharge well. In operation when water is introduced into the upper region, flow occurs down and out through the perforations into the unsaturated, permeable sediments. Alternatively, water may be dropped down the casing permitting flow directly into the water table. A third possibility is to recharge water through the pump column. When the latter method was used, it produced a siphon, leading to cavitation. The resultant air bubbles eventually clogged the aquifer near the well.

The recharge shaft portion of the well may be used to recharge intermittant supply such as urban runoff, allowing the intervening sediments to act as a filter. At the same time, the pumping operation of the well will not be interfered with.

Several shaft studies were conducted. By monitoring water samples in nearby wells, it was found that coliform bacteria was removed completely during the flow of water through the vadose zone. No studies on the fate of organics were conducted.

The deep well turbine pump was installed to permit pumping tests for determining the aquifer properties, transmissivity and storage co-efficient. A pumping system also facilitates redevelopment of the well. Periodic reclamation or pump back removes sediment from aquifer formation, thereby sustaining favorable intake rates.

Figure 37 is a view of the Packer Assembly at the base of the twelve inch liner. The assembly was pushed into the 20 inch casing. The packer consisted of a neopreme seal and a disk.

Figure 38 is a photograph of the well prior to the installation of the piping, showing inlet facilities and the head of the pumping plant. Figure 39 shows the completed facilities including the inlet lines and plant. A small instrument shelter was located near the well to permit on-site measurement of water quality (Figure 40). During some trials, pH and specific conductance was monitored continuously.

Figure 41 is a view of a downstream 16-inch diameter pumping well. This well is about 200 feet from the recharge well. During "two-well tests" this well serves as the pumping counterpart of the recharge well. The well is 150 feet deep and perforated in the same interval as the recharge well.

An interesting hydraulic feature of the groundwater system at the site was found by pump testing the 16-inch well. In particular, it was found that even though the wells are only about 200 feet away, the capacity of the 16-inch well is only about half the capacity of the 20-inch recharge well. Apparently, the recharge well was constructed in a buried stream channel. An instrument shelter, shown in Figure 40, was also installed near the pumping well.

The initial well recharge studies were patterned after investigations by Israeli workers who were very concerned with mixing surface and groundwaters of dissimilar quality. The tests were designated "no pause" tests because pumping was started immediately after recharge ceased.

Figure 42 shows representative breakthrough curves during a no-pause test on the center well and on an Israeli well in a sandstone aquifer. Chloride was used as a tracer. Relative concentration on the ordinate refers to the ratio of chloride concentration in pumped water to the concentration in recharge water. The pumped volume ratio is the ratio of volume pumped to the total volume recharged. For both the Israeli test and the test on the center well, only recharge water was pumped initially, as evidenced by a relative concentration at 100%. Gradually, more and more native groundwater mixed with the recharge water and the relative concentration decreased. After pumping-back a volume of water equivalent to about three times the volume recharged, chloride concentrations were back to the level found in native groundwater. As shown on the figure, the curves in the Arizona and Israeli tests were practically identical. In other words, underground mixing in alluvium (Arizona) and sandstone (Israeli) was effected by the same type of process namely hydrodynamic dispersion. In contrast, the breakthrough curve for a limestone aquifer shown in Figure 43 indicates a greater degree of mixing than for the alluvium system in Arizona. For the limestone system, the higher natural flow rate of the aquifer was mainly responsible for mixing.

Figure 44 is a chloride breakthrough curve obtained during pumping in the 16-inch well during a "two-well" test in 1970. In this test, water was recharged continuously in the 20-inch well, and simultaneously the 16-inch well was pumped at a continuous rate. The curve shows that after about five days the tracer (chloride) had arrived at the pumping well. The chloride level gradually increased until after about 14 days the relative concentration of recharge water in the pumped water was 26%. After 14 days, recharge was stopped but pumping was continued. The curve shows that the relative concentration decreased gradually indicating that a prolonged time is required to remove recharged water from the aquifer.

The operation of recharge well-pumping well combinations is an effective mechanism for underground mixing of waters of dissimilar quality. Thus, the technique could be used for diluting surface or groundwaters high in undesirable constituents, such as nitrite.

