SECOND SYMPOSIUM ON ARTIFICIAL RECHARGE IN ARIZONA

May 2-3, 1985

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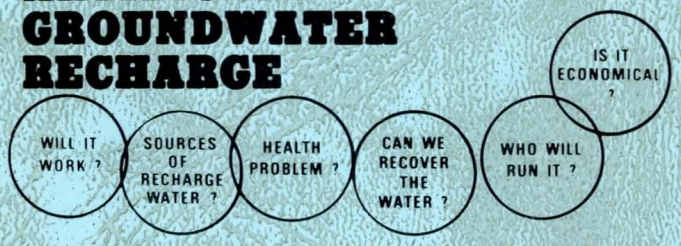
Symposium Proceedings

ARTIFICIAL GROUNDWATER RECHARGE



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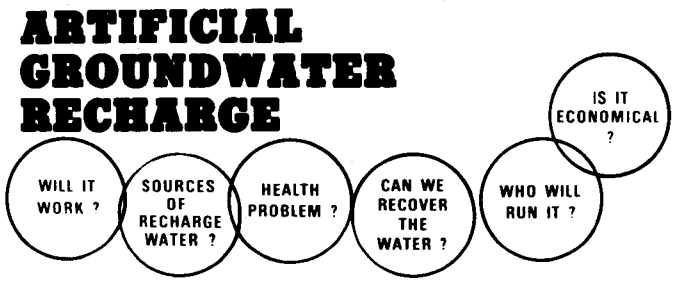

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SECOND SYMPOSIUM ON ARTIFICIAL RECHARGE
FINAL PROGRAM

THURSDAY, MAY 2, 1985

7:00 - 8:15 am	Program Participants' Breakfast	hosted by Engineering Enterprises, Inc. & Johnson Division-UOP, Inc.
8:00 - 8:30	Registration	
8:25 - 8:30	Welcome and Opening Comments	Dr. L. G. Wilson University of Arizona, Water Resources Research Center
8:30 - 8:45	Keynote Address- Impacts of Artificial Recharge on Arizona Water Management	Reid Teeples Associate General Manager Salt River Project
8:45 - 9:15	Overview Paper- Artificial Recharge as an Element of Conjunctive Water Management: A Definition of Concepts	Don Maughan Deputy Director Arizona Department of Water Resources

TECHNICAL AND ENVIRONMENTAL ASPECTS OF RECHARGE

9:15 am. - Noon
Moderator: Gary G. Small, Salt River Project

9:15 - 9:45 am	Overview of Recharge Methods: State of the Art	Dr. L. G. Wilson
9:45 - 10:15	Water Quality Impacts of Recharging CAP Supplies	Ms. Kate Vandemoer University of Arizona, Department of Watershed Management
10:15 - 10:30	Coffee Break	sponsored by Dames and Moore
10:30 - 11:00	Water Quality Impacts of Recharging Effluent	Dr. Herman Bouwer USDA Water Conservation Laboratory
11:00 - 11:30	Recharge Programs: A California Overview	Dr. Iris Priestaf David Keith Todd Consulting Engineers

MODERATOR'S SUMMARY AND DISCUSSION

Noon - 1:30 pm	Hosted Lunch Break Luncheon Speaker Mario Lluria Senior Project Hydrologist	hosted by Cella Barr Associates

LEGAL AND INSTITUTIONAL ASPECTS OF RECHARGE

1:30 - 5:30 pm

Moderator: Ms. Marybeth Carlile
Southern Arizona Water Resources Association

1:30 - 2:00 pm	An Overview of Institutional Considerations in Artificial Recharge Programs	Dr. Michael Bradley University of Arizona Dept. of Hydrology and Water Resources
2:00 - 2:30	The Present Legal Framework for Recharge in Arizona	Ms. Kathy Ferris Arizona Dept. of Water Resources
2:30 - 3:00	Current Legislative Proposals for Recharge in Arizona	Bob McCain Arizona Municipal Water Users Association
3:00 - 3:30	Recharge and Urban Planning	Dennis Davis Rio Salado Development District
3:30 - 3:45	Coffee Break	sponsored by Layne-Western Company, Inc.
3:45 - 5:00	Current Agency Planning and Program Activities	David Gudgel Lower Colorado Regional Planning Officer Bureau of Reclamation Joseph Dixon Corps of Engineers Chief of Planning of Arizona Los Angeles District Susan Keith Chief Hydrologist Arizona Department of Health Services Robert Yount Chief, Natural Resources Division Arizona State Land Department
	Moderator's Summary and Discussion	
5:30 - 7:00 pm	Hosted Reception	sponsored by Anderson-Nichols and Company

SECOND SYMPOSIUM ON ARTIFICIAL RECHARGE
FINAL PROGRAM

FRIDAY MAY 3, 1985

ECONOMIC AND FINANCING ASPECTS OF RECHARGE

9:00 am - Noon
Moderator: Mr. Gary Woodard
University of Arizona
Division of Economic and Business Research