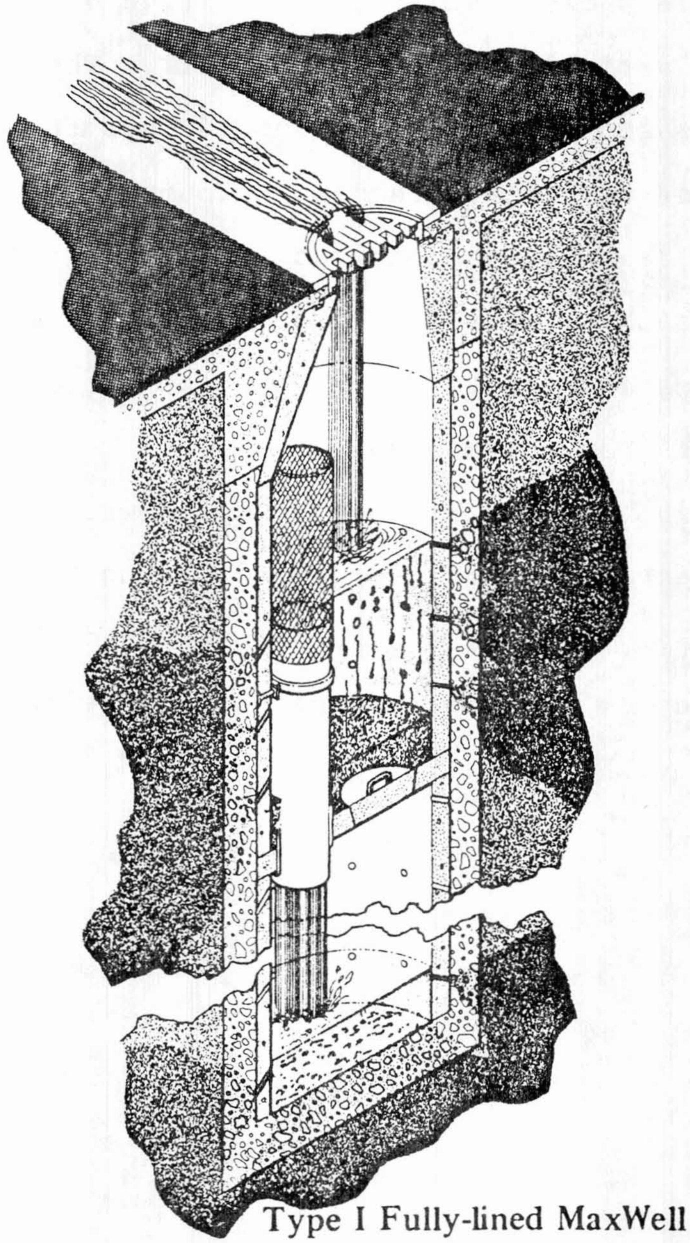


FIGURE 1 - CROSS-SECTION OF "MAXWELL" DRY WELL

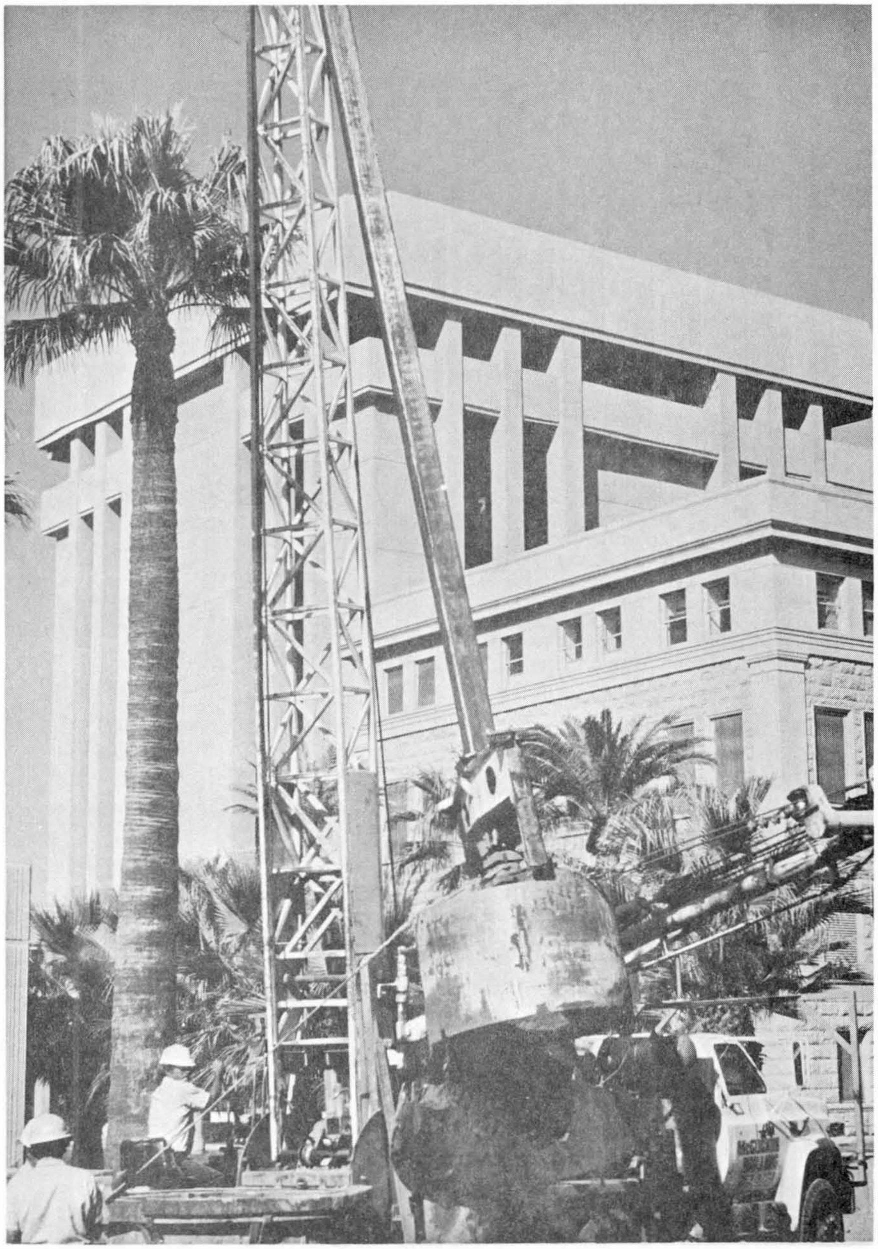


FIGURE 2 - CONSTRUCTING A DRY WELL OUTSIDE THE STATE SENATE BUILDING IN PHOENIX USING A BUCKET AUGER

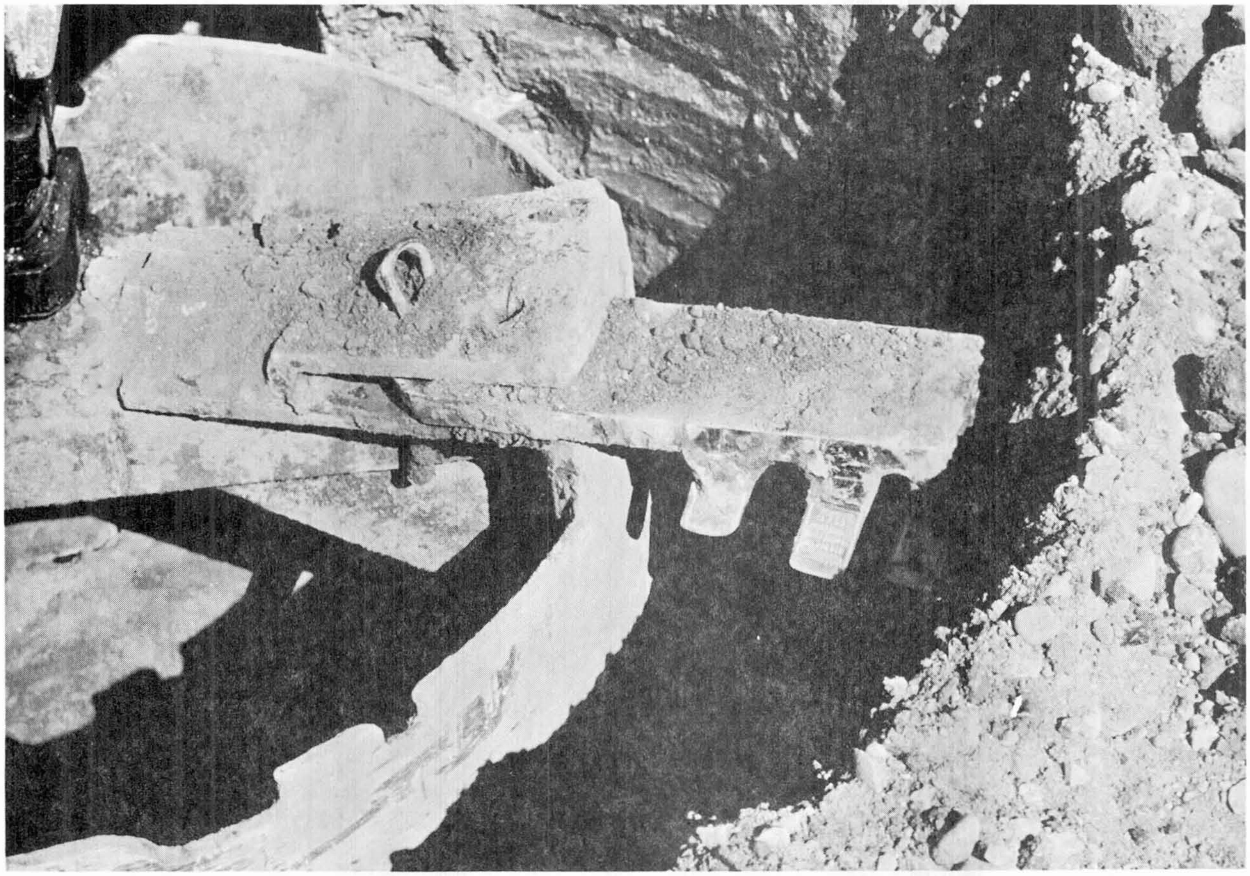


FIGURE 3 - REAMING TEETH ON BUCKET AUGER

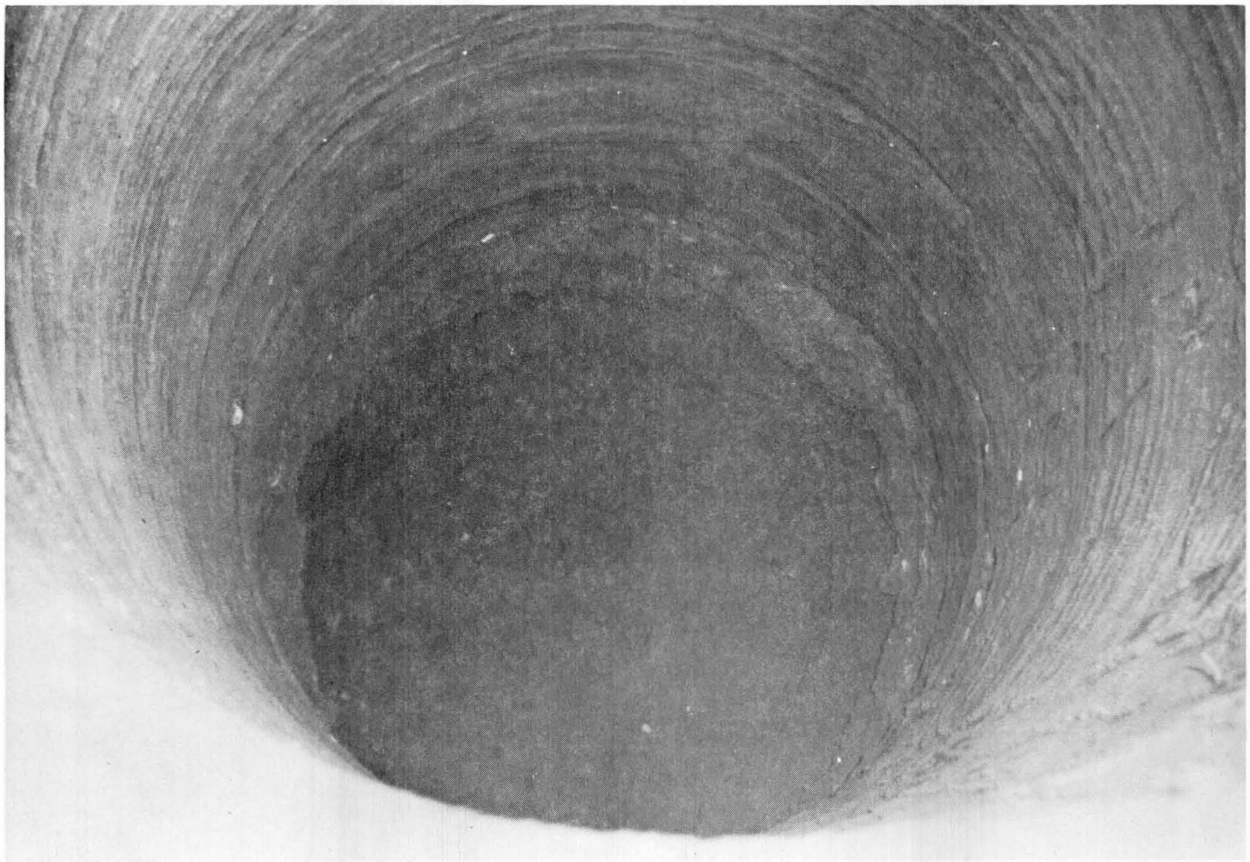


FIGURE 4 - DOWNHOLE VIEW OF CAVITY USED FOR DRY WELL

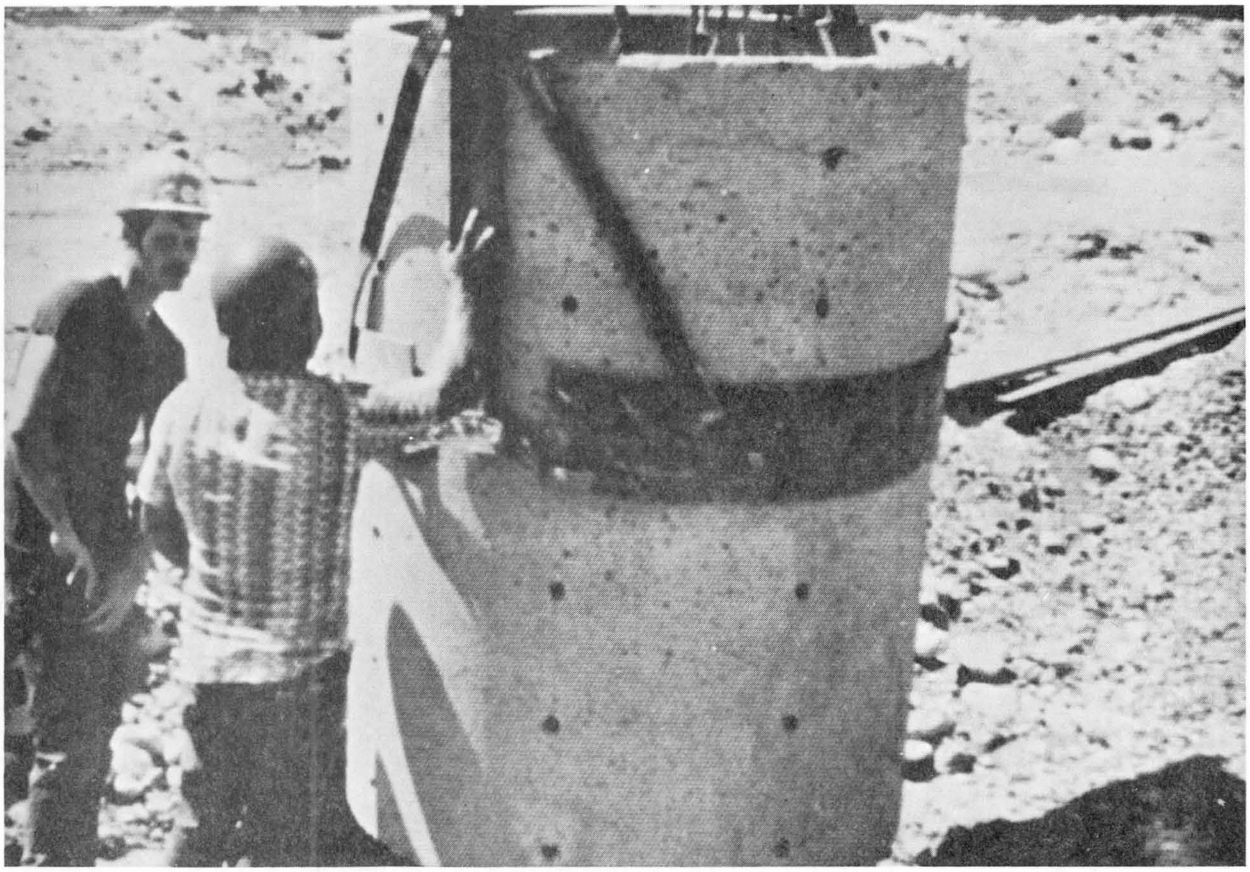


FIGURE 5 - INSTALLATION OF PRECAST LINER USED IN "MAXWELL" SHOWING PERFORATIONS

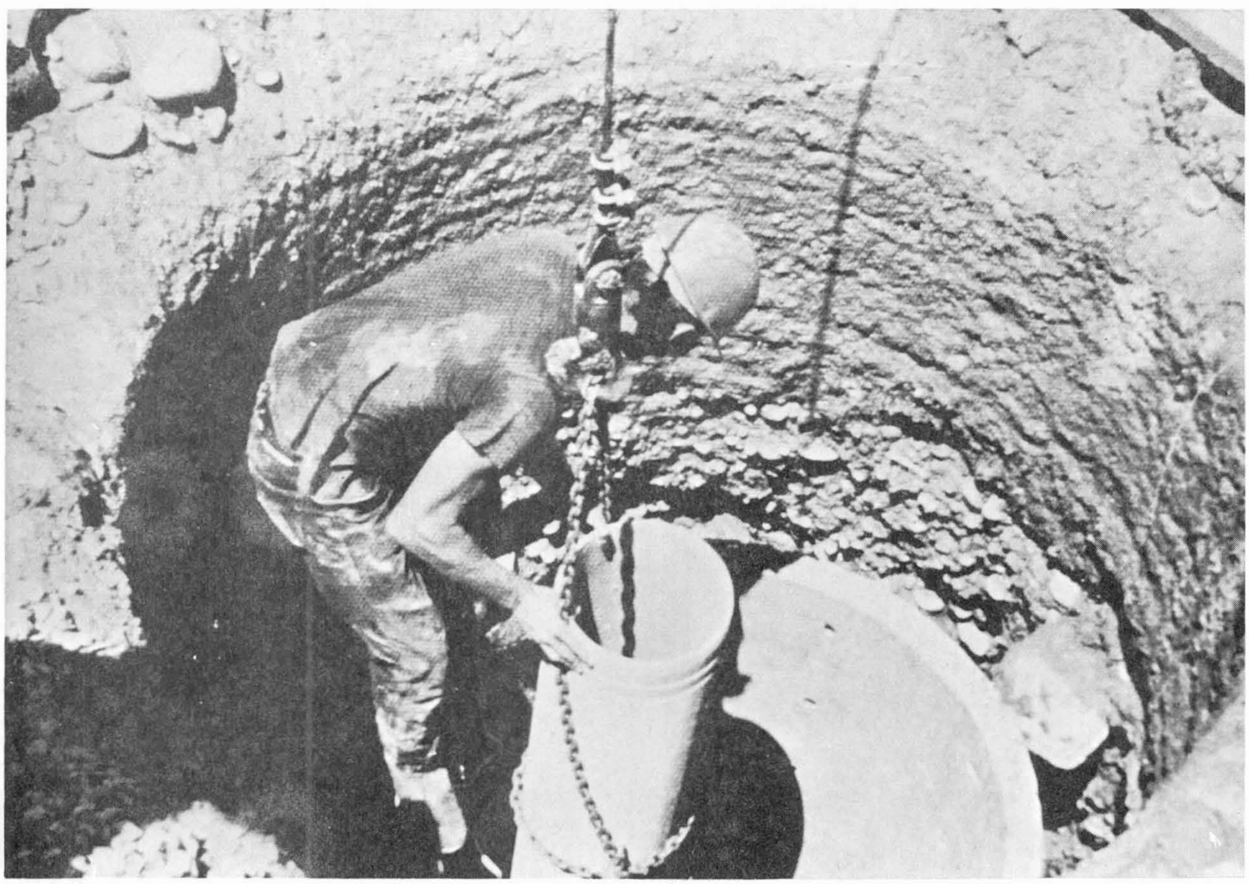


FIGURE 6 - INSTALLATION OF OVERFLOW PIPE BETWEEN SETTLING CHAMBER AND DRY WELL

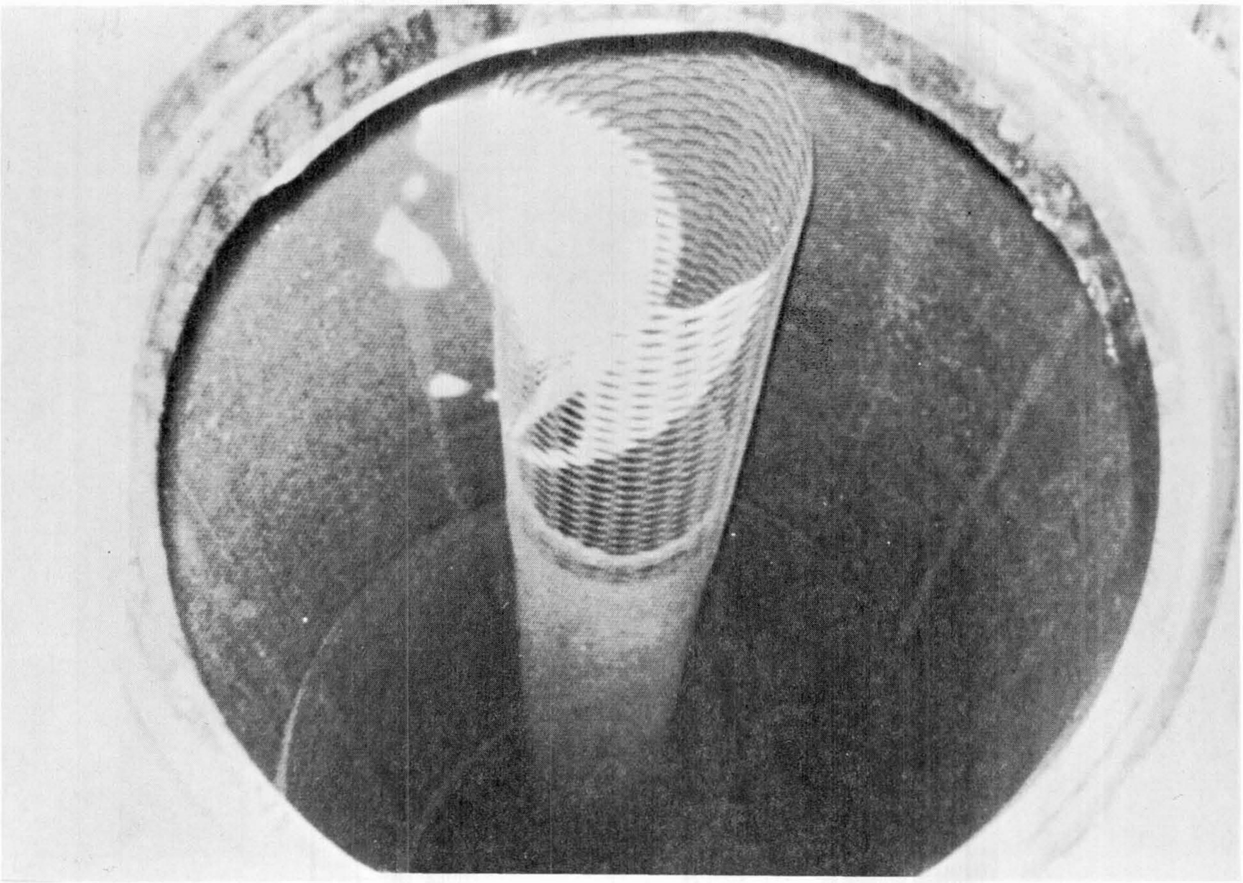


FIGURE 7 - DOWNHOLE VIEW INTO CATCHMENT BASIN SHOWING SCREEN AND OVERVIEW PIPE

FIGURE 8 - "MAXWELL" INSTALLED IN RETENTION BASIN OF HOUSING DEVELOPMENT

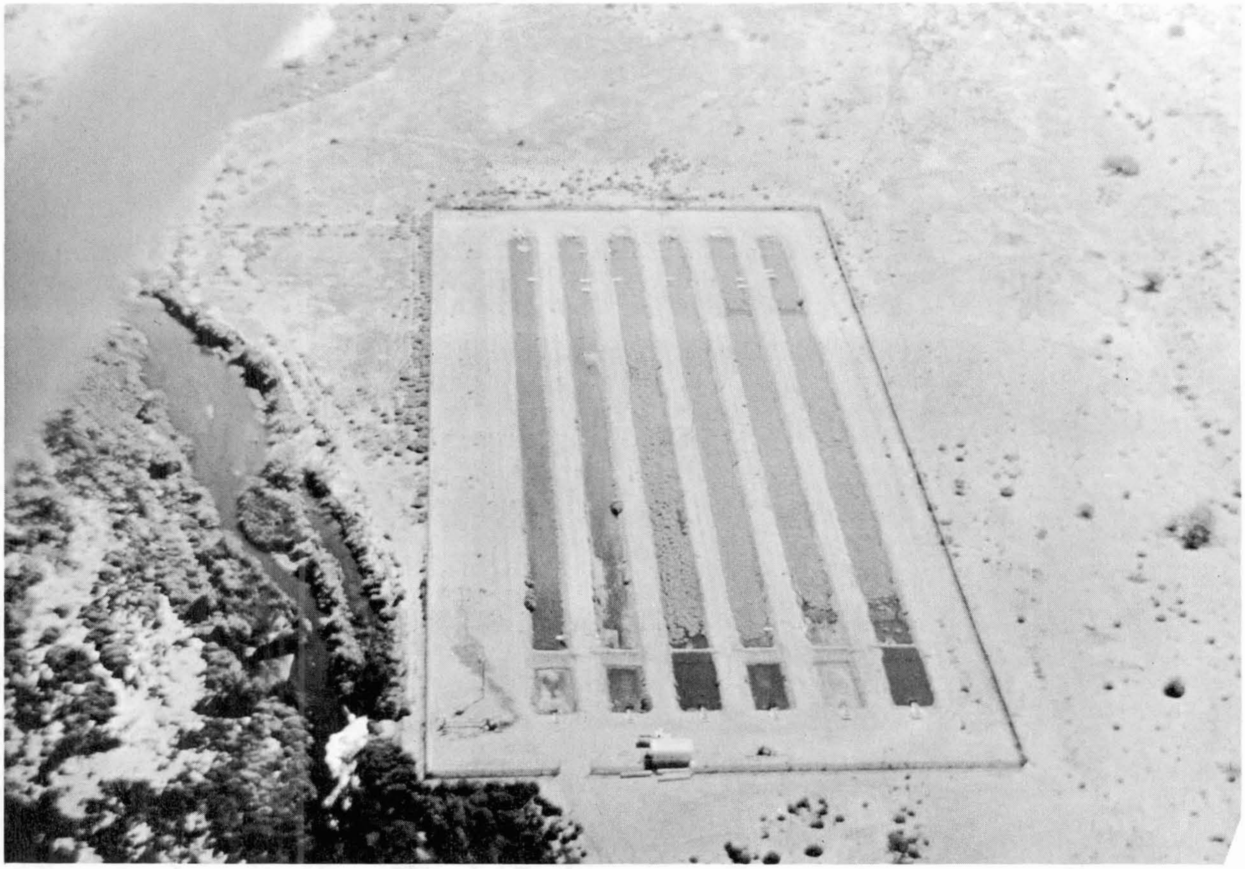


FIGURE 9 - AERIAL VIEW OF FLUSHING MEADOWS PROJECT ALONG SALT RIVER IN PHOENIX

FIGURE 10 - SPREADING BASIN ON FLUSHING MEADOWS PROJECT SHOWING WATER METERING FACILITY

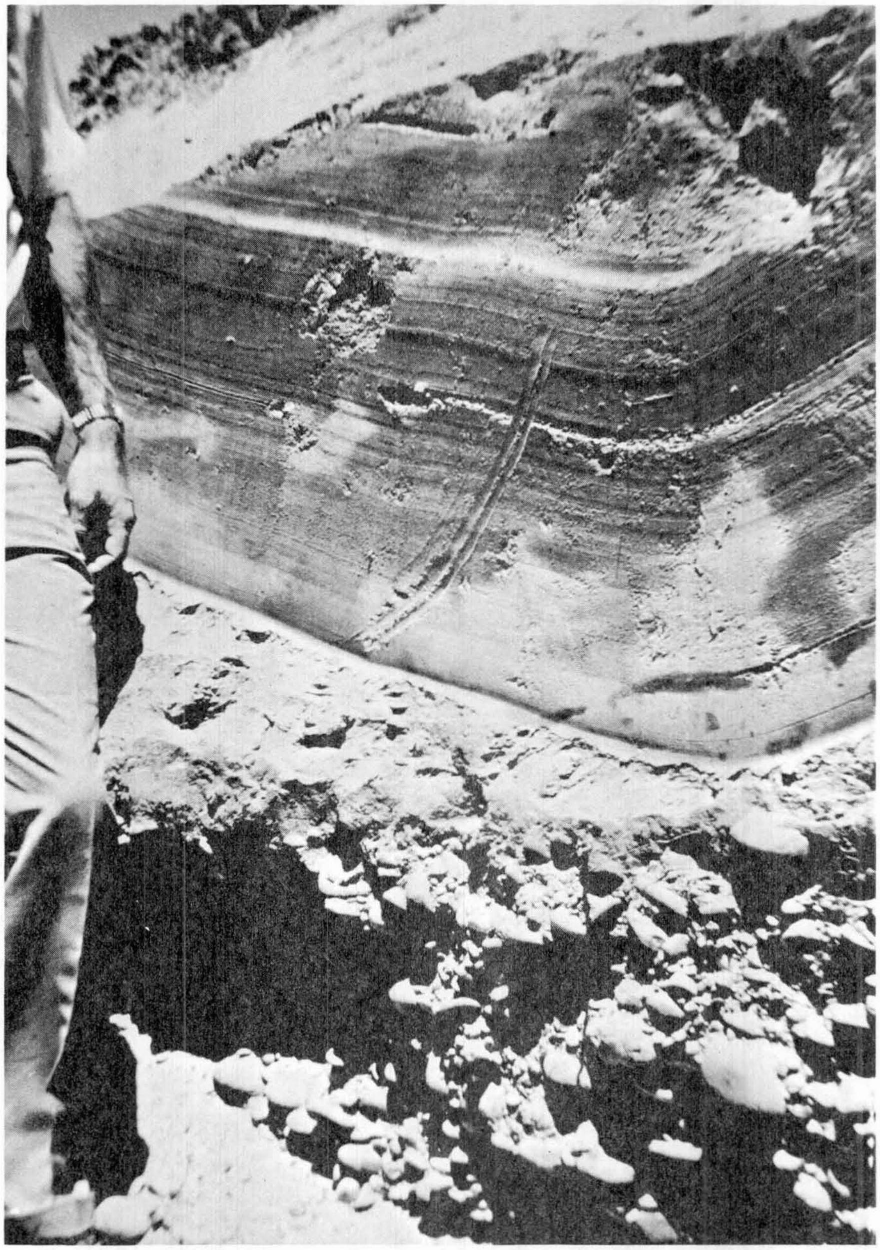


FIGURE 11 - CROSS-SECTION OF SOILS AT FLUSHING MEADOWS PROJECT

FIGURE 12 - SPREADING BASIN AND MONITORING FACILITIES FLUSHING MEADOWS PROJECT

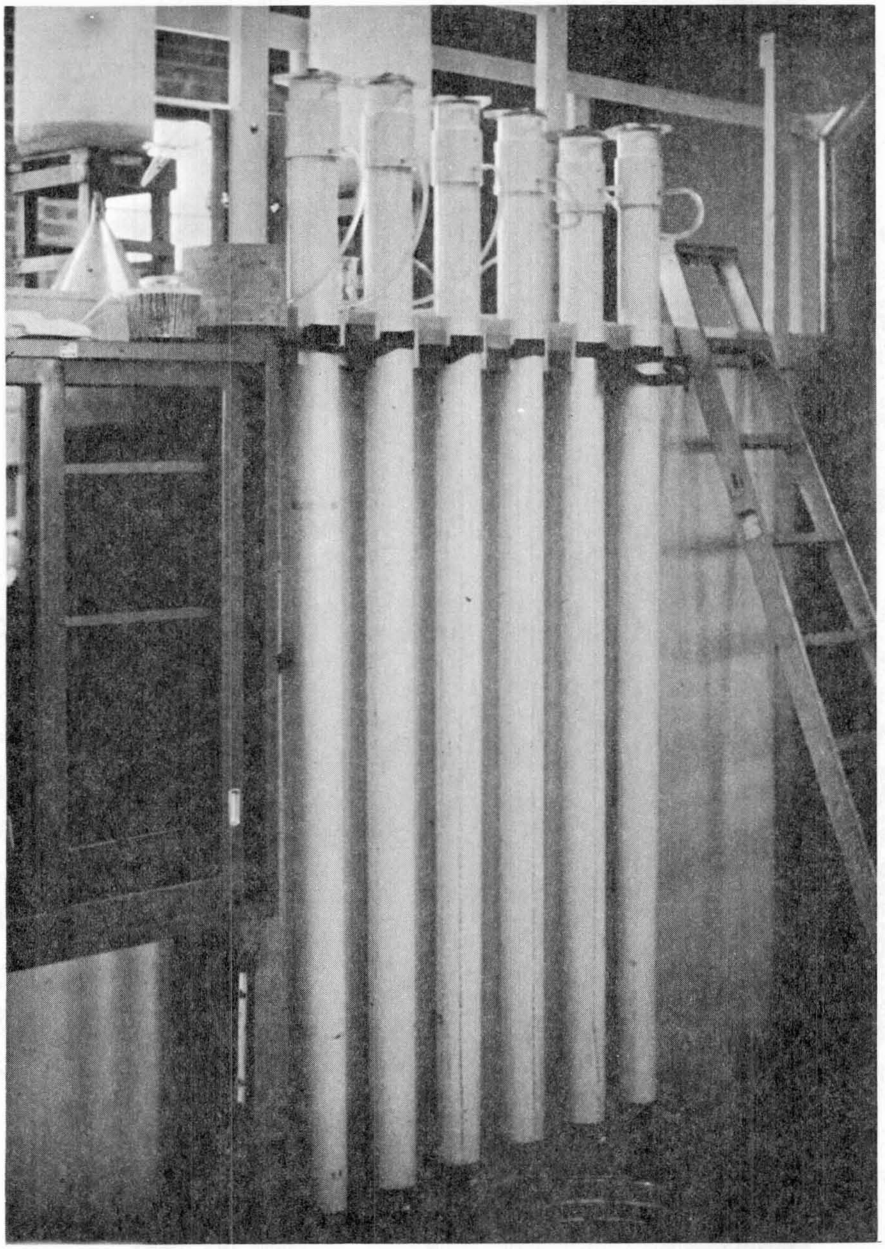


FIGURE 13 - LABORATORY SOIL COLUMNS AT U.S. WATER CONSERVATION LABORATORY

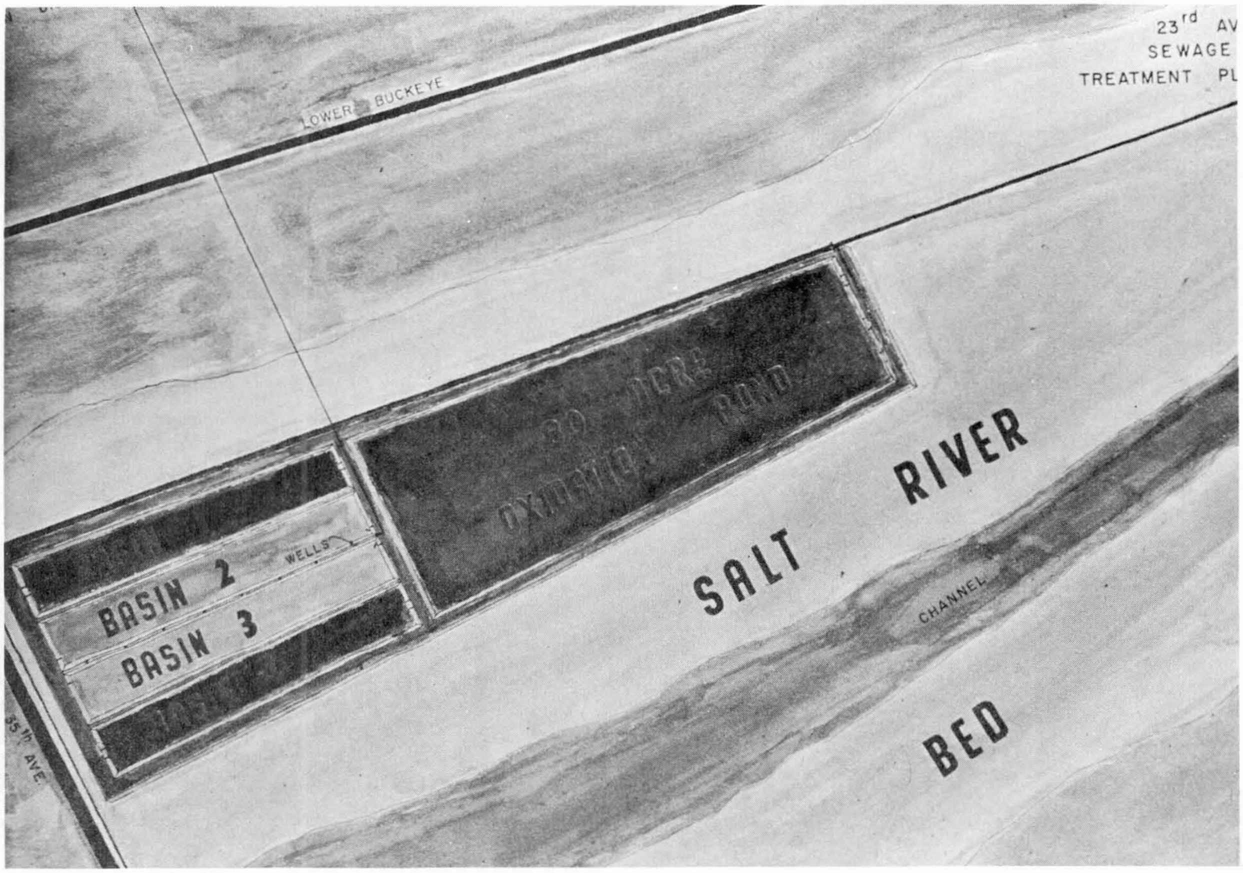


FIGURE 14 - MODEL OF 23RD AVENUE LAND TREATMENT FACILITIES

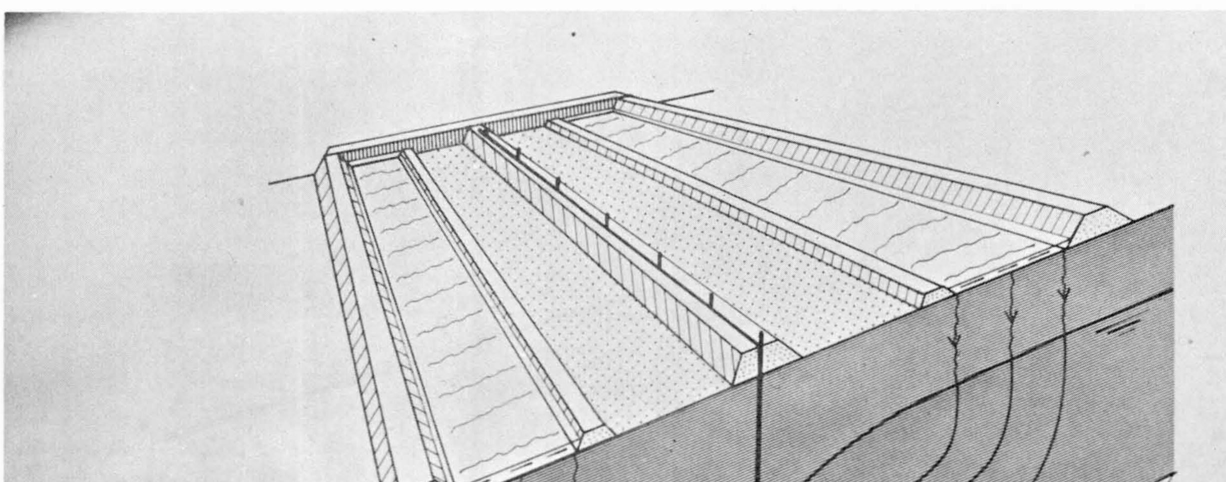


FIGURE 15 - MODEL OF SUBSURFACE FLOW LINES BENEATH 23RD AVENUE SPREADING FACILITIES

FIGURE 16 - AERIAL VIEW OF 23RD AVENUE SPREADING FACILITY

FIGURE 17 - VIEW OF A SPREADING BASIN AT 23RD AVENUE LAND TREATMENT FACILITY SHOWING PUMPING PLANT. CITY OF PHOENIX IS IN BACKGROUND

FIGURE 18 - CROSS-SECTION OF LAYERED SEDIMENTS SHOWING VARYING THICKNESS AND TEXTURE NEAR 23RD AVENUE LAND TREATMENT FACILITY