9:00 - 9:30 am	An Overview of Economic Considerations in Artificial Recharge Programs	Dr. Bonnie Saliba Dr. Dennis Cory University of Arizona Department of Agricultural Economics
9:30 - 10:00	Linking Physical Processes and Economics of Artificial Recharge: A Conceptual Framework	Dr. Tom Maddock III Mr. Gary Woodard University of Arizona Department of Hydrology and Water Resources
10:00 - 10:30	Identifying a Groundwater Recharge Project: The Tucson Active Management Area Experience	Lester Snow Craig O'Hare Tucson Active Management Area
10:30 - 10:45	Coffee Break	sponsored by CH_2M Hill/Rubel Hager
10:45 - 11:15	Financing Recharge: The California Experience	Dick Rhone Bookman-Edmonston Engineering, Inc.
11:15 - 11:45	Privatization of Ground-water Recharge and Recovery Projects	Tom Reilly Thomson-McKinnon Securities, Inc.

Moderator's Summary and Discussion

Noon - 1:30 pm No-Host Lunch Break

CASE STUDIES OF ARIZONA RECHARGE PROJECTS

1:30 - 4:00 pm
Moderator: Ms. Jacqueline Rich, Rich and Associates

1:30 - 2:00 pm	Utility of Butler Valley as a Recharge-Recovery Basin	Floyd Marsh University of Arizona, Water Resources Research Center Alan Haws Engineering Enterprises, Inc.
2:00 - 2:30	Recharge in the Phoenix Metropolitan Area	Bill Chase City Water Advisor

CASE STUDIES OF ARIZONA RECHARGE PROJECTS (CONT.)

2:30 - 3:00 pm	Recharge in the Scottsdale Area	Leonard Dueker Executive Assistant to City Manager
3:00 - 3:15	Coffee Break	sponsored by John Carolla Engineers
3:15 - 3:45	A Demonstration Recharge Project in Tucson, Arizona	Bruce Johnson Chief Hydrologist, Tucson Water Richard Randall CH_2M Hill

Moderator's Summary and Discussion

4:00 - 4:30	Symposium Wrapup and Closing Remarks	Dr. L. G. Wilson
4:30 - 6:00	Closing Reception	hosted by Water Resources Associates, Inc.

Sponsored by the *UNIVERSITY OF ARIZONA WATER RESOURCES RESEARCH CENTER, USDA WATER CONSERVATION LABORATORY AND SALT RIVER PROJECT.* Support and cosponsorship by the following interests is gratefully acknowledged:

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PREFACE AND ACKNOWLEDGEMENTS

Artificial recharge of ground-water basins has a central and increasingly important role in ground-water management, particularly in the conjunctive use of surface and ground-water resources. It has the potential of yielding significant net benefits when compared to surface water storage alternatives. Although artificial recharge is by no means a new idea, growing public interest in this essential element of ground-water management has created a need to critically examine the technical, institutional and economic feasibility of artificial recharge in Arizona. Such was the foremost objective of the Second Symposium on Artificial Recharge in Arizona.

This symposium, which followed an initial symposium sponsored by the Salt River Project in 1978, was a resounding success as reflected by the total registration of 179 individuals and the superb quality of the program. The symposium served to focus attention on the current high level of broad-based interest in recharge as a central component of conjunctive water management. Benefits will continue to be reaped as state legislation on recharge is formulated prior to the next symposium scheduled for 1987. Results of this symposium have set the stage for a biennium conference on recharge issues and programs. I trust that these proceedings will serve as a long-term, authoritative reference to this important topic, which will continue to be refined and updated.

Organizing the Second Symposium on Artificial Recharge in Arizona and carrying it to a successful conclusion was done with the capable assistance of numerous individuals and interests. Collectively, appreciation is gratefully accorded the excellent session speakers and moderators who willingly gave of their time and expertise. Session speakers are congratulated for attaining the symposium objectives. Support of the financial sponsors listed individually on the last page of the final program is graciously acknowledged. Their financial support as co-hosts made the symposium a viable activity.

In addition, I extend my thanks to Herman Bouwer, Gray Wilson and Gary Small--companion members of the symposium planning committee--who lent their counsel and moral support in organizing and carrying out the symposium. A special acknowledgement is also extended to Shirley Rish and Lenore Murphy

of the U.S. Water Conservation Laboratory for their efficient and cordial assistance with registration desk activities. Thanks are also extended to Robyn Grimes, Steve Brooks and Peter Feldman, all University of Arizona graduate assistants, who capably assisted with on-site symposium coordination. Efforts of Jack Edmonds of the Salt River Project staff, who assisted by transcribing the symposium program, are also appreciated. I extend my sincere gratitude to Jean Clancy, Water Resources Research Center (WRRC) secretary, who assisted with processing and accounting of registration records. Finally, and in particular, I offer my deepest gratitude to Pat Neid of the WRRC staff, who assisted with mailings and typed numerous manuscripts and supporting materials for the proceedings. I am particularly indebted to Pat, since her endless dedication and cordial follow-through in large part made the following proceedings a reality.

By way of conclusion, it was personally gratifying to have been involved with this level of interest and support, and such a quality symposium program. At the risk of sounding trite, artificial recharge is an issue whose time has come! Inevitable conflicts will arise as we proceed, but the barriers are surmountable <u>and</u> must be surmounted if Arizona is to progress with a conjunctive water management policy.

Floyd L. Marsh

Floyd L. Marsh

Symposium Coordinator and
Proceedings Editor

OPENING COMMENTS

By L. G. Wilson

Good morning ladies and gentlemen, my name is Gray Wilson. I am currently the Acting Director of the Water Resources Research Center at the University of Arizona. My colleagues, Gary Small of the Salt River Project and Dr. Herman Bouwer, Director of the U.S. Water Conservation Laboratory are the co-hosts of this symposium. We would like to welcome you to this the Second Symposium on Artificial Ground-Water Recharge.

As you all know, there has been an explosion of interest in artificial recharge within the past year or so, stemming from the realization that recharge methods could be used for the "banking" of surplus CAP waters; offer the possibility of capturing flood waters and storing such waters in underground reservoirs; as well as storing reclaimed wastewater underground for alternative uses such as golfcourse irrigation.

Gary Small, Dr. Bouwer, together with Floyd Marsh and myself realized about a year ago that this would be an appropriate time to hold a second symposium to address the current state of art of artificial recharge in the State of Arizona. The goal was to hold a symposium that would focus not only on the technical issues but on other important elements that ultimately drive a recharge project. Such elements include legal, institutional and economic considerations as well as environmental concerns. If you peruse the program you will see that we have been fortunate in drawing together an excellent team of speakers to address these different elements.

Before beginning the program, I would like to use this opportunity to thank each of the sponsors who are contributing to the breakfast, lunches and break periods as well as the receptions during and after the program. It is also appropriate at this time to express our gratitude to Floyd Marsh, of the Water Resources Research Center, who bore the brunt of developing this Symposium.

We are indeed fortunate that Reid Teeples, Associate General Manager of the Salt River Project has agreed to give the keynote address for this Symposium. By training Mr. Teeples is an engineer with a degree from the University of Arizona. He has been very active in water related issues in the state for the 30 some years that he has been with the Salt River Project. Reid's keynote address will focus on the role of artificial recharge in Arizona's water management. It is with personal pleasure that I introduce Mr. Reid Teeples.

KEYNOTE ADDRESS

before the

Second Symposium on Artificial Recharge

"Impacts of Artificial Recharge on Arizona Water Management" 1/

by

Reid Teeples
Associate General Manager - Water
Salt River Project

Thank you Gray. It certainly wasn't my viewpoint yesterday afternoon to be here occupying this position at the podium. But when Chuck Kupcik, Arizona State Land Department, called the office and said that Governor Babbitt couldn't come, he said the Governor recommends that Jack Pfister or yourself give the keynote address because he has to meet with the Legislature. So I feel it an honor and a privilege to say a few words to this symposium. It was just a few short years ago, about seven, that we had our first groundwater recharge symposium. We held it at the Ramada Inn on East Van Buren. And so I'm glad to be back again talking about the subject of groundwater recharge.

I know the Governor has water on his priority list and I'm sure that it is probably close to number one. As you know, since he has been Governor he has been very active in water matters. He personally took charge in organizing and getting people together to pass the Groundwater Management Act and many other things. So I know that he would applaud all of us that are here today as we meet to discuss the subject of groundwater recharge.

Last week I had the opportunity to attend a water symposium in Canada at the invitation of the Canadian Government and it was very interesting to meet with people not only from Canada but they had invited several people from throughout the world - from the countries of France, Germany, England and Japan. It was interesting for me to sit there and listen to them talk about their problems and they weren't anything like ours. It seemed like they weren't worried about a water supply, they were worried about the quality and so on. They all seemed to have plenty of water not like us here in the semi-arid regions. It gave me an opportunity to explain to some of them - and most of them had never been in the southwest or in semi-arid regions - and so it gave me an opportunity to explain to them the challenge that we have here in a semi-arid region to use the resources that are available to us.

I went into some detail as I met with some of them for dinner. I pointed out that our rivers in this area are very erratic and that we have to take the years of plenty and balance them out with the years of drought. They just

1/ Edited from taped transcript

didn't seem to quite understand that because their rivers seem to flow all the time and they have so much water, it just runs into the ocean. I invited them to come down to our area. I said I think you can learn some lessons from us in that we have to really guard and manage this precious water resource.