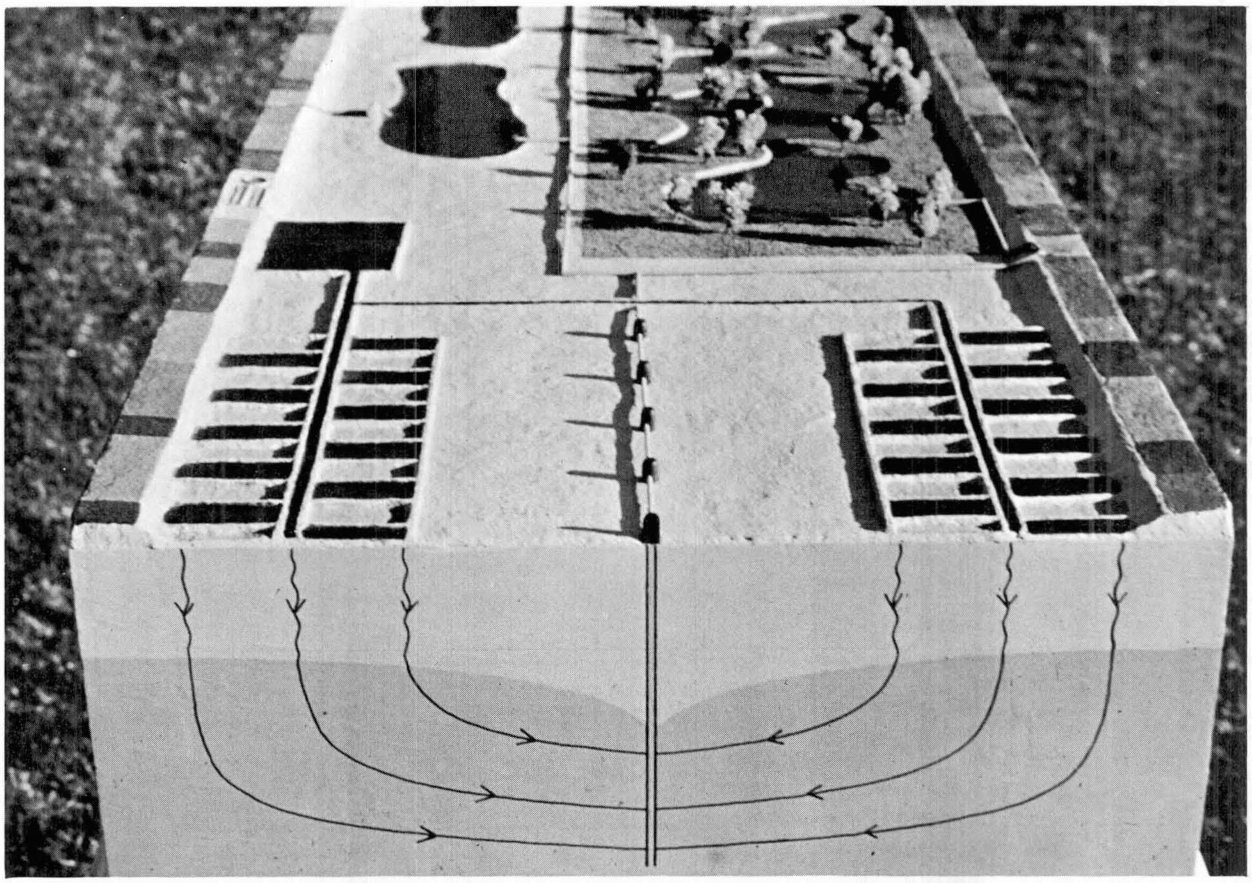


FIGURE 19 - MODEL SHOWING LAND TREATMENT FACILITY (INCLUDING PUMP-BACK SYSTEM) FOR THE RIO SALADA PROJECT

FIGURE 20 - RECHARGE PIT NEAR BEARDSLEY, ARIZONA BEING TREATED WITH COPPER SULFATE

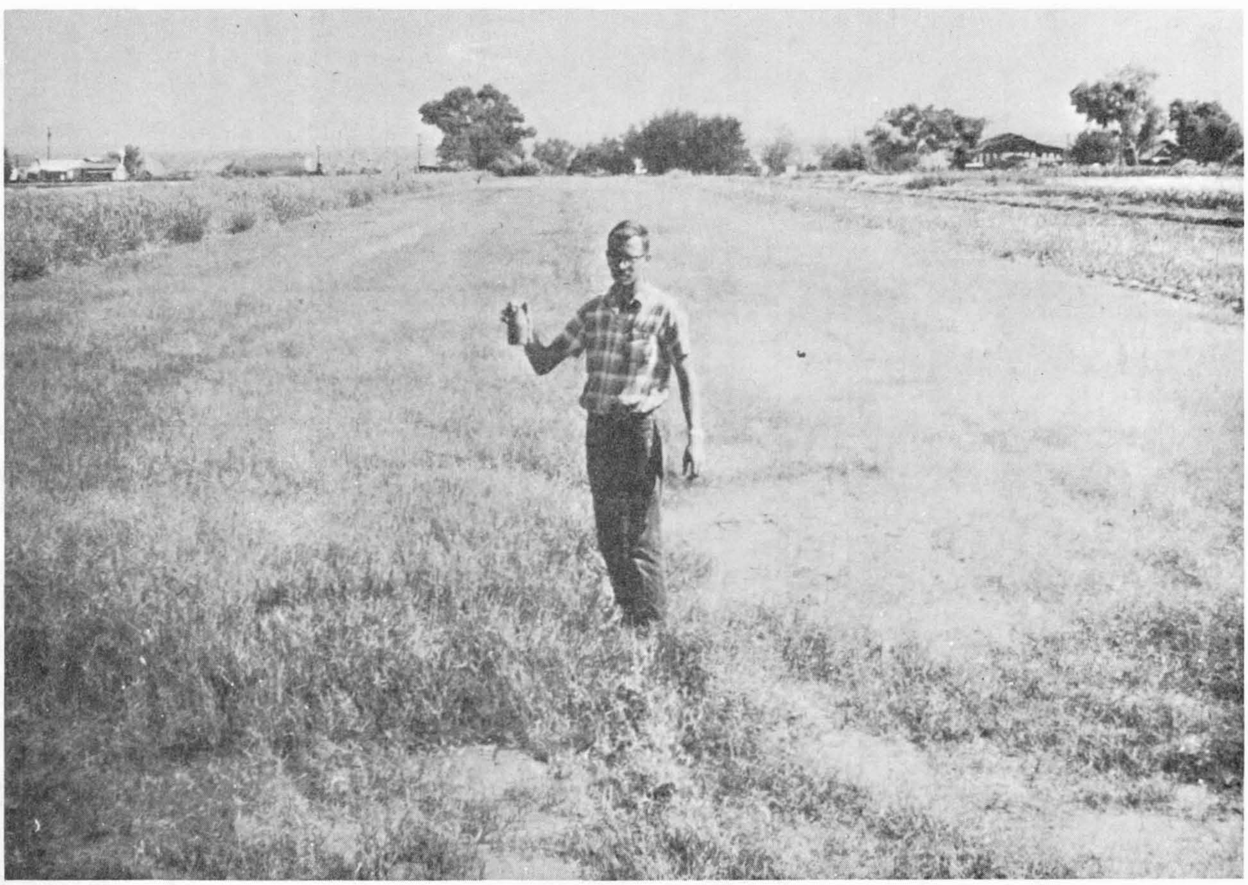


FIGURE 21 - SAMPLING DURING GRASS-FILTRATION STUDIES

FIGURE 22 - WATER SAMPLES COLLECTED DURING GRASS-FILTRATION STUDIES -- SAMPLE ON READER'S RIGHT FROM INLET, SAMPLE ON LEFT FROM OUTLET OF GRASS PLOT

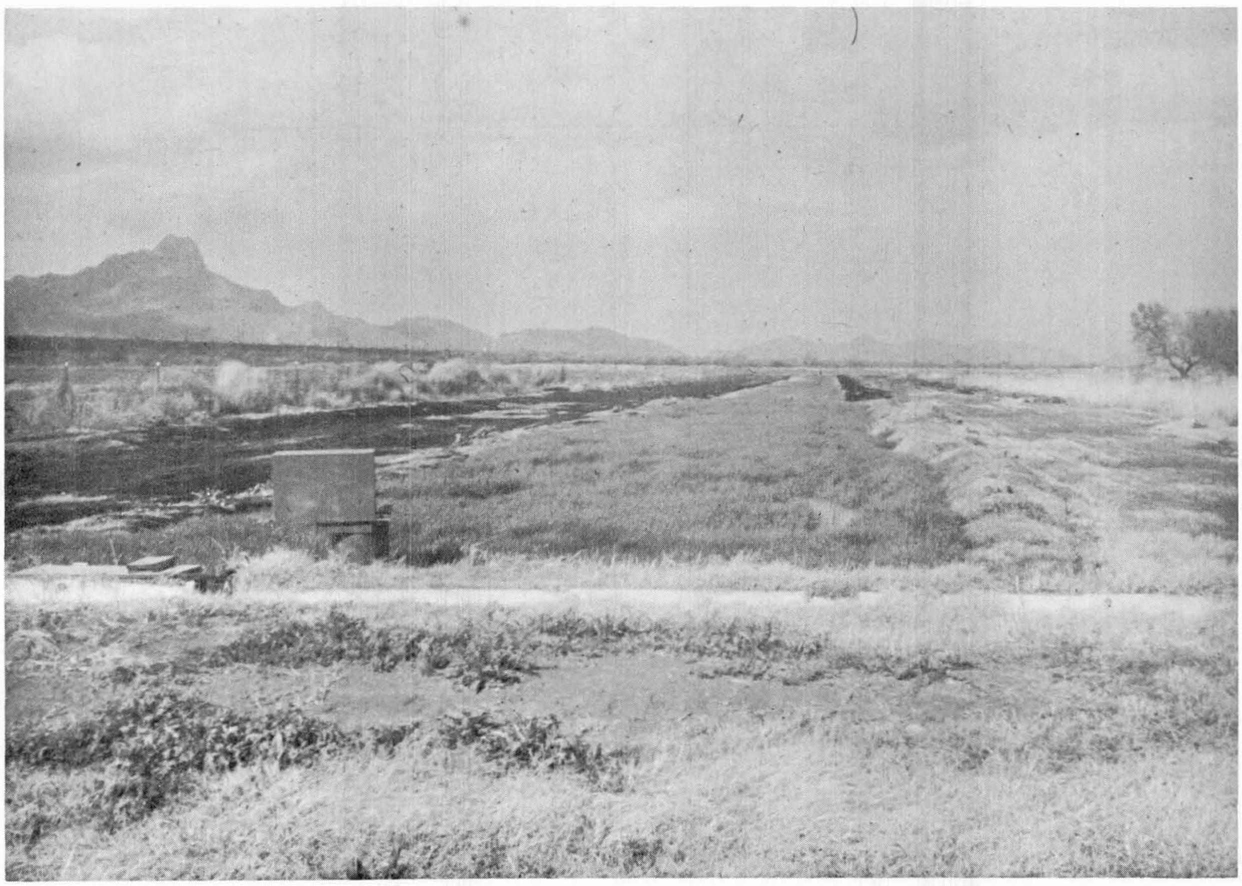


FIGURE 23 - PLOTS USED TO STUDY GRASS FILTRATION OF OXIDATION POND EFFLUENT

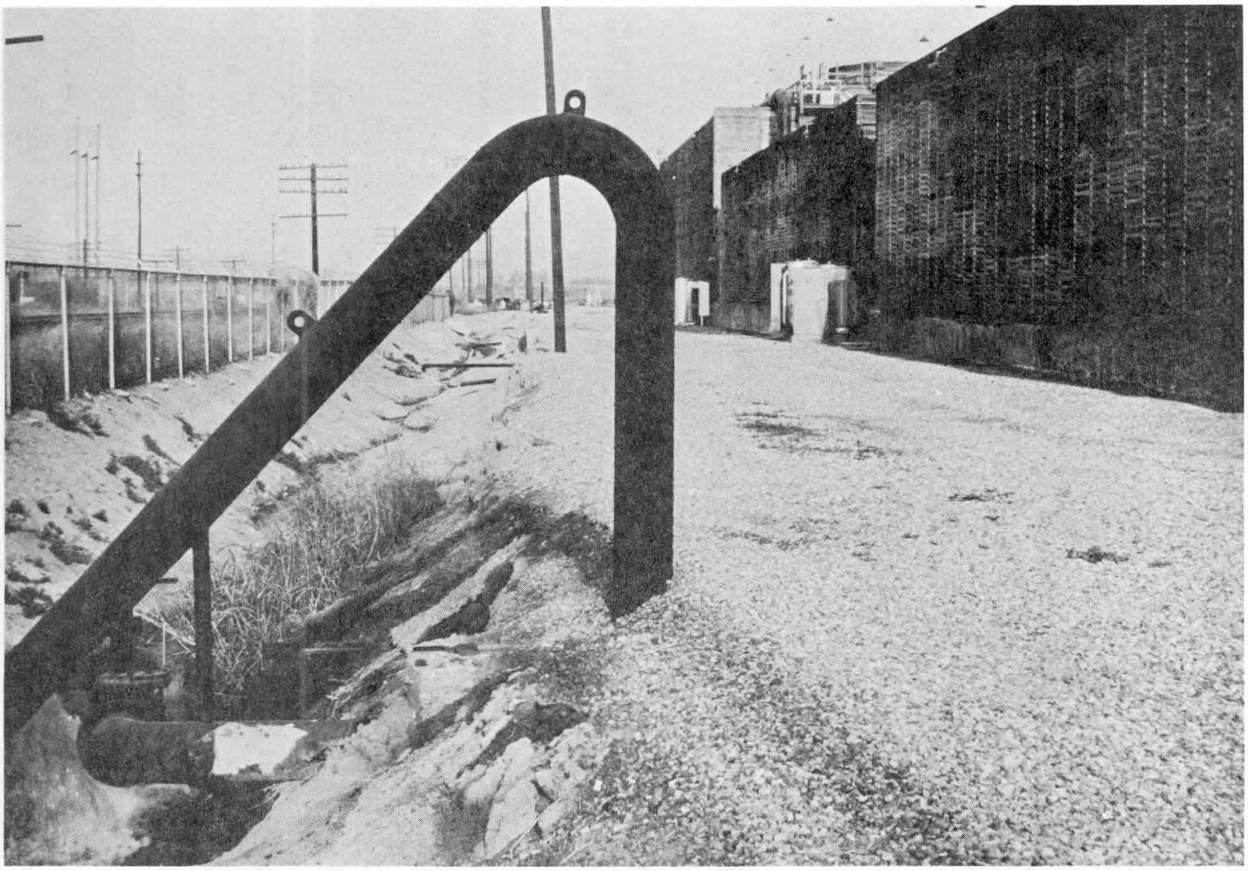


FIGURE 24 - COOLING TOWERS AND BLOWDOWN DRAINAGE -- DITCH AT TUCSON GAS & ELECTRIC CO., GRANT ROAD PLANT. PIPE IN FOREGROUND IS DISCHARGING COOLING WATER FROM AN ADJOINING TRANSFORMER STATION

FIGURE 25 - DRAINAGE DITCH SHOWING MEASURING FLUME. PIPE IS DISCHARGING BLOWDOWN EFFLUENT

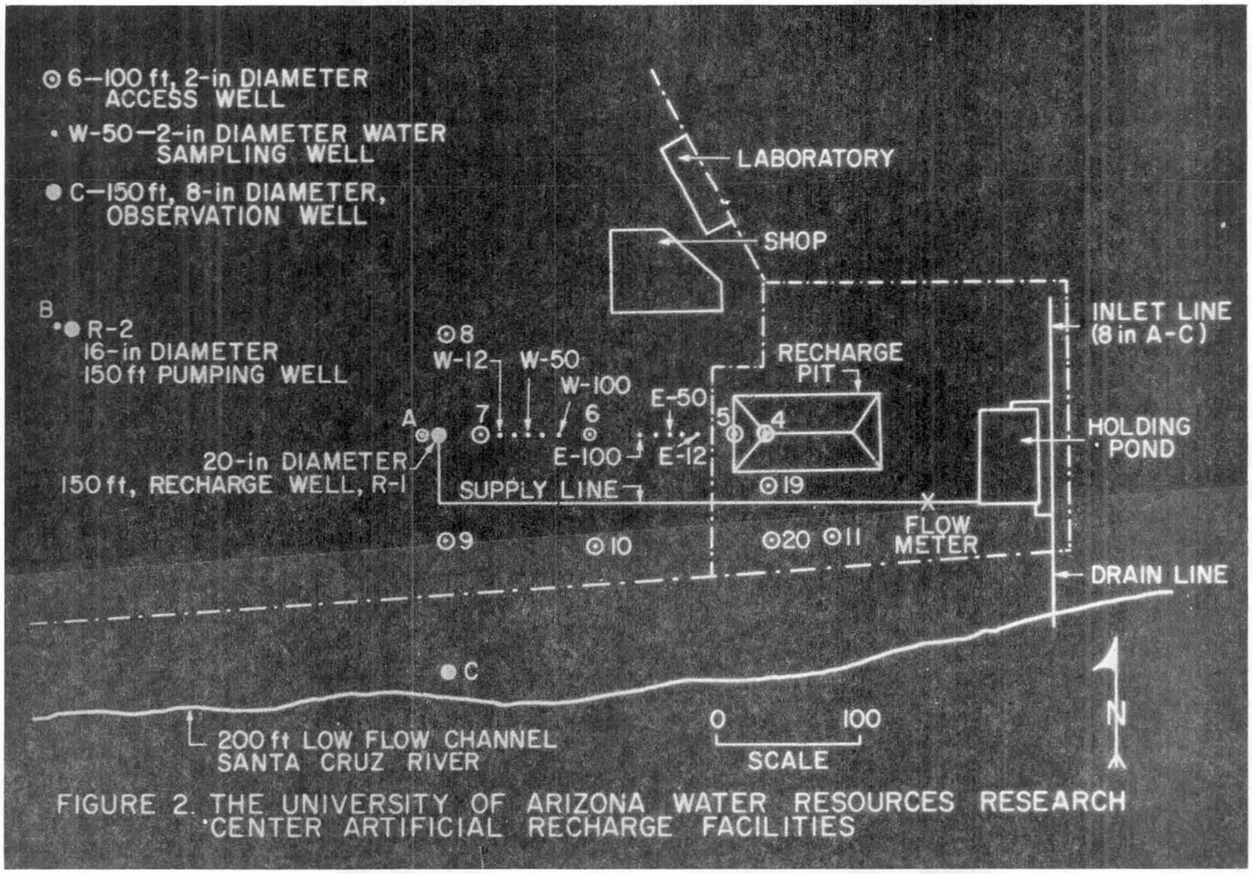


FIGURE 26 - THE UNIVERSITY OF ARIZONA, WATER RESOURCES RESEARCH CENTER, ARTIFICIAL RECHARGE FACILITIES

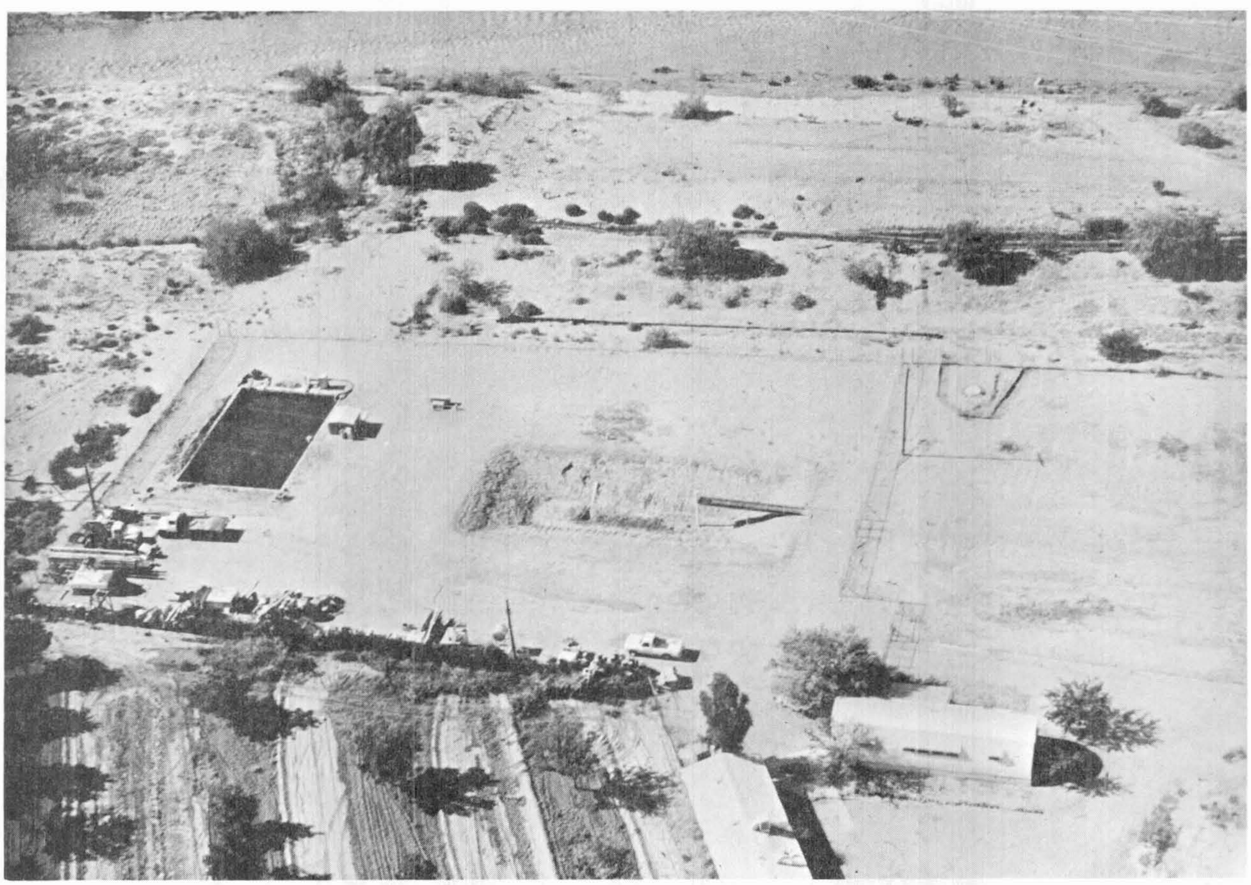


FIGURE 27 - AERIAL VIEW OF WRRC'S RECHARGE FACILITIES

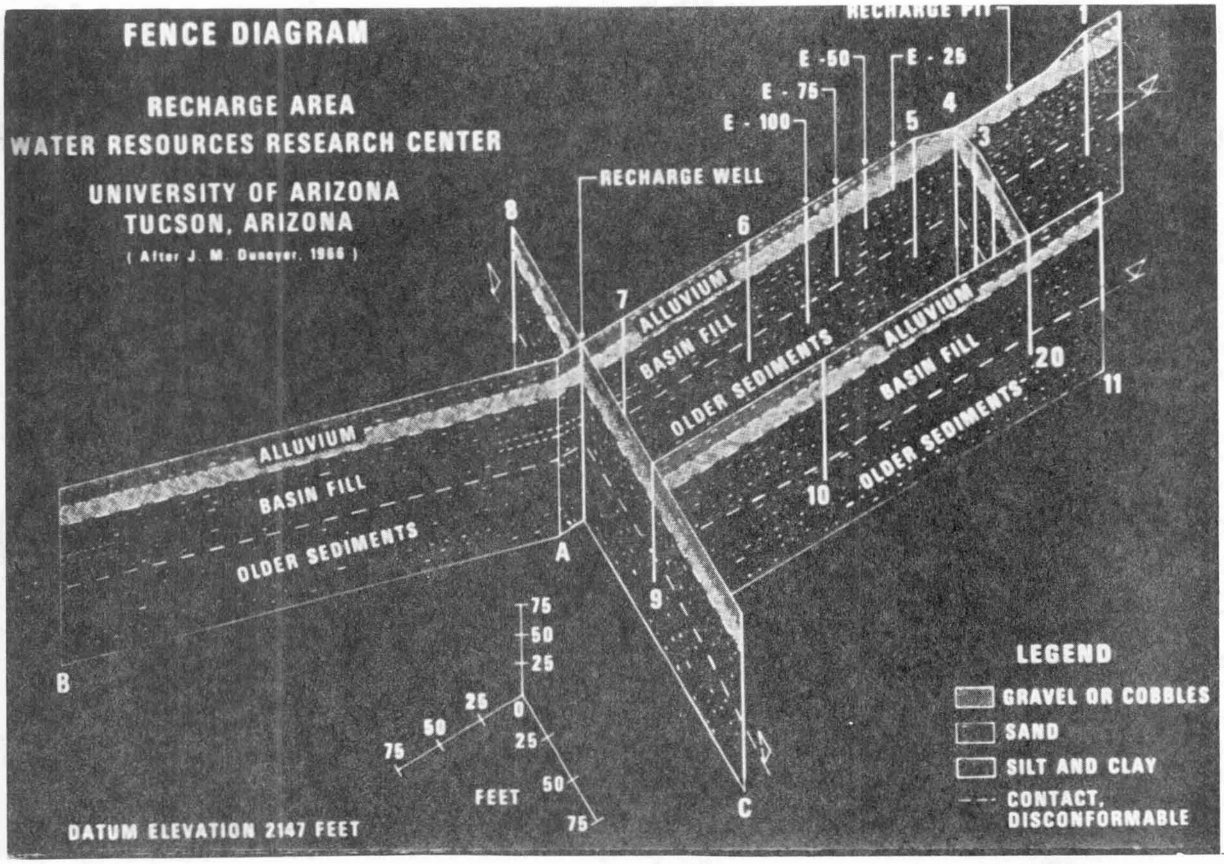


FIGURE 28 - FENCE DIAGRAM, WRRC RECHARGE AREA

FIGURE 29 - RECHARGE PIT, WRRC FIELD LABORATORY

FIGURE 30 - WRRC RECHARGE PIT DURING TEST

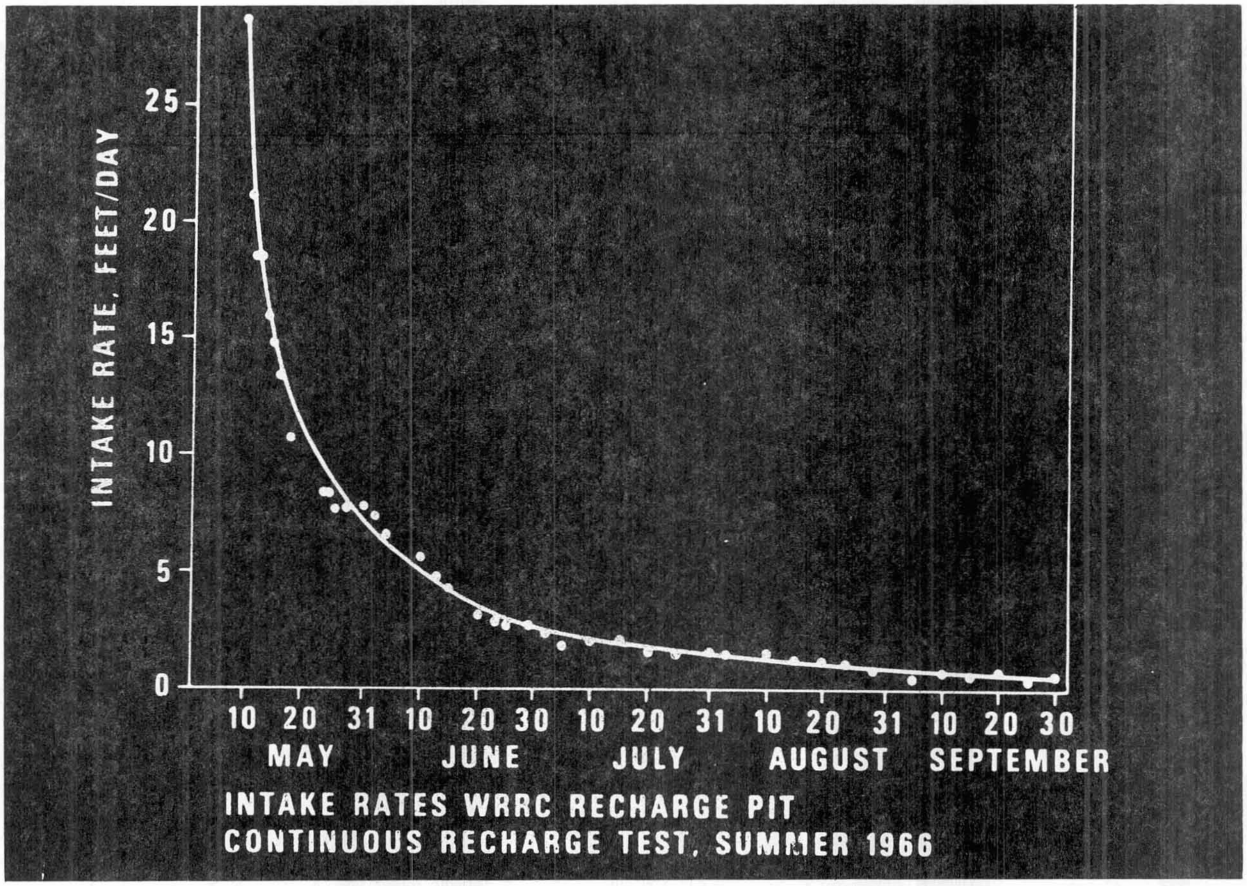


FIGURE 31 - INTAKE RATES WRRC PIT TEST, 1966

FIGURE 32 - MOISTURE LOGGING DURING PIT TESTS

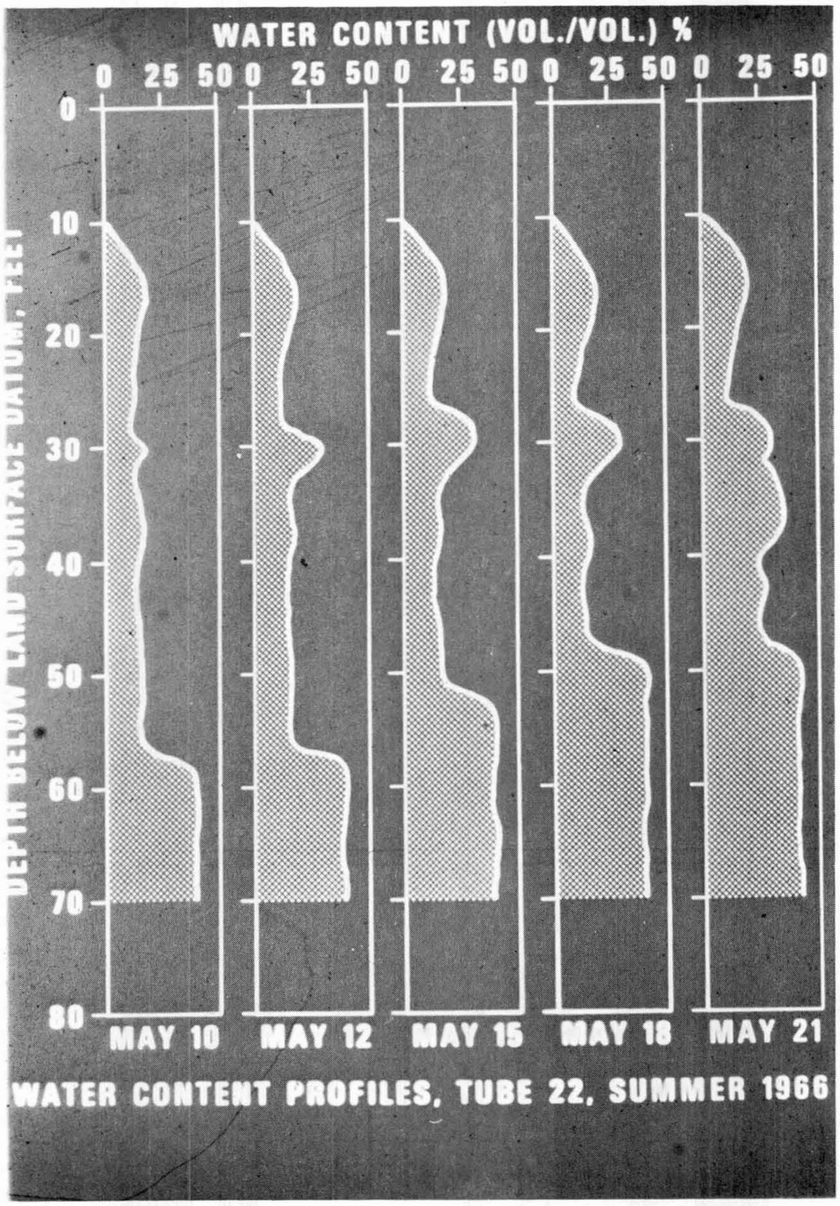


FIGURE 33 - WATER CONTENT PROFILES, 1966

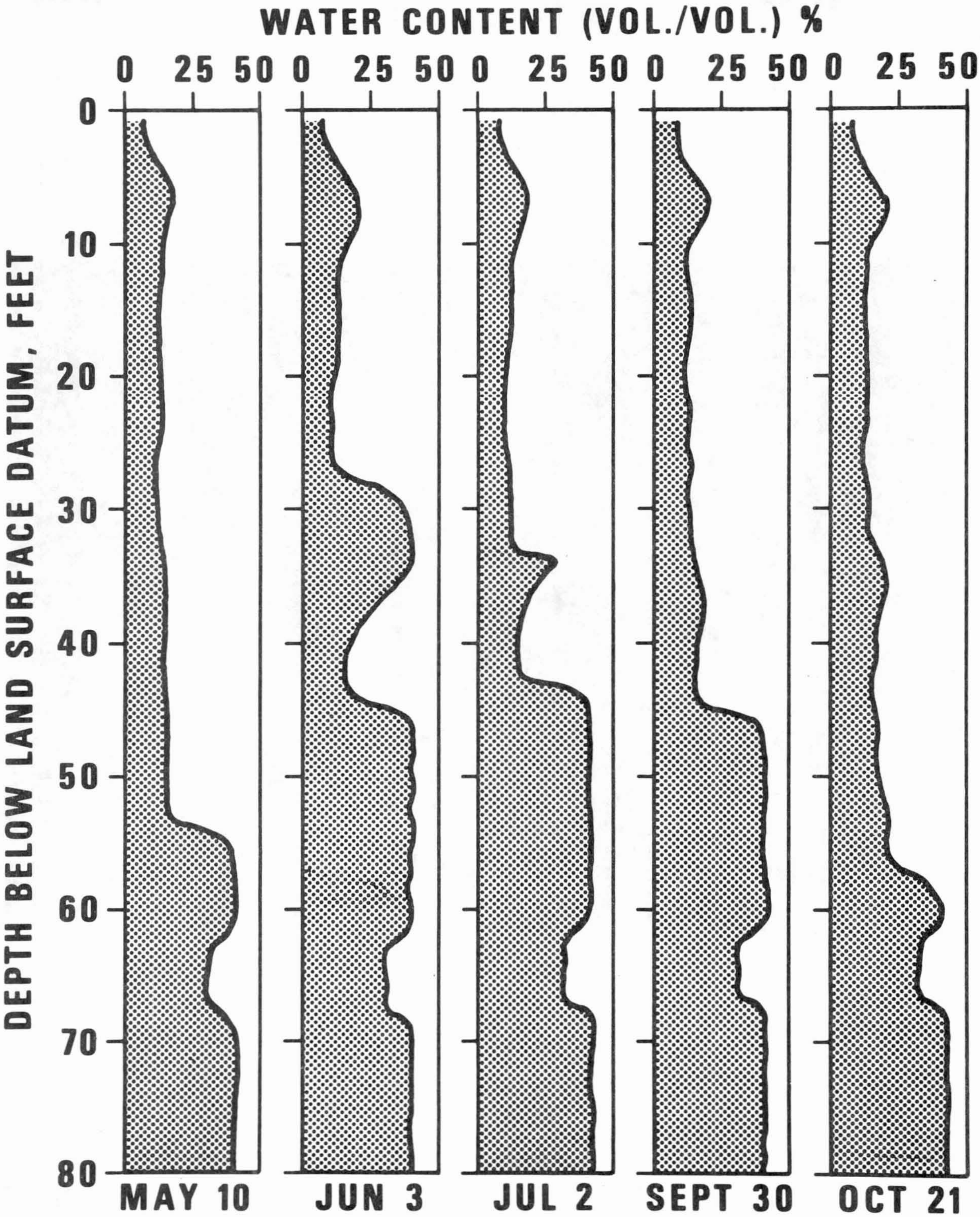


FIGURE 34 - WATER CONTENT PROFILES, ACCESS WELL 7, SUMMER 1966

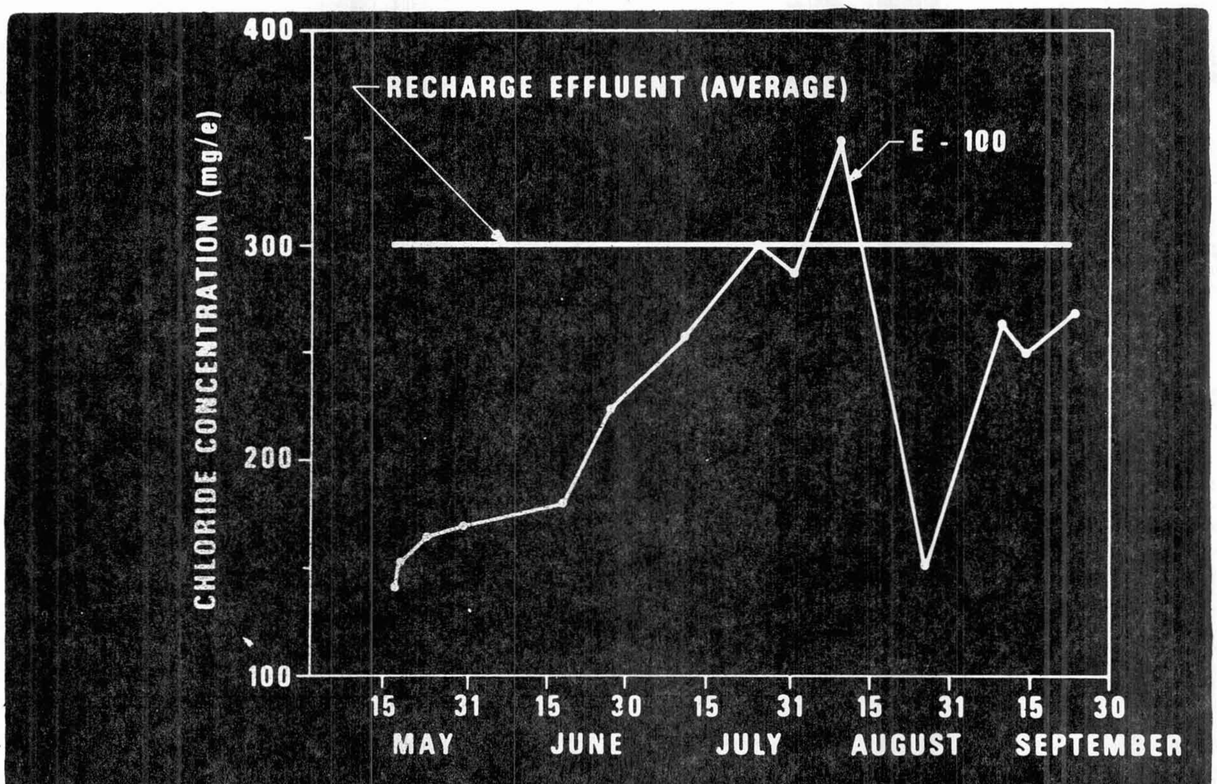


FIGURE 35 - CHLORIDE CONCENTRATION IN RECHARGE EFFLUENT AND SAMPLES FROM E - 100, SUMMER 1966

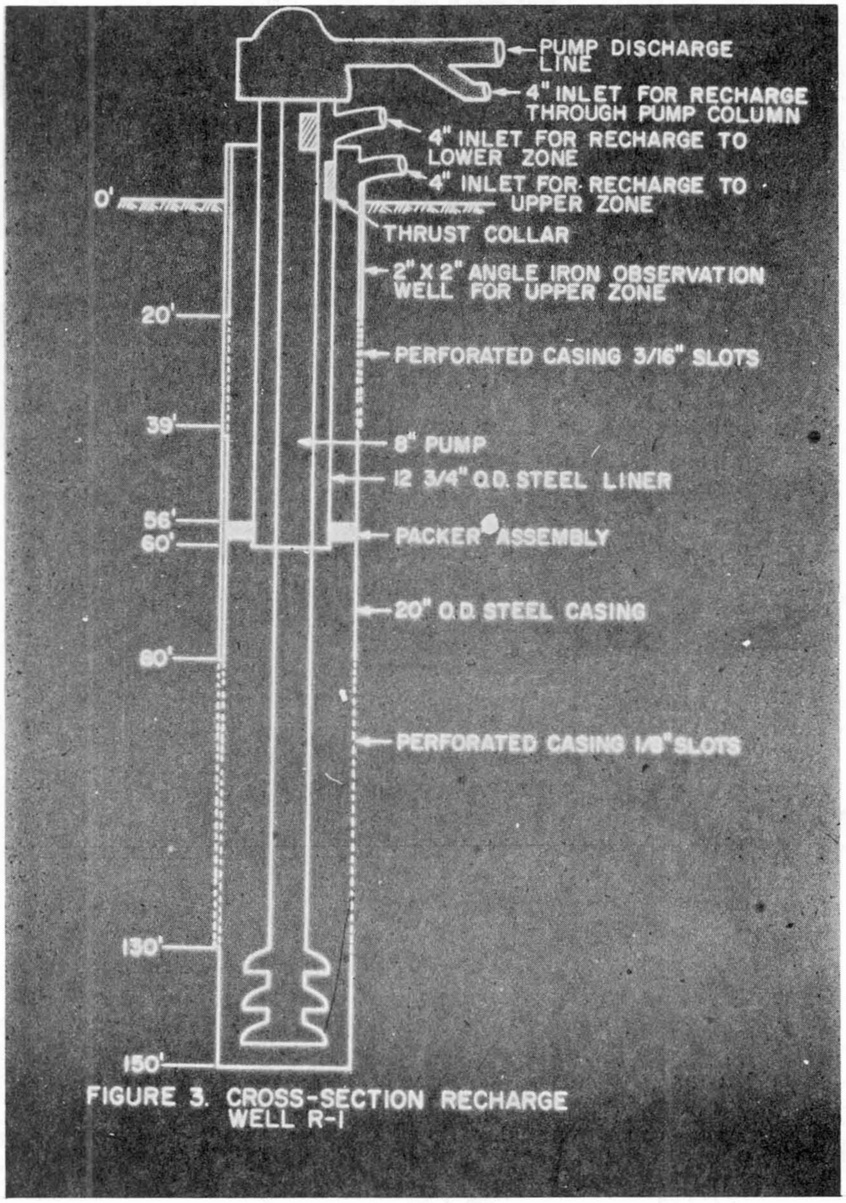


FIGURE 36 - CROSS-SECTION RECHARGE WELL AT THE WATER RESOURCES RESEARCH CENTER FIELD LABORATORY

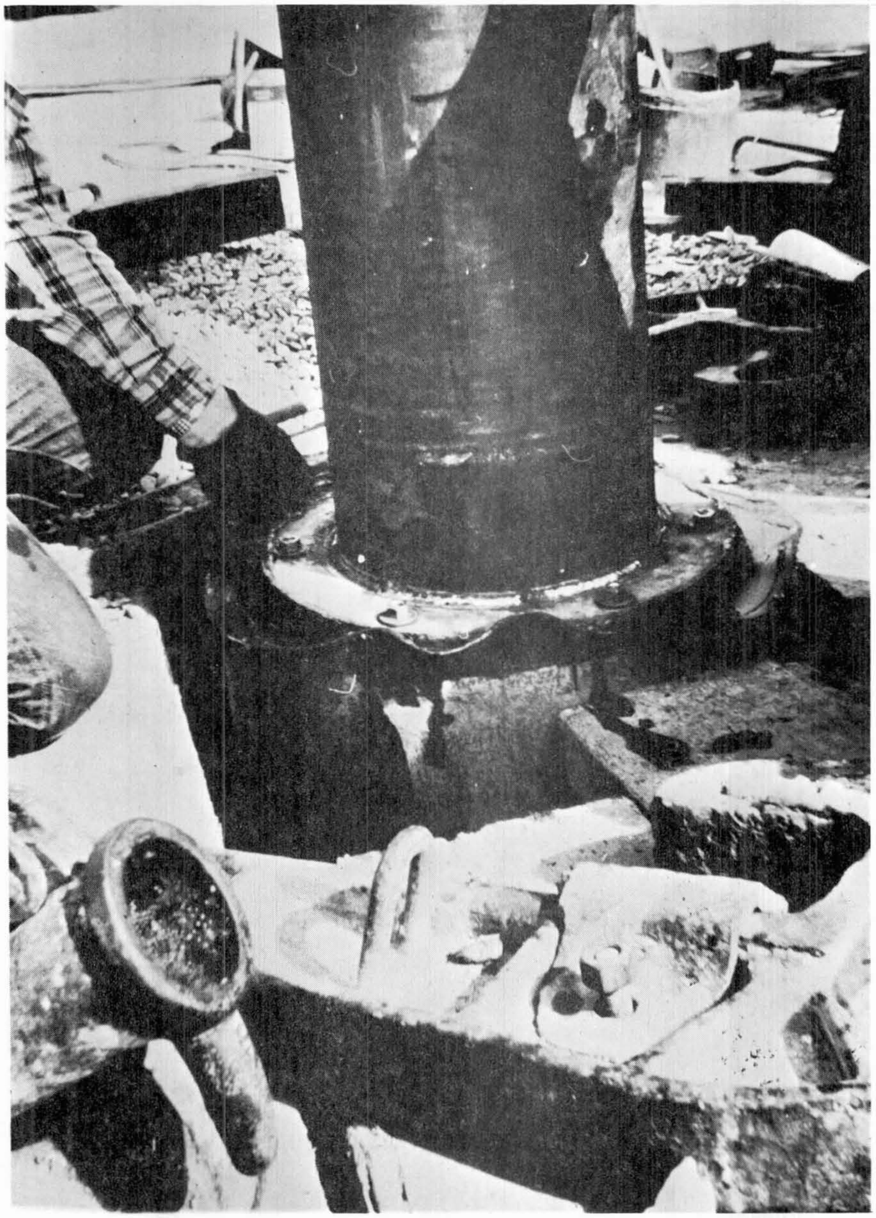


FIGURE 37 - LINER AND PACKER ASSEMBLY BEING INSTALLED IN RECHARGE WELL

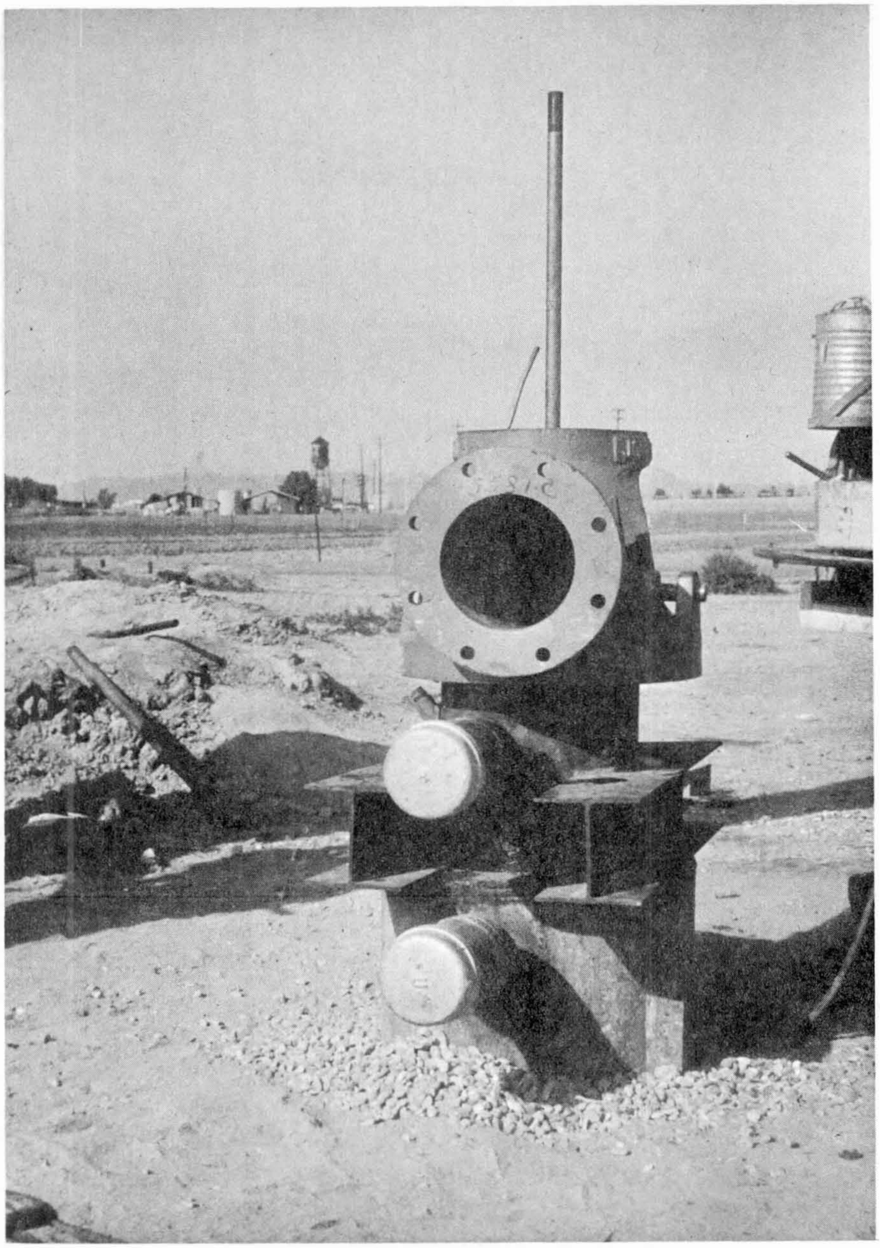


FIGURE 38 - WRRC RECHARGE WELL SHOWING INLETS AND PUMP HEAD

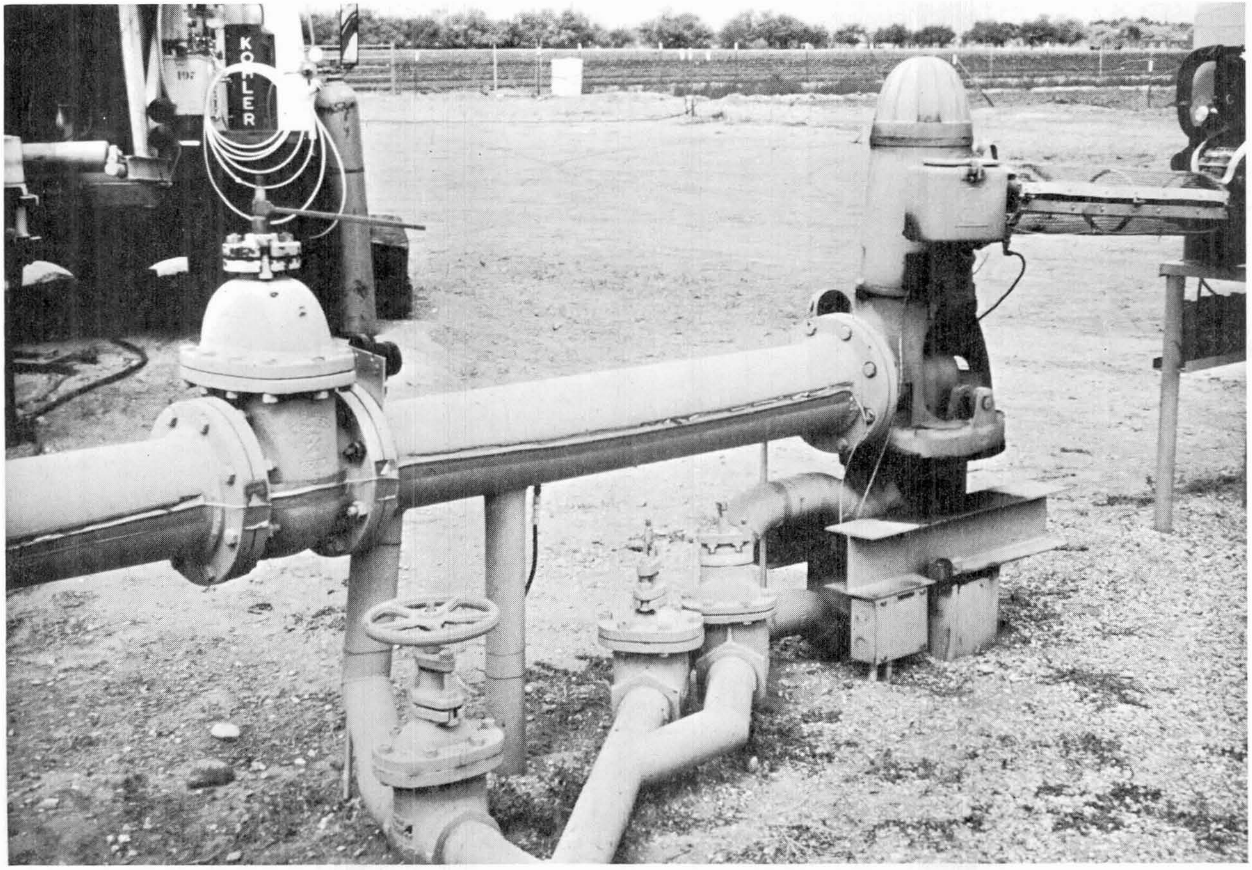


FIGURE 39 - WRRC RECHARGE WELL SHOWING INLET AND DISCHARGE LINES

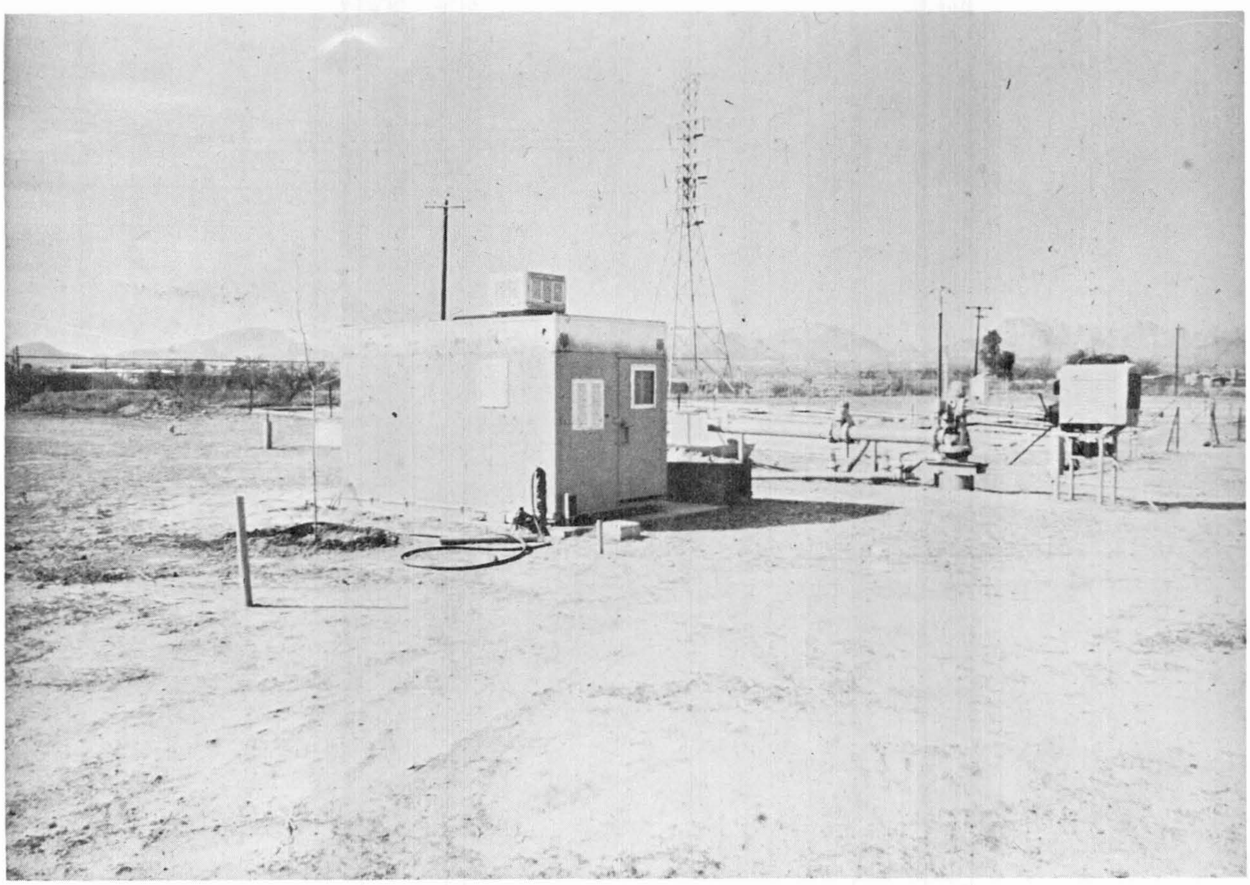


FIGURE 40 - WRRC RECHARGE WELL AND INSTRUMENT SHELTER

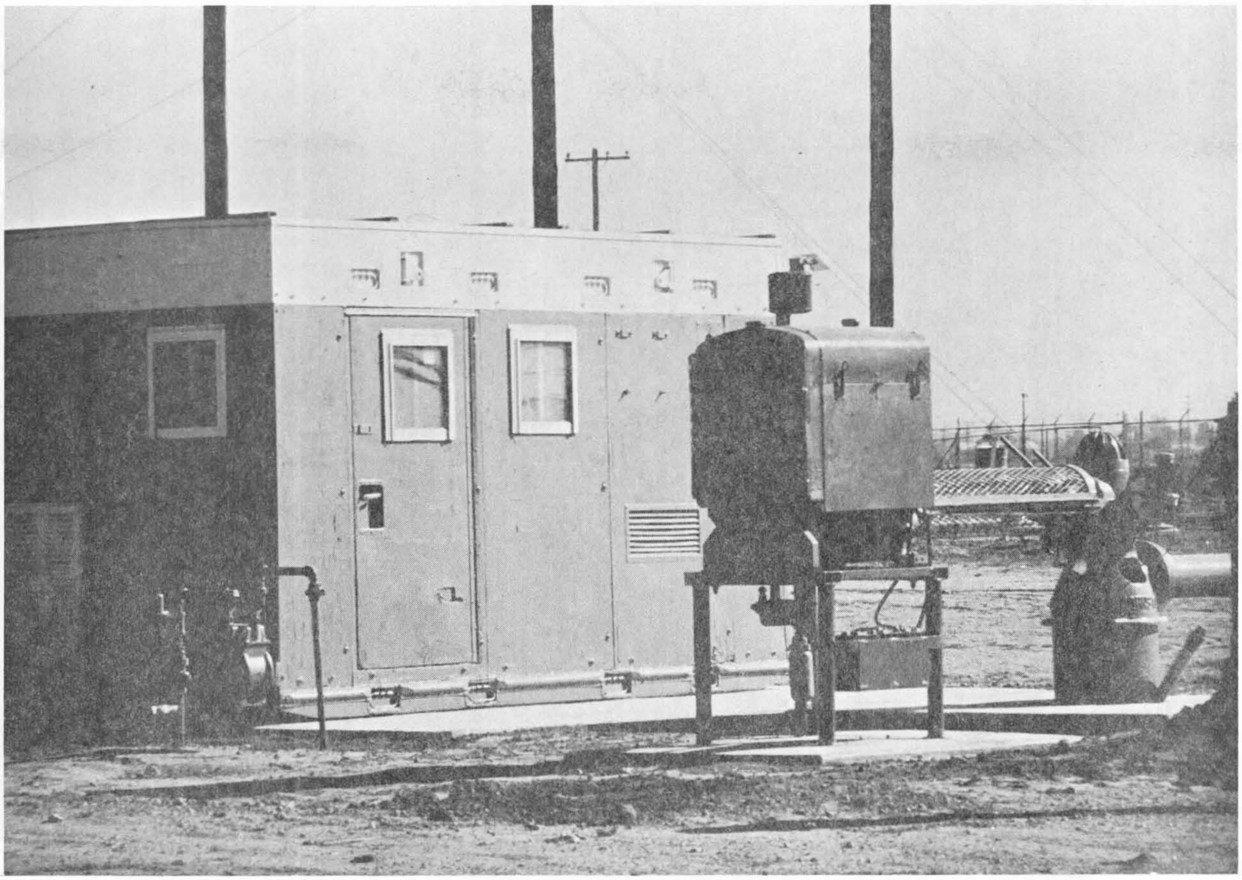


FIGURE 41 - 16-INCH PUMPING WELL USED DURING "TWO-WELL" TESTS AND INSTRUMENT SHELTER

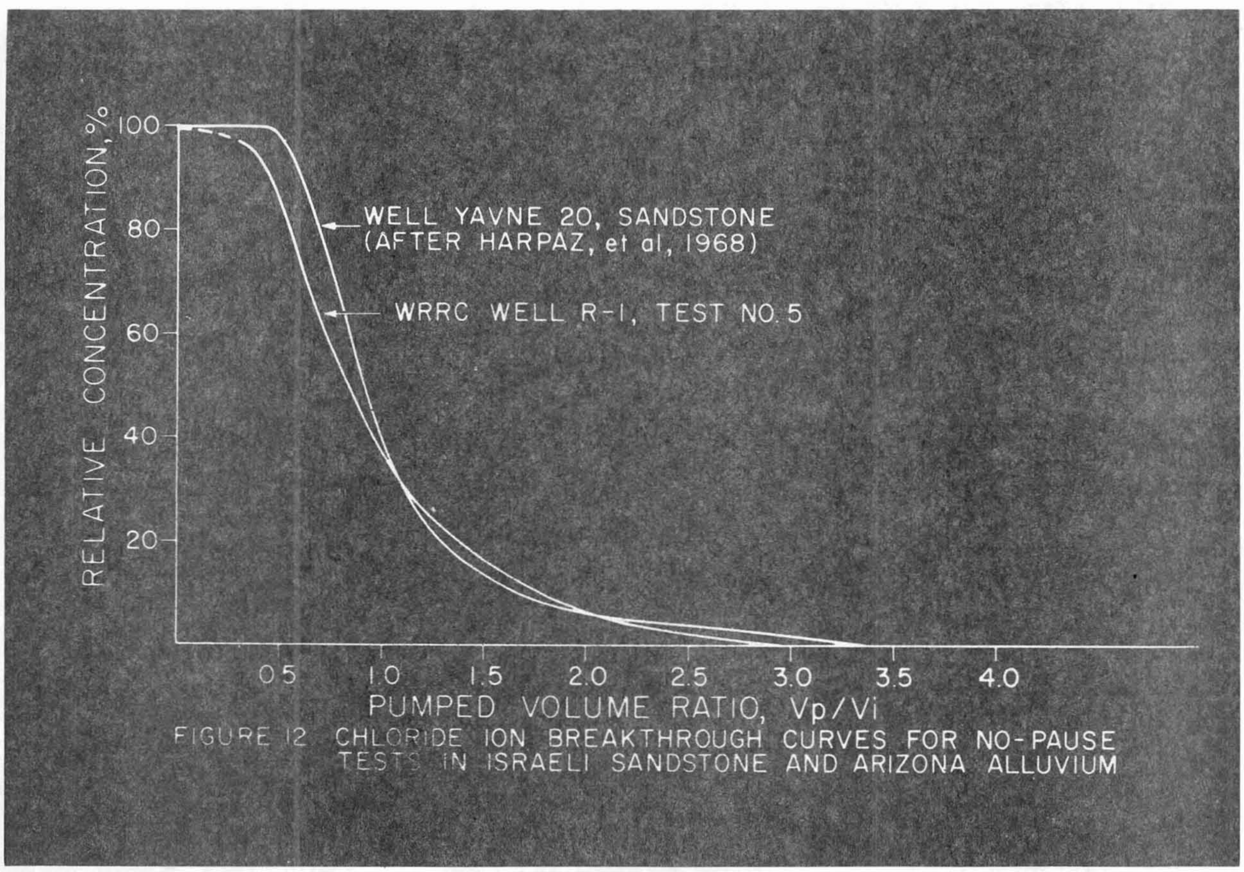


FIGURE 42 - CHLORIDE ION BREAKTHROUGH CURVES FOR NO-PAUSE TESTS IN ISRAELI SANDSTONE AND ARIZONA ALLUVIUM

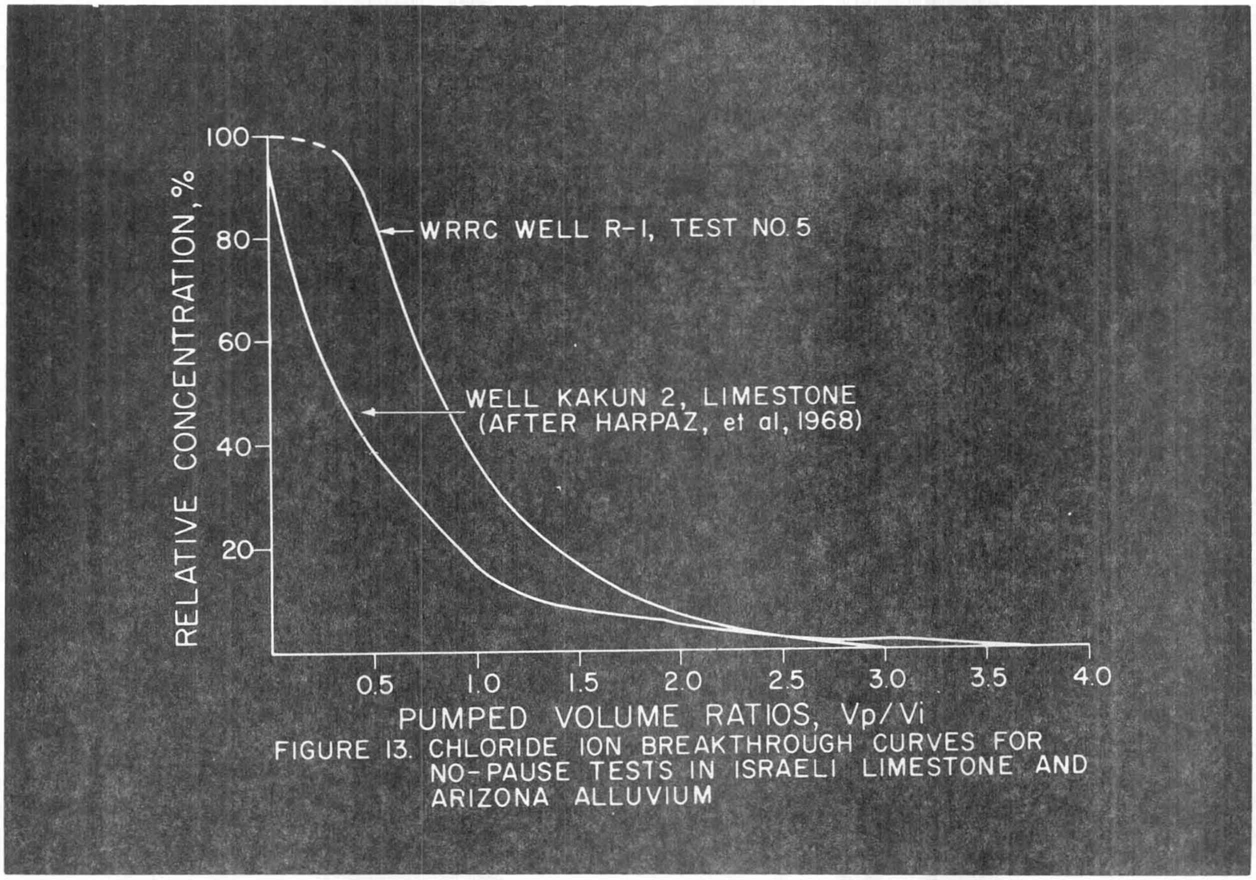


FIGURE 43 - CHLORIDE ION BREAKTHROUGH CURVES FOR NO-PAUSE TESTS IN ISRAELI LIMESTONE AND ARIZONA ALLUVIUM

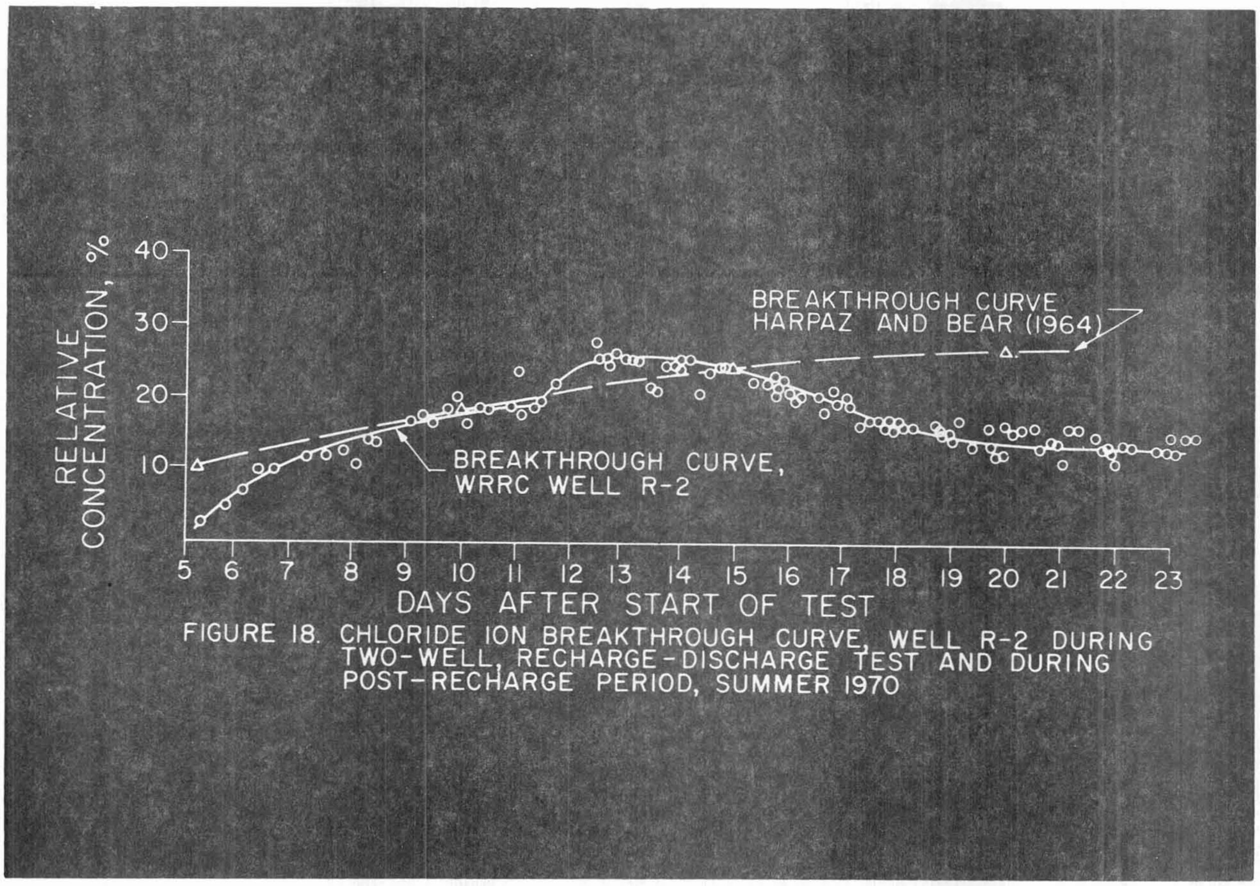


FIGURE 44 - CHLORIDE ION BREAKTHROUGH CURVE, WELL R-2 DURING TWO-WELL RECHARGE-DISCHARGE TEST AND DURING POST-RECHARGE PERIOD, SUMMER 1970

Discussion Panel #1

Herb Donald (Chairman) - General Manager of the Maricopa County Flood Control District, Phoenix, Arizona

Leonard Halpenny - President of Water Development Corporation of Tucson, Arizona

Jim Atterberry - Civil Engineer for the City of Phoenix, Arizona

Ben Dibble - President of Dibble & Associates of Phoenix, Arizona

Phil Briggs - Chief Hydrologist for the Arizona Water Commission, Phoenix, Arizona

Dennis Duffy - Professor of Civil Engineering at Arizona State University, Tempe, Arizona

QUESTION:

I am interested in the amount of recharge that occurs in the Salt River Valley from these various floods. You spoke of the amount that occurred from the 1965, 1966 floods, and the 1973 flood. I started to ask you what figures you might have on the 1978 flood, but Herb answered that, and I was surprised that the amount that appears to have disappeared between Granite Reef and Painted Rock was much smaller than in those other flood events. Do you have any comment on that?

<u>BYRON ALDRIDGE</u>:

I haven't had a chance to study this. I am just starting to get into my report on that flood, but I think that possibly this is somewhat the channel conditions preceding it. There was a lot more precipitation in the Salt River Valley that may have wet the channel considerably more during this later flood than in December '65. Prior to the 1965 flood there had been quite a long period when there hadn't been much rain.

QUESTION:

You have talked about the gauging stations on the streams. How about the rainfall data in the basins? Do you have a program for that and how do you handle it?

BYRON ALDRIDGE:

We do have a small program with Maricopa Flood Control District for rainfall in the area around Phoenix. But, most of the rainfall data is collected by the National Weather Service. We do not try to get into rainfall recording very extensively.

QUESTION:

Isn't it important to relate rainfall on the watershed to run-off in streams?

BYRON ALDRIDGE:

Yes, we relate to the Weather Service data using their data and whatever other information we can obtain locally. During major floods we may conduct a bucket survey when we try to collect data from local residents, to fill in as much precipation information as we can. But, since it has been, basically, the weather services jurisdiction, we try not to duplicate the effort.

QUESTION:

Is the Weather Service providing a new radar system that would give us a much better feeling in the entire state as to the rainfall intensities? Are they giving you any information on this?

BYRON ALDRIDGE:

On this particular system I don't know what is going on, as stated earlier I have been working on a two-year detail in Wyoming so I have been a little removed from some of these things. But, as far as working with the Weather Service, they do provide the information when they anticipate excessive runoffs, that we should be watching for in order to measure the flood peaks.

QUESTION:

Do we have an adequate data collection system, and secondly, what is the role of other agencies in the Valley in participating in a data collection and evaluation system, and then third, how much interchange is there on, both among agencies and on a national basis as far as information that is collected?

BYRON ALDRIDGE:

As far as the adequacy of the system that would have to be studied in detail for the particular purpose which you are speaking of. For one thing, it could be considered entirely adequate. For something else, it might not be.

QUESTION:

How adequate is the data collection system for groundwater studies?

<u>BYRON ALDRIDGE</u>:

I think that we have an adequate data base to know pretty well what the capacity of the aquifers would be; how frequent we would be able to get runoff. As for some of the problems that Herb addressed, I am sure that we do not have all the information that we might need there, but he felt that there was enough to study the economics of it. We would need research on the problems he discussed. As far as the second part of your question, that was, role of the other agencies. The Geological Survey is the data collection agency on water information. There are many other agencies involved in similar type of studies, the Bureau of Reclamation and the Corps of Engineers are studying reservoir design and flood flows through the city for design work. The data that we collect is used by all of these agencies and there is a great deal of interaction between the agencies. For the present report that I am working on, we have six different agencies cooperating on that right now financially. The third part was...

QUESTION:

How much interchange of information on a national basis? Some of our problems here, perhaps, would correlate to problems in other parts of the country.

BYRON ALDRIDGE:

I don't think that there is the degree of interchange that there could be. There are a large number of reports written, and people are relying very heavily on the reports as being an interchange of data, whereas oftentimes, the reports are not read to the degree that they should be. But, symposiums like this will probably tend to increase that interchange.