Now in looking back over the history of our great State, I think you will agree with me that we have experienced a few drought periods within the last 100 years, however, we survived those droughts and I believe the reason we have survived the droughts is because we have always been able to call upon our groundwater when we have those low run-off years. I think that we are quite fortunate in that we never had a really catastrophic event occur here in the State as far as a major loss in crops or in rationing water for urban people. I think our neighbors to the west in California and even our friends back east along the east coast that seem to have a lot of water, they haven't had the same experience. They in fact have had to ration water. I believe it is because we know what water really means here in the desert. So I think it is a pat on the back to all of us who manage the water resources of this State that we have been able to live with the drought years. But here again, I emphasize I believe that the reason why we may be able to brag a little in that regard is that we always had this insurance of calling upon our groundwater resources when we needed them.

I think you recognize, as well as I do, that Arizona is on the threshold of changing how we will manage our groundwater resources. As you know this year, water will be flowing from the Colorado River down the Central Arizona Project (CAP) Aqueduct and it will start replacing what we have done for so many years and that's calling upon our groundwater reserves. Again, also, a second item that is going to be next year is the effects of the conservation brought about by the Arizona Groundwater Management Act. And this vehicle, we know, will help us reduce the overdraft of the groundwater. However, these two operations are just part of the total program we are going to need in this State if we are going to reach the goal of safe yield. We must implement all of the viable programs that we can come up with in order to bring about the goal that we have set of safe yield after the turn of the century.

Now we are here today and tomorrow to discuss potential groundwater augmentation methods and I'm sure that when we leave here tomorrow evening that we will have discussed some things that I believe will bring about definite programs on artificial recharge.

In 1978 at the last symposium we discussed rather generally, and yet in some cases very specific, the successes that have been obtained elsewhere. We had

speakers from California and I see that we will have reports from people from California again because they have been utilizing the techniques of groundwater recharge for many years. Today and tomorrow we will be talking more about specific things that we can do here in Arizona and not be talking about the generalities that we did in 1978. So I think that we need to recognize in the past seven years the progress that's been made and know we are ready, I think, to move ahead on specific programs in Central and Southern Arizona.

Involved in this whole process of managing our resources, of course, is the implementation of Plan 6, a final component of the CAP, where a lot of effort is being placed to help capture more surface water from our rivers. But there is still going to be flood waters below the dams even after the implementation of Plan 6 which is also going to take a number of years. So I think it is ludicrous if we think that Plan 6 will do it all because it won't. Now during the past eight years, for some of those that may not know it, we have released 8-1/3 million acre-feet of water from our storage reservoirs on the Salt and the Verde Rivers. That means that on the average and, of course, Mother Nature doesn't work in averages, but on the average that means a little over a million acre-feet a year, we have had to release, through the Salt River Project reservoirs on through the Salt River Valley. I'm not saying that some of those waters were not put to good beneficial use. Some of those waters went back into the underground but by and large most of that water was really sort of wasted. So Plan 6 is going to help overcome problems like that, but we are still going to need other techniques like artificial recharge to utilize those precious water resources that we have. If you add the Salt and Verde River flows that we weren't able to capture and use in the future and add to that the Colorado River releases and that was a lot of water, the flood water from the Gila, from the San Pedro, the Santa Cruz and all of the other flood waters that we know have been available in our State in recent years, we have quite a resource that we could tap and use for artificial recharge. I think our challenge is quite clear for those of us that are meeting here today and tomorrow and we know that you in this room are the experts that we are going to need to call upon and look forward to implementation of groundwater recharge opportunities. So we all need to put our shoulder to the wheel and provide ways to restore our groundwater reserves. I commend the committee members that have organized this symposium and I commend all of you who are participating, those of you who will speak and those of you who will listen. I think that

a few years hence, we can look back upon this symposium and recognize that our efforts were not in vain because I believe that the efforts that we put forth today and tomorrow will bring about good things and that the State of Arizona and the people that are here and the people that will be coming here will benefit from the work that is being done by you the experts in the field of groundwater recharge.

Reid Teeples holds a B.S. degree in engineering from the University of Arizona and is currently Associate General Manager-Water for the Salt River Project.

OVERVIEW PAPER

to the

Second Symposium on Artificial Recharge

"Artificial Recharge as an Element of Conjunctive Water Management: A Definition of Concepts" 1/

by
Don Maughan
Deputy Director
Arizona Department of Water Resources

Well, it is good to be here with you today. As I was just sitting there, I thought of a little story that may be appropriate to start out with -- about things not being exactly as they appear sometimes. This is a little story about a southern farmer who is going along with his cart and two mules when a man in a sports car came zipping by and side-swiped him and ran he and the two mules off in the ditch. As it happened, a highway patrolman was coming along right afterwards, he stopped and the patrolman got out, went over and saw one of the mules, saw he had a broken leg and shot it and found the other mule with his legs broken also and shot it. The whole point of this is that this man was in court seeking to get damages from this accident and the judge said how come the official report said that you were fine. He went through and explained how this patrolman shot one of the mules and then the other mule and when he arrived to him with the smoking gun and asked him how he felt whether he had any broken bones or not and he said no he was fine. Things depend upon how they do appear.