QUESTION:

In areas of extensive groundwater mining, subsidence resulting cracks often occur. Has the U.S.G.S. or Salt River Project, explored the possibility of using these features to overcome the antisyntropic soil permeabilities or used these features to place the water deeper in much closer proximity to the regional groundwater table?

BYRON ALDRIDGE:

We are doing a study on earth cracks, where they are forming, what causes them, but as far as whether they have been studied as a possibile method of recharge, I cannot answer that.

QUESTION:

In the existing reservoirs on the Salt and Verde Systems, what kind of infiltration losses are now occuring?

SID WILSON:

In terms of seepage losses in the reservoir system, I cannot answer that specifically other than to say the losses are surprising low. In my opinion, the reservoirs appear to be very tight. In fact, this was dramatically demonstrated not too long ago. We were concerned about a well that was being drilled near one of the reservoirs by the Sheriff's Office for water supply to an AID Station. That well was located essentially at the high water line of the reservoir. An analysis of that well water to determine if it was picking up infiltration water from the lake indicated that it wasn't. There was no hydrologic conection. So, generally speaking, I don't think the infiltration losses are too great.

QUESTION:

You stated that in 1965-1966 flood, about 600,000 A.F. release to the Salt River, 200,000 A.F. infiltrated and 400,000 A.F. feet reached Gillespie Dam. Have you determined how much infiltration occurred from the 529,000 A.F. released in March 1978; if so, how much?

BYRON ALDRIDGE:

I have not gotten into this yet myself. The closest figures that I have is that given to us by Herb Donald of 141,000 A.F. did not reach Painted Rock.

HERB DONALD:

Actually this 200,000 A.F. figure I had rounded both the inflow and the outflow, which, 175,000 A.F. is the true figure when you subtract both of them.

QUESTION:

Is the 200,000 A.F. infiltrated from the flood release, the same release that resulted in 114,000 A.F. infiltrated as mentioned by Herb Skibitske?

BYRON ALDRIDGE:

I was talking of the December 1965-1966 flood. Herb was talking of the March 1978 flood. We also had a fairly extensive release in 1973, not high flow, but over a long period of time and I do not have the figures of what the infiltration was at that time.

QUESTION:

Does the Salt River Project use a radar system here in the Salt River Valley for precipatation monitoring purposes?

SID WILSON:

Because of the Salt River Project's water management responsibilities, we have maintained, over the years, a very close working relationship with various federal and state agencies. One of these agencies is the National Weather Service. Through their cooperation and assistance, we now possess a weather radar unit in our own Operation's Center that is an extension of the primary unit located at the Weather Service offices. The radar gives us a better picture of what rainfall intensities are occurring within the Salt River Valley, over the areas immediately adjacent to the reservoirs and, to some extent, the entire watershed area. We also participate in precipitation data collection with the Soil Conservation Service as well as the Weather Service. This information is used for both long-range water supply forecasts, and near-time flood forecasting.

QUESTION:

Is the released water at Granite Reef generally of poor quality?

SID WILSON:

It's of poor quality from the standpoint that flood water releases have a very high sediment content, which I believe has a definite impact on that water's suitability for groundwater recharge.

QUESTION:

How much available water for recharge and how much water was used for potential recharge during the 1965-66 release, 1973 release and 1978 run-off periods? Have you done any statistical analysis to give us an estimate of the water available on an average annual basis?

SID WILSON:

If you total the annual run-offs as shown on the historic hydrograph and then divide that total volume of water for the period of record; the result is misleading. It would appear that while our average annual demand has been about 1.2 million acre feet, our annual supply has been very close to 1.2 million acre feet. In the last 30 years, annual inflows have averaged less than 1 million acre feet. The problem, which was demonstrated in my presentation, is that we have very high peaks periodically that bring our averages up but we have sustained periods of time in between those high peaks when we experience generally lower than average inflows. So it is very deceiving to take a total volume of water over a period of time, divide it by the number of years and derive an average for planning and working purposes. Again, when you consider that the purpose of our operation is to maximize the use of our surface water in a manner which provides carry-over storage for periods of low flow. We do not have pumping capability to meet our entire demand from pumps alone.

QUESTION:

Is there any water available for groundwater recharge?

SID WILSON:

Periodically, there are very large flows such as the 1978 event when some half-a-million acre feet was spilled to the Salt River bed. But, aside from those infrequent major events, the water that is normally available as releases at Granite Reef is very minimal. To answer your question, I feel that the significant amounts of water that we are talking about for recharge purposes, occur in big slugs that are far and few between.

QUESTION:

How extensive is your study, your data base, and your data collection, as far as the status of the groundwater, and the interrelation between these surface flows, and the impact that this has on the groundwater?

SID WILSON:

That question should be deferred to Byron Aldridge or Herb Skibitzke who have a greater knowledge of groundwater and what is happening to it as a result of the surface water flows I have discussed.

QUESTION:

How great an impact is evaporation, either in the water courses or in the reservoirs themselves?

SID WILSON:

First of all, we maintain evaporation records for the reservoirs in conjunction with the National Weather Service. We have pan data at Roosevelt Lake and Bartlett Lake, as well as pan data at Granite Reef. At Roosevelt, we experience 80 to 85 inches of evaporation in a typical year. When we drop to lower, hotter elevations down around

Bartlett it may go into the mid or low 90's. At Granite Reef we are probably talking around 120 inches or so of evaporation. I guess the point that I'd want to make is, the further up the drainage that we store water, the less evaporative losses we are are going to incur. If we move water down here into the Salt River Valley, and store it in some sort of surface retention structure for recharge purposes, we are going to suffer greater evaporation losses because of increased temperatures. In terms of actual quantitative losses that occur in the reservoir system; it varies, depending upon the weather conditions in any given year or period of time and the amount of water that is in storage which, relates directly to the surface area. Historically, it has varied anywhere from 70,000 to 140,000 acre feet per year.

QUESTION:

Given a long narrow recharge pond, what would be the relation of the infiltration rates as between standing water in that pond and flowing water in that pond?

HERMAN BOUWER:

The main effect would be that of velocity on sedimentation of fine particles. In standing water, all the fines will eventually accumulate on the bottom. However, if you have a slight flow, some of the fines are carried downstream. So, I would anticipate that if you maintained a certain velocity in long narrow basins, you would have higher infiltration rates than when the water is completely stagnant.

QUESTIONS:

Have your studies indicated whether or not the amount of recharge that can be accomplished through these ponds is meaningful, or is it so small that it is, perhaps, not of any great value?

HERMAN BOUWER:

I can only speak for the sewage effluent that we have worked with, and there we get about 200 to 400 feet of water into the ground per year, so one acre of basin infiltrates about 200 to 400 acre feet per year. The sewage effluent periodically has fairly high suspended solids contents. The key to successful operation is to regularly dry the basins and get a recovery in infiltration rate by decomposition of the fines that have accumulated on the bottom, or by scraping the stuff off. In using floodwaters for groundwater recharge, you have the high sediment content, of course, and that's what you want to keep out of your infiltration basin. So, you have to work with pre-sedimentation basins, and get the suspended solids content down to very low values before you put them in your recharge basins.

QUESTION:

The stratification and anisotropic permeabilities seem to present some severe problems to getting infiltration fronts down to the deep regional aquifers. For the Salt River Valley, how attractive are smaller, much close to the surface perched water zones as a water storage?

HERMAN BOUWER:

What you want to resolve here first, is what kind of aquifers do we have below the Salt River, are they confined or unconfined? If you look at some of the gravel pit profiles, and the response of water tables near the river bed to flow in the river, you get the distinct impression that you are dealing with an unconfined situation. From 23rd Avenue on west, there is probably a clay deposit at a depth of about 200 feet, you want to work with unconfined systems above that clay deposit. The transmissivity of the aquifer above that clay deposit is quite high, so groundwater mounds should not be much of a problem, as long as you work with relatively long, narrow basins. So, you can put water into the ground there, and the groundwater mound will transmit water laterally away from the river bed.

QUESTION:

Recovering water from these shallow zones, is that, in your estimation, economically feasible and a good possibility?

HERMAN BOUWER:

Well, a number of the wells that are near the Salt River bed come from that zone.

QUESTION:

Speaking about entrapped air, would not the periodic resting and recuperation of a pond aggravate the problems of entrapped air?

ED WEEKS

Periodic drying does affect the problem of entrapped air. Don Signor will present a slide that shows the effect of losing water to the basin for a short period of time. This allowed more air to move into the basin-floor materials. Once water was restored to the basin, it took considerable time for infiltration to recover to its prior rate. Moreover, when the pond is allowed to dry completely, the sequence of an initial declining rate, a leveling off, an infiltration rate buildup, and a final rate decline, as shown in Figure 7 of my talk, would be repeated each time the pond is refilled. Air would be trapped and would have to be dissolved out each time.

QUESTION:

Again relating to air entrapment, is there any preconditioning, other than putting water to it, that has been tested or tried, in order to ease the air entrapment problem?

<u>ED WEEKS</u>:

I am not aware of any pretreatment techniques for avoiding air entrapment problems that are really feasible. In the laboratory, the problem can be reduced by introducing water at the bottom of the column, rather than at the top. The viscous drag caused by the rising water will act in the same direction as the buoyancy force to purge much of the air from the system. Also, soil gas may be purged from a laboratory soil column by running carbon dioxide through it. The carbon dioxide is highly soluble in water, and is quickly dissolved out. However, for a practical recharge project, I am not aware of any method for preconditioning the basin. I think the entrapped air problem is just one that must be lived with.

QUESTION:

Could you comment on the method used in the high plains of Texas a few years ago with their recharge wells? A plan at that time was to inject for 18 hours and back pump for 6 hours to clean the sediment off the well screen and, presumably, remove the algae.

HERB SKIBITZKE:

I would imagine that's probably the thing they're trying to do in the rainy collectors. That was to recirculate it every so many hours. If you could cut your system out injecting some kind of flood waste, it's not possible to reverse it; it might be different, but I think that would help an awful lot if you could truly get it out of the well then. The air apparently does not move. The air is a reversible process, capillarity just holds it in. You have got to be sure the air does not get in there in the first place. But, the small particles and the chemical effects can be reversed.

QUESTION:

In your opinion, in the Salt River Valley, are groundwater recharge & storage programs viable?

HERB SKIBITZKE:

Well, what you get, what appears to be is the fact that you've got an expensive public works program to build to take this groundwater recharge if you are going to go through the well injection system. You'd have large reservoirs to hold it, you have a distrbution system to get it to the wells, you have the wells, and you are going to leave this public work sit for years at a time without using it for anything, essentially. It's going to have problems of corrosion, problems of chemical changes - it is going to have all of these problems occur. Then, for one fleeting instant we are going to use it, and it's all got to work during that time, and over a relatively short period of time. If you don't make it a relatively short period of time, you increase reservoir problems, you increase evaporation problems and losses. So, it seems to me it's economic, you're cycling something you are going to use very seldom, and yet having an expensive public works program to take care of it. It's just, economically, it looks very very difficult; scientifically, it looks like you could do it. That's the difference. I think it's an economic problem more than anything else. I think it is way out economically.

QUESTION:

Do you know of any successful groundwater recharge through injection well projects in the United States where they are doing it just to replenish groundwater supplies?

HERB SKIBITZKE:

I don't know, most of the stuff from the West has not been successful. It has really been frought with difficulties, and these are single small point injection systems, essentially, and you have at least a radial distribution flow that helps an awful lot to get the water out. If you start large regional systems, you have a single dimensional flow problem that you have got to go through all our formations, and it does not look physically feasible at all. But, at this point, there are limited successes. I think they've had small successes in various parts of California, near Fresno. The big projects to really do away with large quantities, such as floodwater, the work hasn't led to any reason to think that it would be successful. They never have made such a project, but I don't think that what they have done looks very good.

QUESTION:

How effective do you think hydraulic fracturing of these alluvium materials would be in overcoming the problem of well bore contaminating and plugging? Do you think that is a viable technique?

HERB SKIBITZKE:

Fracturing the sediments? I don't believe so, I don't know, I have never had any experience with that. I don't know what the relevance to it would be, I really don't.

We will reconvene back here in this Conference Room at 1:30 P.M.

Discussion Panel #2

A. J. Pfister (Chairman) - General Manager of the Salt River Project, Phoenix, Arizona

Roger Evans - Planning Supervisor for the Salt River Pima - Maricopa Indian Community, Scottsdale, Arizona

Elijah Cardon - Citizen's Advisory Committee of the Maricopa County Flood Control District, Phoenix, Arizona

Meade Stirland - Manager of State Bureau of Water Quality Phoenix, Arizona

Paul Ruff - Professor of Civil Engineering at Arizona State University, Tempe, Arizona

Eva Patton - League of Women Voters, Tempe, Arizona

Al Colton - Manager of Environmental Planning for the Salt River Project, Phoenix, Arizona

QUESTION:

Were there any other uses for the ponding systems on your project considered to off-set costs, if so, were they implemented.

IRV SHERMAN:

Originally, the spreading facilities were set up on a single purpose basis. Since that time, there has been a certain amount of additional use for recreation and for wildlife refuge, but so far, none of the costs for the water spreading activities have been allocated to these other functions. As recreation has been added, the additional costs for recreation has been paid for separately by the recreation interests. We have tried to separate the various costs for these different purposes and allocate them to the particular function which was being supported so that we didn't have recreation paying for groundwater recharge or visa versa.

QUESTION

What effect does the use of chemicals, fertizilers or pesticides in the irrigation waters have on the groundwater quality?

KEN SCHMIDT:

Water from wells in this area has not had pesticides that I know of. Properly constructed wells in alluvial basins generally do not produce water with pesticides. They apparently are broken down or absorbed in the topsoil and do not percolate to the groundwater. We have probably not tested enough wells for enough different types of pesticides to know this percisely. However, there are no data to indicate that pesticides are a problem for properly constructed wells.

Fertilizers and/or chemicals boil down to nitrogen and phosphorous. We know from Herman Bouwer's experiments that phosphorous can be somewhat mobile in very coarse-grained materials. Virtually none of the large capacity wells that I know of have been sampled for phosphorous. This is because it has not been an important constituent for irrigation or domestic use. Thus, I don't know what the phosphorous content is in much of the groundwater, although I think it is very small. In the case of nitrogen, I have evaluated this in some detail as part of the 208 study. There is a very large area of high nitrates in groundwater in west Phoenix and Glendale in the West Basin. All of that evidence indicates that it was there in 1920, that nitrate contents have declined with time and thus, the high nitrates are not due to the use of chemical fertilizers. In the Salt River Valley, there is only one small area where fertilizers may have impacted the groundwater quality. In an area south of Tempe, nitrate contents are far below the drinking water limits, but appear to be increasing somewhat. So, my conclusion is that there is certainly nothing to date that indicates fertilizers are a problem in the Salt River Valley.

However, in the basins, where there are no canals or surface water, there were very high nitrates in some of those perched zones. They could well be from fertilizers in this case. Thus, it will be more of a problem in the areas where we do not have surface water for irrigation and large amounts of canal seepage. In other words, where the irrigation return flow is, almost a sole source of recharge is where problems may occur.

IRV SHERMAN:

We do not have any water quality problems to speak of with the water that we are using for recharge. I might mention that in the eastern part of the San Gabriel Valley in Los Angeles County, there is an area with a rather high nitrate content in the groundwater. The exact source of this high nitrate is really not thoroughly pinned down. There is speculation that it is the result of fertilization back in the days when that part of the valley was mostly in citrus, as it no longer is. There is also a lot of opinion to the effect that the high nitrates are due to the use of cesspools rather than the areas being on a sewer system. Exactly where the truth lies, I don't think anybody really knows for sure.

QUESTION:

You indicated that the Advisory Committee to Governor Brown was looking at changes in the law in relationship to groundwater recharge. Did the Advisory Committee look at the question of water quality?

HARRISON DUNNING:

No, that is excluded from the mandate. The water quality law in California was redone very thoroughly in 1969 and various changes have been made since then to conform to federal requirements, so that mandate for the Commission did not include water quality.

QUESTION

It was mentioned that those that put the water back into the ground have the right to recapture it. This has been the thing that has been litigated in California. How would that effect and what implications would that have for farmers and for private landowners, private developers?

HARRISON DUNNING:

Well, the City of Los Angeles vs. City of San Fernando litigation involved not just the four cities that I have mentioned, but also private pumpers who had been pumping water in some of those areas and who argued they had rights to do so. California for a period of time had had a theory of prescription, so that if you pumped water and in fact used it and invaded the rights of others, you acquired the rights to it. One of the notable things for us that came out of the San Fernando decision was the conclusion that you couldn't have this prescription against a city. So, the farmers lost there.

QUESTION:

Would L. A. County Flood Control District have become involved in water recharging had the impetus to keep out the salt water not been there?

IRV SHERMAN:

As a matter of fact, we became involved in groundwater recharge in 1933 and we didn't get into the sea water intrusion control business until about 20 years later. That was a later development. As a matter of fact, we got into the sea water intrusion control business not of our own volition but because the water users along the coast recognized the need for something to be done. They petitioned the State Legislature to appropriate money for studies and I am not sure exactly how, but we ended up as the agency that was asked to conduct the experiments. After we demonstrated with a one mile long line of recharge wells that the process did actually work, we ended up building all three barrier projects.

QUESTION

How do you handle odors? Were there complaints or just sensing by the operators?

HARRY NIGHTINGALE:

There haven't yet been any complaints about odors from the urban areas. Odors are evident within the area of the recharge due to the low level of continuous biological decomposition of organic matter. Fortunately for Leaky Acres, the prevailing winds are from the northwest and the runways are to the southeast and so the winds usually carry any odors down towards the runways, rather than directly into the urban area. Odors would probably be a problem only for those people who are living within three or four hundred feet of the basins themselves. No attempt has been made to reduce the causes of the odors, because the level of odors has not generated complaints.

QUESTION:

We have heard here in the Valley of different sources of water used in recharging; for instance, flood run-off, waste water effluent. What is a kind of water that could be used to protect those uses? Then, if we are going to use some waters that have a high sedimentation or other things like waste water treatment plant discharge, what kind of treatment costs are we looking at to be able to use those waters for recharge purposes?

IRV SHERMAN:

As far as the cost of reclaimed water goes, the County Sanitation Districts in Los Angeles County have so far taken the attitude that they are required to treat the water anyway, operating under the directive of the State Health Department. So, they do not try to recover their entire costs from the agency that purchases the water for groundwater recharge. At the moment, we are operating under an interim contract and the water is being sold for $7.00 per acre foot. If they are to try to recover their entire costs, I don't know where it would be; things are so complicated now with federal subsidities for waste treatment plants that I am not sure just exactly how the costs would be sorted out. In terms of quality, the reclaimed water that is now being provided for groundwater recharge in Los Angeles County has gone through tertiary treatment. So, really there is no problem at all with the quality of that. As far as storm water goes, the only quality problem with storm water is the sediment content. In terms of total dissolved solid, storm run-off is generally the best quality water we have, with the exception of the water in the first storm or so of the season; at which time, we have the effect of urban run-off picking up all sorts of accumulations off the streets and very often we will simply let the water in that first storm go by to the ocean rather than try to spread it because of those quality problems. Outside of that first storm or so of the season, the sediment is a problem for the facility operator but it doesn't really have any adverse problem on the quality of the groundwater because the sediment is obviously filtered out in the spreading basins.

QUESTION:

Was salinity, waterlogging or drought the probable reason the Hohokum Indians left the Salt River Valley?

KEN SCHMIDT:

I haven't made an analysis of that. Of course, about 80% of the question is beyond my field of expertise. The only thing that I know relevant to that at all is that, we never began our sampling of groundwater until large-scale pumping began, which was in the 1920's. We know then that the salinity was high in the shallow zones and that it decreased due to pumpage. I don't have any information back beyond the turn of the century, so I obviously can't tell you about the Hohokum Indians. I would like to add one point about the previous comments on storm run-off. A lot of storm run-off is disposed to the groundwater in both Fresno and Phoenix. I don't believe we have any information whatsoever on what it does to the groundwater quality. A major concern besides trace elements is total organic carbon.

QUESTION:

What is the criteria for determining surplus groundwater and what is the criteria for defining a scarcity of groundwater?

HARRISON DUNNING:

The California court in 1949 started with a series of adjudications of groundwater basins and since then a lot has changed in the norms that they have used to decide in these adjudications. But the one thing that hasn't changed is the premise that total pumping should be cut back to safe yield. Now, your questions, as I understand it, is how do you figure out what is the "safe yield". What happened in 1949 with the Pasadena vs. Alhambra case was that the Court referred the matter to an administrative body, the Department of Water Resources. It was with the Department of Water Resources for a long time and the department came back with the recommendation as to what constituted the safe yield. This determination was not challenged. I suppose the various parties could have brought in experts and said well, they're wrong in their figure; but, the figure was not challenged and they went ahead with the adjudication and said so much could be taken out each year and still maintain some kind of balance in the basin.

Obviously, safe yield represents some notion of long-term balance between inflow and extraction from a groundwater basin. The adjudications that took place between 1949 and

1975, when the San Fernando case was decided, were essentially negotiated settlements leading to stipulated judgments. So, the parties themselves would decide what they thought was an appropriate aggregate amount to take out of the basin and that, in effect, would be rubber stamped by the court. Now, in San Fernando, another wrinkle was added in that the California Supreme Court said that in order to engage in effective conjunctive use management, you have to have storage space available in the basin and this may mean drawing down the water table to some point. They developed a notion which they called "temporary surplus" and said well, you could take out the temporary surplus and that won't count in terms of safe yield.

I don't have a ready answer myself as to what is safe yield, except to point out that the courts have relied on administrative judgments as to what an appropriate balance is and that such judgments must take into account decisions as to the economics of recovery, water quality degradation and so forth.

Now, the other part of the question was when do we know the criteria for determining scarcity of water? Well, I suppose that once you are exceeding that safe yield figure, however, arrived at, then you are overdrafting. Many people in California agriculture say eventually economics should be the balancer. We don't go nearly as deep as in Arizona, and I was startled when one of the panelist mentioned that some of the wells here go as much as 1,500 feet down. In the southern part of the San Juoquin Valley, they sometimes go 600 or 800 feet and people think that is a long way. Many of the pumpers believe economics should lead to a balance. But the Governor's Commission has recommended that there be more of a planning process to determine how the balance should be struck.

QUESTION:

Has the Governor's Commission addressed the question of Federal Reserved Rights as it relates to groundwater recharge rights and the responsibilities?

HARRISON DUNNING:

No. On the theory that this Commission advises the Governor, the Governor proposes statutes to the California Legislature and the California Legislature cannot do much about Federal Reserved Rights. I suppose a resolution could be passed, calling for this or that. The western states have called for various thing with regards to Reserved Rights for years and we didn't think it was particularly effective. All these other problems needed study and provide opportunities for the Legislature to be effective, so we did not take up any of the Federal questions, whether Reserved Rights or Federal water quality standards or anything else.

QUESTION:

In any of the recharge districts, is there an issue of Reserved Rights that will have to ultimately be confronted?

HARRISON DUNNING:

Well, it certainly wouldn't be in the Los Angeles plain or Santa Clara Valley. I have not heard of any.

IRV SHERMAN:

If this has come up in California so far, I have not heard of it.

QUESTION:

Concerning reservoir cleanout, what do you do with sediment and debris?

IRV SHERMAN:

Okay, that depends on the situation. The cleanout in 1970 that I mentioned at Whittier Narrows Reservoir is in the middle of an urban area where the contractor had a use for the material and he hauled it away somewhere to be used as fill. So, we didn't have that problem. For the contract that is under way now at Big Tujunga Reservoir, we have a derbris disposal area that is immediately downstream of the dam on both sides of the stream bed. The contractor will move the debris 1,000 yards or so and place it on this debris disposal area. When he gets the area up to grade, it is going to be a recreational area administered by the Forest Service. Other debris disposal areas depend on the particular circumstance. This last winter when we were cleaning out debris basins, trying to get them emptied before the next storm came along, we were hauling debris by dumptruck as much as 20 miles to a public dump simply because that was the only way we could get rid of it.

QUESTION:

What is the average depth of your recovery pumping?

IRV SHERMAN:

Well, that varies. In the San Gabriel Valley, it is something in the order of 200 feet to groundwater; in the coastal plain, it may be anywhere from 100 feet to maybe 150 feet, depending on location. In the coastal plain, the levels have been drawn down to as far as 100 feet below sea level, but those are in locations where the ground surface may be only 25 or 30 feet above sea level. In the San Fernando Valley, the ranges are somewhat similar, perhaps 250 feet; those are the major groundwater basins in the coastal parts of the County. In the Antelope Valley, on the desert side, water levels are down probably about 300 feet below ground level and keep getting deeper and deeper because at the moment, there is no recharge program there that amounts to anything.