I really want to talk today in a vein that perhaps may be a little bit disturbing . . . I hope not! I'm very strong for artificial recharge and for conjunctive surface and groundwater management. I think it's the future for the State of Arizona and the future for most of the southwest is dependent upon successful execution of those things. But I have also been around long enough to know that there have been a lot of failures in water programs. A lot of us don't like to admit them, a lot of us feel that every water program is good; some of them are better than others but they are all good and yet I have observed that there are problems associated with some water programs. I think the main reason for that -- and I really say this sincerely -- is because there is not good preparation and not real good understanding of all the elements that are essential to implementing a good program. I think artificial recharge and conjunctive management in surface and ground waters

1/ Edited from taped transcript

is probably the most challenging thing that any of us in the water profession have ever faced. I say that even though I know there are successful artificial recharge projects in several foreign countries. I am personally familiar with them in southern California, which are largely dependent upon reclaiming waste water. I also know there is a program under way in El Paso, Texas. The California effort was started back in 1962 which is obviously over 20 years ago. They disinfected activated-sludge secondary effluent at first and recharged around 12,000 acre-feet a year. Recently in 1978, they added tertiary treatment and filtration and along with that plan and two others there has been about 32,000 acre-feet a year recharge since 1978. However, there was sort of a significant event in 1978. That's when it was decided by the control agencies - the Health Department and water control agencies - that there should be a five-year study undertaken and $1.4 million was put into it to develop a report and I quote ". . . they needed a data base which would enable health and regulatory authorities to determine whether the use of reclaimed water for groundwater replenishment at the Whittier Narrows Plant should be maintained at the present level, to cut back or expand it." A report was made about a year ago that the control agencies still have not made a decision yet on those fundamental aspects. Also, when I left California, there was a big push to have by 1980 at least 400,000 acre-feet of groundwater recharge occurring in the State. It is my understanding that they don't have that as an objective anymore because they encountered so many problems in a number of places that they abandoned that as a particular goal. So, there are problems but that doesn't mean we can't solve them.

I think that we not only need to get good data, have outstanding hydrologic and geologic studies, make good financial appraisals and legal interpretations, all these present problems, but I do think that we need to hurry up and get some projects probably in the demonstration status going so that people can actually appraise them from things that have gone on. I know that Reid Teeples mentioned a lot of the water, of course, has gone to waste in the last few years here but before that I have a number of questions, some thoughts and then some further questions which I will try to answer also.

One of the things that I think is very much needed is to make sure that any water that we earmark to recharge cannot otherwise be used directly because it doesn't make a great deal of sense to put water underground and then repump it. It makes more sense to use that water directly some way and just refrain from pumping water during that period of time. You can take a city that usually

gets 100,000 acre-feet and say 70,000 acre-feet comes from the ground water and 30,000 acre-feet from surface water and for a few years like on the Colorado River, they might have an entitlement of 50,000 acre-feet. Well, some people would say let's put it underground and store it until we need it, but the simplest way is to use it directly. I know there are problems in terms of timing and so on, wouldn't it be better to use the 50,000 acre-feet directly and leave the extra 20,000 acre-feet under ground without withdrawing it. So I think we need to look at that. Are there legal or physical constraints preventing direct use of that water? We need to look at that, also.

Can ground water storage be substituted for surface regulatory storage with an overall net benefit, weighing the monetary cost including time values and surface evaporation? But those are all negatives on the surface waters. Some of the ground water migrates and obviously, you have to have some authorities to protect it and to recover it. One of the most serious aspects that we need to look at -- can artificial recharge save water treatment costs or will artificial recharge have any real chance of polluting the drinking water quality of our groundwater? I think that -- this is not my own personal view because I think risks sometimes are worth taking -- when it comes right down to it because of the recent findings in ground water and the great attention being paid to ground-water pollution and the talk of spending $1 billion to clean it up, even the slightest risks in terms of health aspects might be totally unacceptable. I think we have to keep that in mind. And, of course, ground-water basins can be used to substitute for a surface pipeline distribution system if you have a good basin to do it in and you have control over the entire basin.

If you are thinking about sewage effluent as a source of recharge, I have selected two or three statements from that Whittier Narrows study and these were the kind of answers they sought to find in that study. They needed to know what the water quality characteristics of ground water, reclaimed water and other recharge sources were in terms of microbiological and inorganic chemical content. They had to know the toxicological and chemical studies of ground water, reclaimed water and other recharged sources to isolate and identify health significant organic constituents. Then they had to make percolation studies to evaluate the effectiveness of soils in attenuating inorganic and organic chemicals in reclaimed water and also, hydrologic and geological studies to determine the movement of the reclaimed water through

natural occurring ground water and the proportion of the mixture.

I also point out that the location of the recharge area or areas in relationship to the area of withdrawal are important. In large groundwater basins it is not correct, I don't think, to say that we can put water over here, 40 miles away from where we are going to withdraw it and not realize that it may be years to get to the cones of depression and that recharge water may either constitute a windfall for some nearby person who has the right to withdraw and the additional taking further away may have an adverse effect on others. So those things need to obviously be looked at. In terms of recharging water that is evacuated from reservoirs -- like the Salt and Verde system and the Aqua Fria to some extent and the Coolidge Dam in another respect -- if you use natural stream feds for your artificial recharge but then you have wet years like we have experienced here lately, you may fill up the same areas that the natural recharge would have during those wet periods. So you have to keep some sort of running account of how much water you have put in and whether or not it has replaced other water that could have gone underground. There are all of these things that I think need to be addressed straight forwardly and without sort of passing over them and thinking that we can do it now and solve those kinds of problems later.

As I said earlier, I have noticed that we have had difficulty in some of our water programs and I could rename quite a few. There is a magnificent example right now in the northern end of the San Joaquin Valley where the entire Westland's project, which is a 600,000 acre project, is under a serious cloud because of a selenium problem that people may have been able to find out earlier and now are facing billions of dollars worth of either failures or restitutions. I could name you some other projects that I even worked on that just have not panned out. Anyway, what happens is that recharge and conjunctive management projects which are not adequately prepared for can cause great problems over the long run.

The sources of artificial recharge are in five categories in my mind. One of them is flood waters and this would include the rain and snow melt floods down natural gulleys and in places you don't have regulation. Then we have the partially controlled high flows where you do have the regulatory storage and you release early so you can take off the peaks and also store for later on in the year. They provide excellent opportunities to divert and recharge. You have urban run-off because as we have paved over and built over a lot of the land in Arizona that means there is a lot more surface run-off in the urban areas than there used to be and you could intercept that

and recharge it. You obviously have treated sewage effluent that is not directly usable for crops or turf industries. Then you have the Central Arizona Project supplies available beyond the capability of direct use.

The uncontrolled flood waters here in Arizona, are often of very short duration. They are often accompanied by silt and earth movement that makes extensive artificial recharge very difficult. That doesn't mean that I don't think we ought to try some demonstration projects and I know some are under consideration to see what really can be done in this area. Reid has already mentioned one of the most promising ones about the evacuation of regulatory storage in the Salt-Verde drainage system to make space for run-off that we know is coming. I think that is a great opportunity provided that we divert it and spread it out.

I think urban run-off can be collected and artificially recharged in a lot of locations around this State. The big problems in this case are the relatively small quantities again and there is a water quality aspect that really needs to be closely examined and that's why I support demonstration projects. Urban run-off does contain chemical compounds, instable organics and perhaps heavy metals and even biological hazards.

I have already gone into the sewage effluent. While talking to a gentlemen yesterday from one of the small cities, he pointed out that if you filter it and use reverse osmosis and things like that you can undoubtedly recharge without too much fear of health risks. Those costs are very substantial, maybe on the order of $350 an acre-foot to treat it. If you want to go to that expense I don't think we'll have any problems, but if you want to have less treatment than there is the potential for problems. These health aspects are very serious things that will have to be addressed and satisfactorily agreed upon by people who want to do these things.

Regarding the Central Arizona Project (CAP) as a potential supply for recharge, as you know, Colorado River water is quite salty. The TDS where we take it out for the CAP is about 600 to 700 milligrams per litre and sometimes over that. The Arizona Water Quality Control Council about a month ago, cited four Pima County mines for violating the State's program to protect ground-water quality. One of the excess levels that they identified was TDS and they used the standard of 500 milligrams per litre. And if I understand it correctly, they said that if any of the recharge water exceeds that numeric value it is an impairment of the natural ground water and, therefore, won't be allowed. Now if the TDS of ground water is greater than

that, they would allow it. But as I say since the CAP supply exceeds that TDS concentration, you could extend the Council's actions and see that there might be some prohibition of the recharge of CAP water in certain areas. The aforementioned citation was adopted after considerable discussion on a 12 to 1 vote with strong support from several commentators in the audience. There is also a concern over sulfates, nitrates and other compounds of water to be used in artificially recharging ground water and they could be stumbling blocks to artificial recharge in the future years. To me it appears that water quality problems added to the legal unknowns and the technical and cost factors may be difficult to resolve during these early years when CAP water might be available for recharge. As most of you know, as the years go on and the upper Colorado Basin continues its development, the CAP supply will be reduced and the capability of the cities to use the water directly will increase. The extra water available for recharge may not be here for too many years in the future.