QUESTION:

Have you noticed any effects, either positive or negative on the recharge and recovery on land subsidence in the areas in which you have these recharge districts?

IRV SHERMAN:

I am not aware of any particular effects in Los Angeles County due to our recharge operations. We have had subsidence along the coast, particularly due to withdrawal of petroleum from the Wilmington Oil Field and I know that there have been subsidence problems in the San Joaquin Valley, but I am not aware of any in Los Angeles County.

QUESTION:

What agencies or departments have been leaders in getting these recharge projects off the ground? Does any one department or agency in California have the final authority in the recharge programs? What methods do you have for coordinating between the various groups that have to cooperate in order to do the planning and implementation of these programs?

HARRY NIGHTINGALE:

I am with the U. S. Department of Agriculture and we do have cooperative research agreements with the City of Fresno and the County of Fresno. We have found that our cooperative research agreements are very beneficial to us as well as to them. We have always had excellent cooperation with the city personnel in sharing of equipment and labor on recharge projects. I think that it is very important that the people involved in research have cooperative agreements with these other water agencies. They point out problem areas where research must be done which may not be evident to the researcher. So, it is important to have these water agencies cooperating with the researchers.

IRV SHERMAN:

Let me just give the example of what has been done in southern California. In general, despite a multiplicity of special districts and various local governments, there has been remarkably good cooperation and that has been necessary in order to make possible the things that have happened. For example, in the spreading of reclaimed water, we have a three-party contract between the Flood Control District, the County Sanitation Districts and the Central and West Basin Water Replenishment District. Originally, we had a four-party contract that included the County of Los Angeles; they loaned the money to allow the Sanitation Districts to build the Whittier Narrows Water Reclamation Plant. The sale of that water to the Replenishment District provided the funds that paid off the loan to the county. That plant is now totally paid for. In the main San Gabriel Basin, we don't have reclaimed water being spread, but we have similar contracts for spreading imported water between the Flood

Control District and two municipal water districts and with the Main San Gabriel Basin Water master, which is a nine man body appointed by the court to oversee the management of water rights in the Main San Gabriel Basin. We will have an agreement with the City of Los Angeles to spread Owens River water for them in the San Fernando Valley when they want more spreading than they can do in their own facilities, and so on. We have a cooperative agreement with the Orange County Water District for the joint management of the Alamitos Barrier Project which is a sea water barrier project which crosses the county line, part of it being in each of the two counties. And so on and so forth. The work that we did originally on the experimental barrier project was supervised by the Department of Water Resources and we were the contractor that conducted the research for them. So, there is a very vast and interlocking chain of cooperative efforts and I would say that, by and large, it has been amazing to me how well all these different individuals and agencies get along together.

QUESTIONS:

Is there one state agency that has the ultimate responsibility--who has the ultimate authority and accountability in a groundwater recharge project?

IRV SHERMAN:

I don't know that it has really been tested. I know that the law provides that if there is an overdraft situation which is not being remedied, the State Water Resources Control Board has authority to step in and essentially exercise state control and if need be, force a reduction in pumping in order to bring an end to the overdraft. So far, that has not happened in southern California and I am not aware that it has happened anywhere in the state. The Department of Water Resources also has certain powers, but generally speaking, the management of groundwater in California has been left to the local agencies.

HARRISON DUNNING:

I can agree with Irv that there have been some remarkable successes and that they are attributable to local governmental response, by and large, to problems, but I think there is another side to the coin. Ordinarily, in Orange County or Los Angeles County or wherever, a local government has either already had the power to respond to existing problems or, if it hasn't had the power, it has gone to the legislature. The matter has been treated as a district matter and the necessary powers have been given.

However, there have been some problems in several areas in having appropriate coordination between local government action and state government action. One particular situation which comes to my mind involves the Kern County area, the southern part of the San Jouquin Valley, which is a very productive agricultural area. The voters in California approved financing in 1960 for a State Water Project which moves water from the northern part of the state to the southern part. Part of the purpose of the State Water Project was to replenish the depleted groundwater basins in agricultural areas like Kern County. Kern County Water Agency was formed as an intermediary between the state and the water districts. The agency holds one of the big contracts for State Water Project water, but as it has turned out, not a great percentage of the water has gone to replenish the groundwater basin in the overdrafted areas. A great deal of it in Kern County has gone to irrigate new land that had never been brought under irrigation before.

Part of the reason I think this happened was that the Kern County Water Agency lacked the tools to require that the overdrafted areas take the surface water and pay for it. The overdrafted areas preferred to continue overdrafting, which remained a lot cheaper than paying for the imported water, and so much of the water went to other areas. There was no state policy that would require Kern County to exercise the kind of control over its pumpers that, let's say, the Orange County Water District has exercised over theirs.

The Department of Water Resources, as the operational body in the state, in the last few years has had a policy of not only developing new water through water projects, but also of heavily emphasizing reclamation, water conservation and conjunctive use. I think there have been some problems between the state level and the local government level in this regard. There are possibly surplus groundwaters in the northern part of the state, and as an alternative to construction of new surface water impoundment facilities, some consideration has been given to using some of these surplus groundwaters. That creates enormous fears locally among the water districts and the agricultural interests, and there has been a lot of tension between local government and the Department of Water Resources in that regard. Also, when the Department of Water Resources, itself, wants to engage in conjunctive use by storing water in overdrafted basins or basins where space is available in the south, they run into problems. I mentioned in my presentation, that successful, rather quickly worked out, storing of some 22,000 acre feet, but there have been other areas where the Department has wanted to store Project water and they have run into problems. One of the things, as I understand it, that has held up the final judgment in the San Fernando basin case is an argument over who controls that storage space. Is it going to be controlled entirely by local interests for their own purposes or will the state have an opportunity to store State Water Project waters there?

The State Water Resources Control Board is the regulatory body in California. Some years ago they were given the power, not to cut back pumping themselves, but to initiate an adjudication where water quality is threatened for one reason or another in a groundwater basin. They've never used that power, but they are now investigating the Oxnard Plain, which is in the Ventura area north of Los Angeles, and they're considering initiating an adjudication there.

My observation in working for the Commission has been there is considerable tension between the local governments and the state bodies. There is some fear and distrust of the state regulatory body, partly because it has a water quality function and has issued some rather stringent water quality rulings. These are resented by the agriculturalists who have contracted with the projects whose yield is cut because of the water quality rulings.

There is also some fear and suspicion with regard to the Department of Water Resources. What the Governor's Commission is recommending, basically, is that in those areas of the state which do not now have a groundwater management system and which should have one, a cooperative state-local arrangement be worked out which would have state policy and local implementation. The stickiest point about that has been - well, suppose the state thinks the local governments really aren't properly implementing the state policy - what then? The initial draft proposed that the state have a review function with regard to local groundwater management programs and in effect have the power to veto those programs where the state judged them to be inadequate. That's been extremely controversial.

QUESTION:

Our river beds have been mined for sand and gravel and have become prime areas for landfill or trashfill. What problems would you anticipate from infiltration through landfill-type areas?

KEN SCHMIDT:

Well, this is a problem for recharge projects, such as along the Salt River, where landfilling has been practiced for decades. An abundance of solid materials are present that could create leachate if water comes in contact with these materials. Monitoring programs have been proposed to determine the impact of some of the landfills along the Salt River. Sand and gravel operations may decrease infiltration, due to deposition of fine-grained materials in the channel. We are doing a couple of things that are contradictory in some areas. For example, when we line canals, which we've done here and in Fresno, when sand and gravel operations are conducted in floodplains, then the infiltration capacity is reduced. It is somewhat contradictory to turn around and build facilities and spend money to intentionally recharge water. Often this contradiction isn't recognized or resolved. However, losses in infiltration capacity were not a direct part of my investigation.

QUESTION:

What are some of the mitigating measures in terms of groundwater recharge?

IRV SHERMAN:

Well, I wasn't thinking of any specific mitigation measures insofar as a groundwater recharge project goes because so far we haven't come up with any new recharge projects since the California Environmental Quality Act became effective that demonstrated an adverse impact of our projects on the environment. I was thinking in general terms and just including that in the laundry list of costs that you might incur. Now we have had adverse environmental impacts of some of our flood control projects and, of course, we have had mitigation costs there. Particularly, there is now a law in California that prohibits the alteration of natural stream beds unless you get the assent of the State Department of Fish and Game, and they may have some fairly severe requirements for what they want you to do as a condition of getting their approval for your project.

DISCUSSION PANEL #3

Wes Steiner (Chairman) - Director of the Arizona Water Commission, Phoenix, Arizona

Herb Schumann - Hydrologist for the U. S. Geological Survey, Phoenix, Arizona

Bob Moore - Executive Vice President of Agri-Business Council of Arizona, Phoenix, Arizona

Brent Brown - Executive Director of the Office of Economic Planning & Development, Phoenix, Arizona

Charlie Downs - Professor of Water Resource Systems at Arizona State University, Tempe Arizona

John Replogle - Engineer with the U. S. Water Conservation Laboratory, Phoenix, Arizona

Ed Kirdar - Engineer for the Salt River Project, Phoenix, Arizona

QUESTION:

What percent of the recharge water is recoverable by the City of Frenso's Well System?

BILL BIANCHI:

We take the goundwater contours that, historically, have been apparent in the local area, and these have been measured since 1924 by the Fresno Irrigation District; and take two periods, one period before recharge, and a period after recharge commenced at Leaky Acres, and super-impose these on one another. Now, the current water table in the area is continuing to decline. What we found was a decrease in the rate of decline as a function of the water that was being put in at Leaky Acres, and we observed a plume of pressure differential downgradient from the project. Then we made a decision that, within this plume, we would say that the effective area that was being influenced was an area where the rate of decline had decreased by at least one foot per year; and this amounted to a considerable area, and downgradient from the project, the distance to the maximum closed contour was around five miles.

Now this is not necessarily a storage change - it is a pressure change. We don't have a water table situation, but a semi-confined system. We then used political boundries associated with the City of Fresno (who was doing the recharging). They received only 78% of the total benefit of the project recharge.

QUESTION:

A part of the Corp of Engineers alternative sources, has to do with non-flood flow release from either the Salt or the Verde. Did you consider watershed yield improvement to, so that there might be a chance for extended duration recharge?

JOE DIXON:

When we approach the problem of what would be the potential source of water, we went through a rather grand brain-storming scheme, and as to potential sources of water, we determined that there are two, the Salt and Verde. I realize that it would require an institutional change for the Salt River Project to take water from surface storage and put it into groundwater storage; so that's our approach there. Currently, Salt River Project has informed me that water is not available for groundwater storage. I believe that will continue for awhile. But the point that you are making and that is if one does implement a program which would increase watershed yield, that water could be put into the ground and that was the particular purpose for the watershed improvement. It's a very good method for providing an additional source.

QUESTION:

Is the University of Arizona looking at watershed management to generate a source of water that is not there on a day-to-day basis?

L. G. WILSON:

Researchers at the University of Arizona and the U.S. Water Conservation Laboratory, have been experimenting for more than 15 years with methods for increasing the runoff from small watersheds. These methods, called "water harvesting" techniques, entail increasing the imperviousness of soils on the watersheds. Work at the University of Arizona has been conducted by Drs. C. Brent Cluff and Gordon Dutt. These researchers compared various methods for increasing runoff using data from small plots and full-scale catchments. Cluff and Dutt found that the following types of catchments were the most effective and economical: (1) compacted earth; (2) compacted earth, sodium treated; (3) gravel-covered plastic ground cover; and (4) asphalt-plastic, asphalt chip-coated ground cover. Methods for selecting a particular type of catchment for a specific site and water use were presented in a paper entitled "Economic Water Harvesting Systems for Increasing Water Supply in Arid Lands".

Cluff and Dutt also examined inexpensive methods for storing water from water harvesting catchments. Among the storage methods evaluated were: (1) plastic-lined, rock-filled tanks; (2) reservoirs in which the soil surface is coated with cement-mortar; (3) reservoirs in which the soil surface is sealed with an earth-covered plastic liner; and (4) reservoirs in which the soil surface is treated with sodium.

Water stored in the reservoirs could be used for various purposes such as stock watering and domestic consumption. Alternatively, the "harvested" water could be recharged. The latter approach was used on the White Sands Missile Station in New Mexico. Water collected from asphalt-lined catchments was diverted into small recharge pits. The possibility of linking water harvesting methods and artificial recharge has not been fully examined in Arizona.

QUESTION:

It was mentioned that farmers in Lubbock, Texas could take a depletion tax on the diminishing water table, and that Lubbock was the only place in the country where that could happen. Why only in Lubbock? Does that provide any incentive for people in agriculture to replenish their water tables if they can get that tax write-off.?

DON SIGNOR:

The reason that occurred is that there was a test case filed by a farmer who resided in the area served by the High Plains Underground Water Conservation District, headquartered in Lubbock. The District backed the farmer when he claimed a depletion allowance. They then went through the Courts and it was proven by expert testimony that the natural recharge to the Southern High Plains of Texas and New Mexico is negligible, and thus pumpage was the removal of a naturally deposited resource - a non-renewable resource. The Court case thus allows farmers the claim in that fashion. I think there's been some discussion about what affect this has had on attempts at conservation. Regarding the people involved in claiming this depletion being unhappy if they don't get enough depletion, the land is valued on the amount of water underneath, and with the declining water level, value of the property declines and that's the basis of the allowance. I don't know if there is any information particularly, but I think it's a good point to consider that possibly this has had some affect in regard to conservation. In other words, the water is to be used and it can pay out because it can be taken as a write-off on tax. Possibly, this has had some affect. I don't know if anyone has determined what it would be.

QUESTION:

Does the public understand the role of recharge in comprehensive water resource management; and secondly, is information readily available to the public about this particular alternative or aspect of water management; and thirdly, what is the relationship between pubic acceptance of proposed recharge projects and public information; and fourthly, what needs to be done if we do have a problem in this area?

JOE DIXON:

The answer to your first question is no. The public does not understand. We've got people that have misconceptions and understandings and there's a tremendous amount of information available, a tremendous amount of information not available. It's a complex situation and I would say, in general, the public does not understand all the issues.

The second question had to do with - is the public becoming informed? I think there's a tremendous interest in water resources. The drought of 1975-1976-1977, was kind of a topic for parties. You know, have you watered your lawn, have you not watered your lawn. It never quite got to that level here, but certainly places in California, it was very much in vogue to talk about water resource and water resource plan.

The question that you asked about artificial groundwater recharge, I don't think they understand the mechanisms of that and the importance that it could play. It seems to me that there's discussion here today on whether artificial recharge is a good thing. I'm not sure that we all agree if artifical recharge is applicable in this basin.

I think the next question had to do with public information. I would differentiate between public information and public involvement. I would rather see more public involvement, which certainly would key upon public information and the availabiity of facts to make decisions. I don't believe the public has been involved in this type of water resource planning yet. I know that the Groundwater Study Commission has begun to develop the background and the expertise so that they can make decisions. If that represents the public, we have begun that education process, but as you know, it takes a lot of background before these people can participate in water resource planning and make intelligent decisions with us.

QUESTION:

If we are going to be making investment decisions regarding groundwater recharge projects, do you think that there is a chance that these projects will be publicly acceptable? Will this be a function of how much the public understands the notions that are being addressed and their overall part in a comprehensive water management scheme?

JOE DIXON:

If the Federal government is involved, particularly the Corps of Engineers, there will be a public information, public involvement program. If the program is run by somebody else, I am not going to tell them how to do their water resource planning. I can only speak for the agency that I work with and for. It is very difficult to involve the public in planning, there are more and better things to with your time on a weekend than to sit down and read a 500 page report. Public involvement is a difficult thing to do.

QUESTION:

How much water is available here in the Salt River Valley for infiltration? How much can we increase our water supply if we truly are able to infiltrate it all?

JOE DIXON:

Once again, when we want to look at this, we primarily concentrated on flood-flows. We looked at 86 years of records and we came up with a figure, an annual average number, if you will, which tends to be misleading. These types of statistics can be very misleading, because we know we have periods of drought. But, it appeared, on an average, that the Salt and Verde water could yield, over and above the Salt River Project's ability to store somewhere between 100,000 and 200,000 acre feet per year. That is from flood flows, and once again, that is based on 86 years of record. Now, Sid Wilson went a couple of steps further - but his analysis indicated that some 1.7%, a very small percentage of the time, flood waters would be available. I think that the next step is to look at, if one had the facilities and the desire to maximize recharge we could put a lot of water back into the ground. We realize that recharge of floodwaters is quite infrequent, and you can only do it when the water is available. But, if you have a sewage treatment plant with treated effluent, there is another potential source. The fact is that our sewage treatment plants are not located in the proper part of the basin so as to recharge our depleted aquifers. Colorado River water will be available when the Granite Reef Aqueduct is completed. Whether it is institutionally feasible, I do not know. But once again, a potential source. If you wanted to, you could put all the CAP water in the ground. Everything that they import, you could put in the ground. It would take a good design and some institutional changes. But, to answer your question, we do not know what the number is, and we need to find out what the number is, and we need to look at all potential sources and then start looking at some of the trade-offs involved in using that water. We don't have the facts. Some people tell you that they have the facts, but I haven't seen them.

QUESTION:

It was indicated that some kind of control structure would be needed to control the flow and utilization of the flood water which is to be recharged. Does this mean that recharge is not an alternative to the Orme Dam, but utilization of the capture of the floodwater?

JOE DIXON:

I don't believe artificial groundwater recharge is an alternative to Orme Dam. Certainly, you need to be able to control the waters before you can recharge them. I think the point that I made or if I didn't make it clearly, I'll restate it and that is that you need to have a control structure, and I don't care whether it is an Orme Dam or something else. You need to have a control structure. One could use existing structures to control the flows. If, for some reason, the management of Salt River Project decided that it was better to store the water underground than to store it on the surface, there are the control structures right there. But, the question you asked is whether artificial groundwater recharge is an alternative to Orme Dam. The answer is no. Artificial water recharge could be used in conjunction with a control structure which could be Orme, except that the President said that Orme should not be built.

QUESTION:

The Corps of Engineers report indicates the study is going to prove the feasibility recharge groundwater. Does a monitoring system of our groundwater hydrology presently exist?

JOE DIXON:

We have proposed a four-phase study. Phase one was a feasibility study on the potential for recharge of floodwater. Phase two, which we are wrapping up right now, is the development of a plan of study for a demonstration project. Phase three would be the implementation of that demonstration project, and phase four would be the full-scale recharge project. All we have done to date and all we have planned for to date is the completion of phase two. Phases three and four are as yet undefined in terms of timing and funding. I don't know when they would be implemented or who would implement them; whether it would be the Federal government through the Bureau of Reclamation, the USGS, the Corps, whether through the State Water Commission, through the Groundwater Study Commission--I don't know who would do phase three and four, I don't know if there is any interest to do a demonstration project. But what we have said is that we have a vehicle which could be the plan of study, and it does outline what one would have to do to answer those questions and what it would cost to answer those questions in a demonstration project.

QUESTION:

Is the Corps of Engineers going to address the total groundwater picture rather than just recharge as a finalization of your study or report? Will it have a total recommendation as to what should be done to see the whole picture?

JOE DIXON:

I don't think that's within the Phoenix Urban Study scope of responsibility, we will not make a specific type of recommendation. I think our main mandate was to look at the five study elements which were flood control, water conservation, fish and wildlife, wastewater and recreation. I think we will be talking with the Water Commission, we will be talking to the Groundwater Study Commission or they may be talking to us. They may be interested in some of our findings. But, I think the responsibility to look at comprehensive water resource planning in the State of Arizona or in the Phoenix metropolitan area does not belong to the Corps of Engineers. The Corps can do a lot of things and if we are asked by Congress, through the local governments, to do that, we would be happy to. But that is not our mandate right now.

SUMMARY PANEL

John W. Harshbarger (Chairman) - President of Harshbarger and Associates, Tucson, Arizona

Herb Donald - General Manager of the Maricopa County Flood Control District, Phoenix, Arizona

Manny Lopez - Regional Director of the Bureau of Reclamation, Boulder City, Nevada

Wes Steiner - Director of the Arizona Water Commission, Phoenix, Arizona

QUESTION:

What are the advantages of injection over direct use of surface waters in the distribution system?

HERB SKIBITZKE:

Direct use would be the best approach that we can have, if it is possible, but what we are talking about, in many cases, is a flood that is coming down and we have no way of using it, we have no way of slowing it down in its path down the channel without causing more trouble than we already have. We have, certainly, the desire to do it, but I don't see how direct use would apply to flood-flow. We already have reservoirs to the limit as far as size is concerned and the desire by most of the community not to build any more reservoirs. I understand that there would be some attributes of emptying the reservoirs beforehand and using the space that they have emptied from the reservoir and fill it, but you don't have that kind of warning ahead of time to do it. The problem would be to get the water out of the reservoir in time. Usually, we are suffering with the problem of trying to keep enough water to get through the next season when we might have a dry period.

QUESTION:

What is an average recoverability percentage for injection wells?

HERB SKIBITZKE:

Under the conditions that have been cited here, there has never been a project of injection wells of the magnitude of what we are talking about. In the Salt River Project, where water levels are lowering at the rate they are, we may not get the specific water molecules that we put into the ground out again, but at least the changing in hydraulic heads throughout the area and the redistribution of water would be rather complete. The way we are going, we are in the position now of having to cut off pumping in the years to come if we don't save some of the water or if we don't have water there. But the problem of analyzing whether you are going to get the exact molecules, the exact particles of water out that you put in, I don't think that's relevant. We are looking at the whole situtation economically, as to what it would do with water levels and water supply in the whole area. At the rate we are going, we are going to get use of anything that we put into the ground. I think you have to weigh that use economically, I think that is the big problem. We're talking about bringing water, pumping it up from the Colorado River and then bringing it up into this area and then pumping it back down into the ground and then pumping it back out of the ground and using this sort of approach when the other side of the fence is telling us that we have a severe energy problem. So, if we are talking about moving a lot of water around, I think it is questionable economically. It is a much more complex thing than just saying if I put this gallon in, do I get that gallon out. We are talking about economically, can we change the quantity of what we are paying for pumping and justify it in that sense. The problem in Arizona is that we have an awful lot of groundwater and we haven't even taken a very large fraction of groundwater out that we have in Arizona. Well, the problem simply is that we are not going to get it out. It is not economically sound to get it out. It is in forest material, it is in material that is not very permeable, it is in material at great depths and when we analyze all these things, it is not economically sound to get some of that water out. We have a quantity of water of a similar magnitude as one of the Great Lakes under the State of Arizona today, even after all this pumping that has gone on. Yet we are not going to get it out, we are not going to get it out because of economic considerations. Why do we suppose then, that just because we inject it into the ground with all the formidable problems we have that we are going to have an economically sound project by doing that? The problem is one of just where are we going to put the money? If you don't care about money, just start pumping down here to thousands of feet and putting water collection gallaries down there that will take water out with very low head losses. These are the factors, so I don't think you can exactly answer it in terms of particular gallons of water you put in.

head losses. These are the factors, so I don't think you can exactly answer it in terms of particular gallons of water you put in.

QUESTION:

Have you ever noticed this pressure wave effect in a free water table using an infiltration pond? If so, could you explain this phenomenon?

HERB SKIBITZKE:

The pressure wave or the height that water rises in an aquifer is a function of the hydraulic relationship that travels much, much faster. The hydraulic movement we can see travels considerably faster than the actual movement of water away from the well. We can start injecting water in the well and see the effect of this injection in a matter of days, over pretty large distances, in a matter of months, over greater distances. Yet, during the whole time we inject water, it is only traveling just a very few feet from the well itself. We are changing the hydraulic characteristics and oftentimes the economic entity that is of interest to us (water level) because we are using energy to pump it up. But it is very hard to get the relationship between the head movement away from an area and the water that is moving away. We can effect heads at great distances, and it is very hard for us to effect or move water in any distance away from a well. It is an injection problem. It is very tempting to think well, let's try to inject water into the aquifer, spread it out, radiating the aquifer and flood it up from underneath and fill the pour spaces above the water table. This is really a senseless loss or waste of energy to do so. It would really be much better to fill it in from above and save considerable amounts of energy to move it. So the energy relationships between the head movement and the water movement are somewhat abstract entities from the layman's viewpoint. Hydraulically, we have to possibly analyze it and once again go back to the same question. We don't really care about the particular water we are putting into the aquifer, we care what it does to the regional effect of the water table and water levels there. All we seem to be interested in is the height that the water is in the aquifer, how much pumping lift we have. We have seen projects here north of Phoenix, like Deer Valley, fail in the last thirty years because they couldn't afford to pump the water out. Yet today, we talk and plan where we are going to pump water up and down, move it back and forth without really considering whether that is an economically sound proposition. So this pressure wave as we talk about and the movement of water are two separate entities. So it is a question of just how are you relating it and what is the specific value that you are looking for.

QUESTION:

Generally speaking, would water injection at greater depths allow the partial pressure and the pour fluids to become large enough to dissolve the air bubbles according to Henry's Law?

HERB SKIBITZKE:

I don't think that we can do much to get rid of the air bubbles that are forming in an injection well during the time that we are urgently trying to inject water that has accumulated in the reservoirs that are over-extended. We are trying to get it into the ground as quickly as we can. We cannot take and rinse, depressurize and pressurize the system back and forth to get rid of the air bubbles. The capillary forces involved in holding small air bubbles in force media is so strong that even pumping it under extreme pressure would not get past these air bubbles. As an example, in Arkansas, where they were injecting the water under pressure, they had a 150 horse power pump injecting water into the aquifer and when it closed down, it lifted the pump clear off of its base. This of course, ruined the project. This is something that is not an easy, solveable problem, unless we can dry up the wells and start again over some given interval of time. And yet, when we are talking about Arizona where we have flood water that we are trying to get rid of we are talking about 1,200,000 acre feet of water coming down the river that we are going to do something about getting it into the ground. Where are we going to store 1,200,000 acres of water? If you stored it ten feet thick, it would represent such a big chunk of property that we could never afford that. The problem is how quick can we get it into the ground? How will the public works program get it into the ground and get it out of the way so that we do not need these huge reservoirs for storing it? Well, we can not take the time to cycle things such as air inframents that stopped our flow system or any other factors that are plugging it. Of course, the injection wells are very, very pronounced. We are flowing most of the water right through a few slots of a very concentrated area, and therefore any of these effects we are talking about are more pronounced in a well than they are in the river or a seepage pit.

QUESTION:

How much water could be recharged into the Phoenix area groundwater table by releasing surplus water more gradually over a longer period of time, coupled with a chain of lakes as invisioned by the Rio Salado project proposal?

HERMAN BOUWER:

It depends, of course, on infiltration rates and hydraulic loading that you can maintain, and on the land area available. Suppose you want to reserve space in the existing reservoirs for storing flood water. You would then probably have to release several hundred thousands acre feet of water per year. Let's just say, 500,000 acre feet of water. The hydraulic loading rate probably would be between 100 and 1,000 feet per year. Thus, recharging 500,000 acre feet per year will require about 500 to 5,000 acres. Let's take a figure of 1,000 acres plus another 300 acres for pre-sedimentation. This is approximately 2 square miles.

If the basins are 500 feet wide, you have a string of basins that is 21.5 miles long. Thus, the Salt River bed in the Valley will be pretty well filled up with infiltration basins. Then, we must consider the costs. It's one thing to put this water underground, but it is another thing to pump it up again. To put it underground might cost $10.00 an acre foot, to pump it up again might cost $20.00 an acre foot, so there is an extra cost of $30.00 an acre foot for about 500,000 acre foot per year. This is about 15 million dollars per year that you spend putting water underground and pumping it back up again. To do this just for a flood control measure means that you have to do this every year because you don't know when the flood is going to come, but you may only need it once every twenty years when the big flood strikes. To do this for twenty years would involved an expenditure of about 300 million dollars. Compare that to the cost of Orme Dam, which is about 250 million dollars, and you can draw your own conclusions. Also, there may not be enough wells in the Valley to pump these additional amounts of water, making it necessary to install more wells at several hundred thousand dollars apiece.

QUESTION:

How much ground water recharge occurred during the more gradual 1973 releases?

HERMAN BOUWER:

This is part of the studies that the Geological Survey has been doing. The figures that I have heard range from one to several feet per day infiltration or seepage rate.

QUESTION:

What are the ground water levels in the vicinity of the reservoirs and what do we know about the mounding in the vicinity of reservoirs on the Salt River?

HERMAN BOUWER:

Most of the reservoirs are in fairly impermeable rock, so there is really not any groundwater there on a large basis. Maybe there are some fracture zones so there is some water there that you can pump out and you could classify as groundwater, but there are no major aquifers in the area so I don't think you can talk of groundwater in the vicinity of the reservoirs.

QUESTION:

Based on field data obtained from your field studies, what would be the ratio of horizontal hydraulic conductivity to vertical hydraulic conductivity be in coarse grain soils and fine grain soils considering seepage from reservoirs, considering in situ and laboratory permeability testing and considering saturated and unsaturated flow.

HERMAN BOUWER:

Within the sand layers of the river bed, which appear to the eye to be fairly homogeneous but where there is microstratification, horizontal permeability is about five or six times greater than vertical permeability. Now, if you also take into the account the effects of the layering of the profile, the sand and gravel layers, then the horizontal permeability may be 16 times the vertical. At least this is what we found below the Flushing Meadows Project. Horizontal permeability was about 300 feet per day and the vertical about 18-20 feet per day. Whether the flow was saturated or unsaturated should have no effect on the directional permeabilities, unless coarse-textured layers become unsaturated while interbedded fine-textured layers retain their moisture at or near saturation.

ED WEEKS:

I haven't worked in Arizona, but I have developed an *in situ* aquifer test method for determining the ratio of horizontal to vertical permeability. Use of this method to determine the directional permeability ratio of aquifers in other parts of the country has resulted in values similar to those quoted by Herman Bouwer. For example, we ran six tests on glacial outwash, an aquifer consisting of relatively uniform sand, in central Wisconsin. The ratio of horizontal to vertical permeability ranged from 2 to 20, with a modal value of about seven. These values are very close to Dr. Bouwer's values of 5-6. Also, the Corps of Engineers did a study on Arkansas River alluvium near their Lock and Dam site no. 1 in Arkansas, and determined a ratio of about 4 to 1. A test by the USGS on alluvuim in the Scioto River Valley in Ohio yielded a ratio of about eleven. However, all of these tests were made in relatively homogeneous aquifer units, and much larger ratios should be anticipated in aquifers consisting of interbedded sands and clays.

Two schools of thought apparently exist concerning the general magnitude of the permeability ratio. The low-ratio people think in terms of ratios of from 1 to 1 to about 20 to 1, and the high-ratio people like values of say, 100 to 1 or 1,000 to 1. In general, the experience of the low-ratio poeple has been with a single, relatively uniform aquifer unit, while that of the high-ratio people has been with interbedded aquifers and aquitards. Generally, the permeability ratio in such thick interbedded systems is determined by trial-and-error manipulations of the ratio in a simulation model to match head profiles measured during an aerial study, and the ratios indeed frequently do range between 100 to 1 and 1,000 to 1.

Despite the two schools of thought, it is important to realize that the actual magnitude of the ratio can assume any value from 2 or 3 up to a very large number, depending on the degree of heterogeneity of the aquifer. The actual value depends on local conditions, and should be determined by site investigation.

QUESTION:

Could storage in the Verde and Salt reservoir system be reduced by a year-long ground water recharge program of the Salt River bed and increase SRP's pumping rights?

<u>REID TEPPLES</u>:

Actually, the pumping rights within the Salt River Project area have nothing to do with the reservoir storage. So, I would address the question, from the portion, could the water be released from the reservoirs on a continual basis to recharge the underground. Not unless there is a change in the laws because the Kent Decree and the adjudication of the waters of the Salt and Verde Rivers would preclude that. So, there isn't any connection between the pumping within the Salt River Project area as it relates to the surface water.

QUESTION:

What was the total quantity of water available below Granite Reef and how much of this water was naturally recharged?

BYRON ALDRIDGE:

Generally speaking, a little over two million acre feet of excess water was released in the last twelve years to the Salt River from the storage reservoirs. The key is not the average. What we must look at is the frequency of this. During the twenty years preceeding 1965, between the completion of the existing reservoir system and the releases that began in 1965, there were no spills at all. If you try to distribute the average, which is effected by one, two or three events over a long period of time, you reduce both the average flow to a very small amount and you have a time element such that storage between flow events might be for a long period if you were trying to utilize the entire amount of released water. Pertaining to how much was recharged, a rough figure is that between Granite Reef Dam and Painted Rock close to half of the released water infiltrated to the ground. During the 1965 flood, slightly over 600,000 acre feet entered the reach from Granite Reef Dam to Gillespie Dam; about

175,000 acre feet infiltrated upstream from Gillespie Dam and another 180,000 infiltrated between Gillespie and Painted Rock Dams. Of 1,200,000 that was released in 1973 about 500,000 infiltrated to the ground. This year there was about 141,000 acre feet of infiltration from a release of about 500,000 acre feet.

QUESTION:

Is the difference between the quantity of water released from the reservoirs & the quantity of water that is recharged worth some planning to capture and make available for use in eastern Maricopa County?

BYRON ALDRIDGE:

I think that is the purpose of this whole symposium, that is to consider whether or not the planning and knowledge are available. This would require somebody in an action agency to make a real study of economics and other factors before we ever really knew whether it was feasible and economically justifiable or not.

QUESTION:

Flows over the large reservoirs seem to occur too seldom to be of much use for groundwater recharge. However, the areas downstream of major dams or by virtue of their urbanization produce considerable volume of run-off from fairly frequent small storms. Is this a more valuable source of recharge than the SRP dams?

BYRON ALDRIDGE:

We need to really look at the urban run-off. Everybody thinks that we are losing a great deal of urban run-off but as quickly as that run-off reaches the Salt River channel, it infiltrates very rapidly and very little of the urban run-off actually leaves the basin. The channels that urban run-off flows into (New River, Agua Fria, and Salt River) are all quite pervious and most of the water infiltrates almost immediately under natural conditions. There would be little reason to try to infiltrate this artificially.

QUESTION:

What is the cost of an acre foot of recharge water? Please quote the per-acre-foot value of the five million acre foot spread to date.

IRV SHERMAN:

I don't think it would be too meaningful to try to assign an average value to that full five million acre feet because costs and prices have changed too radically in the forty-five years that we have been spreading water. I think it is more pertinent to talk about the values as of today. That, again, varies rather widely from place to place, depending on the local situation. For example, the alternative to groundwater in the coastal plain of Los Angeles County is to buy water from The Metropolitan Water District on the surface at $95.00 per acre foot. Then, when you compare that with groundwater cost, you have, let's say, the cost of putting local water under ground, which may be, say $4.00 - $10.00 per acre foot for the Flood Control District's spreading operations; a cost of anywhere from $30.00 per acre foot on up for pumping the water out of the ground; a replenishment assessment to support the purchase of imported water, which now runs $24.00 an acre foot, and a property tax on water rights which was, at least before Proposition 13, assessed at a value of $160.00 per acre foot per year. So depending on what the particular situation is and how deep you have to go for pumping the water, you probably have a net value on the order of $30.00 per acre foot for water pumped out of the ground, as compared with buying Metropolitan Water District water on the surface.

QUESTION:

Is the water that is currently being spread useful for other purposes or are you using strictly storm run-off that would have no other purpose?

IRV SHERMAN:

About half of the water that we have spread has been essentially storm run-off that would have little or no other purpose because most of it comes at a time when water demand is low or the water comes at very high rates. It is generally very turbid and the idea of treating the Los Angeles River at a peak flow of 100,000 cubic feet per second is obviously uneconomic. But, about half of the water that we have recharged over the years has been imported water which has been purchased by the local basin managers from Metropolitan Water District and there again, that is economical for them despite the cost of water purchase because Metropolitan Water District has been selling water for ground water replenishment purposes at a lower rate than they charge for municipal and industrial uses. This is for two reasons; first of all, the water sold for spreading is not treated and so the cost of the filtration plant is avoided; and secondly, they deliver the water relatively far from the point of use and a large part of the conveyance cost is avoided because the water comes down the flood control chanels to the spreading grounds rather being delivered through the pipe lines.

QUESTION:

Who assumes the liability for the impacts of recharge on earthquake generation as water injection releases existing earth stresses?

IRV SHERMAN:

That has yet to be tested in court. I am sure that if there is an earthquake and anybody is damaged and thinks they have a case because of higher groundwater levels, the Flood Control District will find that we are defending ourselves in court. How that will be resolved will have to be left to the future.

QUESTION:

What is the average recharge rate at Leaky Acres; what is the average evaporation rate and do you have any estimate of the cost of recharging water at Leaky Acres?

HARRY NIGHTINGALE:

The recharge rate averages now about 12 centimetres per day. The evaporation rate, of course, depends upon the climatic conditions, wind velocity and wind temperatures. Our studies over a year period show that this will average about 3 1/2% of the total volume of water delivered. On the cost of recharge, I'll refer that question to Dr. Bianchi, who has more up-to-date data.

BILL BIANCHI:

Well, after Irv Sherman's presentation, I see I am including many complexities which are going into their evaluations. That is, our evaluation of costs are oversimplified. What we looked at was the capital costs of land, the construction costs and the maintenance costs. As of 1973 prices, recharge at Leaky Acres ran between $3.50 and $4.50 an acre foot. That's just to get the water into the ground. Now, you have to recover this water and in addition, you have the water costs, adding these to our recharge costs brings them up to $16-17 per acre foot delivered to the water mains.

QUESTION:

Is there a really good way to control midges? How did you handle your public relations with respect to the midges?

HARRY NIGHTINGALE:

The control problem is rather interesting. The first year we did not have many midges. It was the second and third year that the midge population really exploded, in April, and at that time, people called the newspapers and they came out and took pictures of awful big white midges flying through the air. As a consequence, pressure was put upon the Water Department and this resulted in taking the water out of one of the basins which apparently was producing most of the midges and drying the soils for a few days and discing. This does, of course, kill the midge larvae. The midge larvae feed on the organic matter in the soil and with time, as long as we are not adding any more organic matter to the system, the organic matter level in the soils decreases and this causes the midge population to decrease. So, since that time, we have not had a midge problem even though anytime you go out at Leaky Acres, even this summer, there were a few swarms of midges around.

QUESTION:

Did you attempt to deal with the public in a formal way on the midge problem?

HARRY NIGHTINGALE:

No, I wouldn't say we did. The City Water Department had to do a little bit and Mosquito Abatement District of course, had their two-bits to add.

IRV SHERMAN:

In general, we have found that we control the midges reasonably well by rotating the basins so that each basin is wet for one week and then allowed to dry for two weeks. This also has the effect of drying up the accumulation of algae or sediment or whatever on the bottom and restoring the infiltration rate that would otherwise drop off to nearly nothing with a continuous innundation program. Last year, particularly, we did have a public relations problem due to midges because we were spreading water out of reservoirs all the way through the month of July, which is not something that usually happens. The telephones were jingling off the hook for a while. We tried to handle that as best we could by explaining to the people that the problem was one that we were going to try to control by initiating rotation of the basins just as quickly as we could without having to waste water to the ocean in so doing. Most people seemed to be reasonably satisfied with that, of course, we didn't make everybody happy. We also have a contract with the Southeast Mosquito Abatement District and when conditions become particularly severe, we call upon them to come into our spreading grounds and channels and do whatever it is that they do to help control insect populations.

QUESTION:

Why would sand and gravel pits decrease permeability in riverbeds?

KEN SCHMIDT:

I was talking about sand and gravel operations where they dispose of silt and other fine-grained materials in the stream channel downstream. Perhaps the question dealt more with placing garbage and other materials in landfills and abandoned gravel pits. The fate of many of the gravel pits along the Salt River, now and in the past, has been to end up as a landfill. There are some problems because they are excravating virtually down to the water levels and surface water has entered from a number of sources such as irrigation tail water and other sources. Leachates are produced and will continue to be produced if this practice is continued.

BILL BIANCHI:

One of the observations of some of the irrigation districts in the San Joaquin Valley, upstream storage has cut off the bed load source. This is a result of release of flood flows, the bed load moves down through the stream courses, exposing some of the sublayers. Bed load acts in a similar fashion to our soil filter in that it protects the macrostructure of the sublayers from being clogged. When these sands are scoured off, the particles that are suspended in the water go directly into this macrostructure and clog it, making appreciable differences in the natural recharge of some of these stream courses. Gravel operations use the sand in the channels also, this accelerates the depletion of this filter material. I think this is important in terms of maintenance of natural recharge.

QUESTION:

What is the potential for using imported Colorado River water for ground water recharge and storage in Central Arizona? What would be the problems involved?

KEN SCHMIDT:

I will talk about the water quality aspects of the question. In some areas the groundwater conditions may become so severe that they will have a choice of either importing water or abandoning the use of the groundwater because of the excessive pumping lifts. I think that there are some great advantages to using imported water directly. In terms of salt balance in areas such as the Salt River Valley, perhaps the imported water could be used for municipal use, if it is of suitable quality. This water could then be exported through the sewage effluent, and much of it would eventually be exported from the Salt River Valley. In this manner, the Salt export would be maximized.

TOM BURBEY

The Central Arizona Project has a conveyance capacity of 3,000 cubic feet per second. This is the maximum rate at which we can import water from the Colorado River. We have recently gone through a period of requesting intents to contract for CAP water through the efforts of the Arizona Water Commission. We received intents to contract which were approximately five times the average volume of flow which CAP will import. We have a latent demand for Colorado River water use in the neighborhood of five times the amount of water that we will have available to deliver. There may be times, there may be years, there may be seasons of the year, when excess Colorado River water may be available above and beyond local demand and thus available for recharge. I think the issue is, can we afford to pay the energy costs to pump the water into Cental Arizona, to pay the costs also for the recharge facilities and then, to pay the cost to recover that water versus the value of that water here?

QUESTION:

Why put flood waters underground, why not keep them behind regulatory control structures and use as gravity water with concomitant reduction in ground water withdrawals and energy requirements?

<u>TOM BURBEY</u>:

If we have a surface use for those waters, I see no advantage to underground storage.

QUESTION:

What is the problem which is being encountered from recharge below the Painted Rock Dam.

TOM BURBEY:

Welton-Mohawk Irrigation District down in the Yuma area has a very shallow groundwater table and the Gila River flows directly through that district. What happens is when we make flood control releases from Painted Rock Dam, it flows down the Gila River and enters the local acquifers in the Welton-Mohawk District. It causes raises in the local groundwater tables so that it interferes with the root zone under the irrigated lands. They have to pump that recharge water out to maintain the viability of the root zone. Also, the local groundwaters in that area are extremely saline so that the entrusion of groundwater into the root zones have significant impacts on their soil quality. So, it becomes a matter of getting groundwater recharge in an area where we don't want it, in an area where they are already having to pump out the groundwater to maintain groundwater level controls. The saline nature of the water that gets pumped out of that area has also necessitated the Salinity Agreement with Mexico.

MANNY LOPEZ:

I think the major problem is the infiltration into the aquifer that already has a water problem. This would increase the amount of water that would have to be pumped out of that aquifer in order to maintain the proper depth of groundwater for agricultural purposes. That water then is exported out of the district and could become part of the water delivered to Mexico if its salinity were not as high as it is. But being that it is highly saline, it has to be treated and this increases the cost of meeting Minute 242, in the agreement with Mexico.

TOM BURBEY:

The channel of the Gila River through the Welton-Mohawk Irrigation District is choked with phreatophytic growth that harbors a large population of white-winged doves and other types of bird life. It has become a very sacred thing to the environmentalists and the fish and wildlife people in the state and nationally. The phreatophytic growth makes water movement through the area very difficult without having a very high level of recharge to that already high water table.

QUESTION:

How long does the water that is pumped into a well as referred to in the Playa Lake Development stay in the general area. Has it proven cost beneficial in Texas?

DON SIGNOR:

The regional gradient in the high plains area is such that the water movement is about two inches a day. When you perform recharge, a steep gradient exists very near the well, the water will move away from the well, but not to the point of injection. If a farmer has been pumping, in an area where he has a fairly large acreage with several wells on it and he has pumped heavily for a number of years, he probably has created a cone of depression underneath his area. This was the situation I pointed out for the City of Midland. The farmer would not get to that point where the cone was that large, but, in recharging the water, he would fill this cone. The water would stay very near to where it was recharged and he could withdraw it. This would also possibly stabilize the level of decline in his area. Economically, again, it is hard to say as we have not really investigated that area; I do know with the energy costs rising as they are, there has been discussions about the economics of getting any water out at all. But, a source of water certainly can mean a very significant difference as far as making or losing a crop and it could be well worthwhile. The conditions would have to be well specified.

QUESTION:

Do you have a measure of the comparative infiltration capacity of the two basins in the Lubbock Site? Does the bare ground infiltrate more or less water than the natural vegetation?

DON SIGNOR:

This is one of the things that we wanted to find out and as it turned out, the infiltration rates were very nearly the same. They both peaked at about one meter or approximately three feet per day.

QUESTION:

Using the manhole or catch-basin dry well technique, what special problems would you anticipate when using sewage effluent as compared to storm water run-off?

L. G. WILSON:

You would not want to use dry wells to recharge sewage effluent, but to answer the question, the clogging would be rather severe and may be accentuated over the effects you would have with storm water. In particular, the microorganisms entrained with sewage effluent, could clog the surface very rapidly and the redevelopment of these wells would be difficult or impossible to effect. Again, I do not think it would be advisable to use dry wells with the sewage effluent.

QUESTION:

Are there any studies being conducted to combat the possible virus build-up in the McGuckin injection well installation?

L. G. WILSON:

Not that I know of. This would be a good subject for investigation.

QUESTION:

How much water can be recharged, at least under your estimates, in the proposed basins as compared to the recharge in the natural channel?

JOE DIXON:

One of the purposes of the demonstration project would be to compare natural conditions or natural recharge with what would happen if you would augment that through some sort of artificial method. We are beginning to get a handle on some of the natural recharge. If the 1978 numbers are correct, it is 20% of a slug flow, but then we have seen 50% of some long term flows for natural recharge. I don't know what happens when you start to modify that with some sort of artificial augmentation. So, the answer is that we would need to explore that through some sort of demonstration project.

QUESTION:

What are some of the institutional problems related to groundwater recharge in the Salt River Valley?

JOE DIXON:

Institutions are attitudes, laws and standards. An institution could be the Salt River Project and the way they operate and maintain their reservoirs. It is the attitude of the people towards water research planning and management. Some of the institutional problems - we could talk about currently are that it doesn't make sense to recharge water because you get no credit for recharging water. Whoever has a well can pump the water that you put back into the ground. So, I would call that an institutional constraint or an institutional problem. Environmental impact statements are institutional constraints. Fish and wildlife issues, such as the Fred J. Wyler Greenbelt, and its white wing dove habitat, water quantity and quality issues, those tend to fall into institutional perceptions. Public involvement is sometimes considered to be an institutional opportunity or a constraint. In some places they are very pro recharge, so that in general, the institution of artificial ground water recharge is thought of in a positive sense. In southern Arizona or central Arizona, the institution of artificial groundwater recharge is not thought of in a positive sense.

QUESTION:

Did you say that the Corps of Engineers considered using groundwater as a source of supply for a groundwater recharge project? If so, what would be the advantage of taking water out of the ground in order to put it back in again?

MIKE MOORADIAN:

What I meant by that was, for a demonstraton project, we were talking about for a source of water. It wasn't on a full scale recharge project. I feel that we need a steady source of water to determine the feasibilty of a recharge and what we were suggesting is to get by some of the institutional legal constraints, maybe some type of transfer of groundwater in trade for a recharge type of situation could occur. We were only looking at it for a demonstration project. It doesn't fit into a full scale recharge project, it is just basically to have a steady source of water to check the feasibility of recharge.

QUESTION:

Why consider recharging expensive CAP water when cheaper Salt River Project water is available and is evaporating from the top of reservoirs? Why not release the water from the top 1/5 of Roosevelt at optimum controlled rates to recharge the natural Salt River riverbed? Vacated storage space could be used to capture peak flood flows.

JOE DIXON:

I think we need to first look at the economics involved and then discuss the availability of what is for sale. Salt River Project probably wouldn't sell its water to recharge. What we'll probably find out is that there are a lot of institutional questions involved and that they cannot be answered in dollars and cents economics.

QUESTION:

Since some of the farmers on the high plains practice artificial recharge, are they running the risk of losing their depletion allowances?

DON SIGNOR:

Their depletion allowances are determined on the basis of the decline each year. The depletion allowance or depletion maps are put together through field measurements and programming by the groundwater