As you know, the ground-water basins in the central Arizona area have been set by statute and while the hydrogeology of those basins are reasonably well understood now, if we introduce artificial recharge and plan withdrawals we really need a lot better knowledge of those basins. It seems a little strange to me that for years its not been difficult to get money for structural programs in terms of foundation exploration, design and all the associated preconstruction activities; but unfortunately, I have noticed the same does not hold true in obtaining funds to better understand ground water basins. Then even if we do get the funds, we need the expertise to not only do the technical aspects which is extremely important but to have people that have some experience to relate it to some of the other problems that we will be confronted with. I think we really need to improve our capabilities in these areas and have a much better understanding of our ground-water basins in which we could keep track of water that is put in and taken out.

The legal and social considerations are pretty big also. I hope every water user is becoming conditioned to know what it means when water rights are couched in terms of beneficial use. I personally, and I am speaking as an individual now, believe that beneficial means not only a good use of the resource but a wise and careful use of it also. Water rights should not be horded to the detriment of society and I really don't believe very much in the "use it or lose it" school of thought. The point being is that Arizona needs to be required to conserve and carefully use this limited water supply so that it will be stretched as far as we can possibly make it go. As you know

Arizona right now, I think, has its water supply limits already terrifically well defined and now it is our job to make it go as far as it can.

How do we conjunctively manage our supplies and deal with artificial recharge? Certainly local entities want to do as much as they possibly can in this regard and I would do everything I could to support them. However, I think that it is acknowledged in the West that water problems usually extend beyond the jurisdiction of local authorities and, therefore, the states have generally been called upon to be the administrators of water programs and management. I think that some states need greater management in accounting than others. Arizona heads the list. Between Arizona's new groundwater code, the adjudications in the Little Colorado and the Gila River basins and arrival of the CAP supplies later this year, I think it pretty well completes our water supply picture. All that will be left is conjunctive management of all sources of supply including augmentation, recycling and water transfers. These last steps are most difficult. They must be taken, but the hazards along the way should not be ignored or casually approached. To be successful -- and I know this is a trite phrase which has been talked about -- I think of some of my long experience in cooperation with federal agencies. You talk about cooperation and everyone wants to do it but it is still hard to put into practice. We need to cooperate at the state, federal and the local levels to get this job done including the University systems and all the capabilities that they have. The participants must include appointed and elected public officials, technicians and private individuals, lawyers and health experts, economists and environmentalists. I think we have a cross-section of all those people here today. This symposium should see to it that the strongest possible foundation be constructed for implementing the kind of artificial groundwater recharge, conjunctive surface and groundwater management that is needed here in the State of Arizona. I know that you will have a number of session speakers dealing with each of these matters. I hope you pay very close attention and earmark and identify those areas you want to work at the hardest and see if we can get good answers to some of these difficult problems. I appreciate the opportunity of being here with you this morning.

Don Maughan holds a B.S. degree in Civil Engineering from the University of Utah and is currently Deputy Director - Water Management for the Arizona Department of Water Resources.

SESSION I - TECHNICAL AND ENVIRONMENTAL ASPECTS OF RECHARGE

MODERATOR: GARY G. SMALL,
SALT RIVER PROJECT

OVERVIEW OF ARTIFICIAL RECHARGE METHODS

by

L. G. Wilson, Hydrologist
Water Resources Research Center
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INTRODUCTION

The purpose of this paper is to briefly overview technical aspects of artificial recharge, to serve as a basis for the remaining papers in this symposium. Artificial recharge may be defined as the controlled release of water, derived from a multitude of sources, into the subsurface to bring about recharge of a ground-water system for a specific purpose. Several features of this definition require elaboration. First of all, the statement that recharge involves the controlled release of water into the subsurface implies that man has constructed special facilities to augment recharge. Groundwater recharge, which occurs when water passes into an unconfined water table from the vadose zone, or into a confined aquifer, is distinct from infiltration at the land surface and deep percolation through the vadose zone. Sources of water for a recharge project include flood waters, imported river water, industrial wastewater, sewage effluent, and irrigation water. Specific purposes of an artificial recharge operation include the following:

(1) Water conservation, (2) underground storage of water for the conjunctive operation of surface and ground-water reservoirs, (3) operation of sea-water barriers in coastal aquifers, (4) flood control, (5) control of subsidence, (6) water-quality management, (7) waste disposal, and (8) storage of cooling water.

A detailed discussion of each of these purposes is not possible because of space limitations. However, two elements are worthy of some elaboration, namely conservation and conjunctive use. The conservation advantages of artificial recharge are especially important in desert regions. In particular, a water source placed into underground storage is largely removed from the losses brought about by evapotranspiration. Conjunctive use involves the coordinated use of underground storage and surface reservoirs to augment the yield of a total water resource (Calif. Dept. of Water Resources, 1975). Artificial recharge methods serve as the link between surface and groundwater reservoirs. Extraction wells are used to recapture water stored underground. Conjunctive management is extensively employed in California. The

possibility of using Butler Valley for a conjunctive management, or "water banking" operation in Arizona using CAP water is discussed in a subsequent paper by Marsh. The U.S. Army Corps of Engineers (1984) summarized conjunctive use activities throughout the United States.

Specific aspects of recharge to be reviewed in this paper include technical considerations for selecting a method at a particular location, alternative methods, and their problems.

TECHNICAL CONSIDERATIONS IN SELECTING A METHOD

Hydrogeologic factors to be considered when selecting a method for a particular site include physical and hydraulic properties of the soils, vadose zone and aquifers. Given that water-spreading methods are used whenever possible rather than borehole methods, soils with rapid intake rates are particularly desirable. Soil properties governing intake rates include texture, structure, porosity, and hydraulic conductivity. Soils properties are frequently available from soils surveys conducted by the Soil Conservation Service and state universities. Intake rates can be estimated in the field using double-ring infiltrometers and test basins.

Vadose zone properties governing deep percolation of infiltrated water include depth to ground water, layering, hydraulic conductivity, initial water content, storage capacity and fillable porosity. Bouwer (1978a) reviewed the processes involved in water movement through the vadose zone, including the development of a transmission zone. As he pointed out, a certain amount of water must be "invested" in augmenting the initial water content and hydraulic conductivity to accomodate the incoming flux; i.e., to develop a transmission zone within the vadose zone. The amount invested depends on the overall thickness of the vadose zone and on the initial water content. Perhaps 10 to 20 percent of the water passing through the land surface may need to be "invested". When the project is shut down, this water will drain across the water table. Hydraulic properties of importance in the saturated zone at a recharge site include the aquifer transmissivity and storativity, and native water quality. Information on the hydraulic properties of the vadose zone and ground water at a site may be already available from drillers' logs or other deep borings, and pump test results, otherwise, a hydrogeologic study must be undertaken.

A desirable first phase of a project at a given location is to undertake a demonstration recharge project, which involves constructing pilot facilities and monitoring units, and determining intake rates and management needs. Ideally, the water source for the actual recharge project should be used in the demonstration project. Results from a demonstration project are useful in estimating the long-term infiltration rate and potential hydraulic loading of a full-scale operation. Also, information on water quality changes in the recharge source during deep percolation may avoid ground-water pollution if leaching of undesirable natural constituents such as nitrate and selenium, is observed.

The presence of recapture wells in the vicinity of a potential recharge operation should also be determined. Ideally such wells should be in hydraulic continuity with the aquifer to be recharged. If wells are not already present, construction of special recapture wells will be required. Recapture wells are an integral part of a conjunctive management operation and are of particular importance for the "hydrological segregation" of recharged wastewater.

Two important water quality implications must be considered when undertaking a recharge project, namely; (1) The effect of the quality of the recharge water on the operation of a recharge facility, and (2) The effect of the quality of recharging water on native ground-water quality. The effect of the water source on intake rates of a facility will be discussed in subsequent paragraphs. Some implications of recharging a water source on the native ground-water quality have already been alluded to in a previous paragraph. More detailed discussions are presented by Vandemoer and Bouwer in these transactions.

RECHARGE METHODS

For purposes of discussion, recharge methods may be categorized as water spreading, pits, and bore-hole methods. Selection of a particular method at a given location will depend on site-specific conditions such as land availability, water availability and quality, and hydrogeological conditions.

WATER SPREADING

Water spreading involves the release of water onto the land surface so that water movement is induced through the vadose zone into the zone of saturation. Spreading grounds are either within off-channel areas, with structures for controlling and directing water movement, or in-channel facilities. In general, these methods are used where abundant land is available, not suitable for other purposes, with the following hydrogeological properties (Bouwer, 1978b):

1. The surface soil is sufficiently permeable to yield acceptable infiltration rates (sands to sandy loams are preferred),
2. There are no layers in the vadose zone of such low hydraulic conductivity that they will form perched ground-water mounds that rise into basins and restrict infiltration to unacceptably low rates.
3. The regional water table is sufficiently deep to keep the ground-water mounds below the bottom of the basins, but not so deep that large quantities of water are needed to wet the vadose zone before any recoverable water reaches the water table.
4. The aquifer is unconfined and sufficiently transmissive to allow lateral movement of the recharge water without building up ground-water mounds that rise into the basins.

In order to determine the overall size of a spreading area, information on the long-term infiltration rate, I determined from pilot studies, is of particular value. Knowing I, and the available quantity of water for recharging, the total land area, A, required is:

$$A = \frac{Q}{I}$$

Generally, the required area must be greater than that calculated in order to allow for desilting basins and alternative basins when renovation is undertaken.

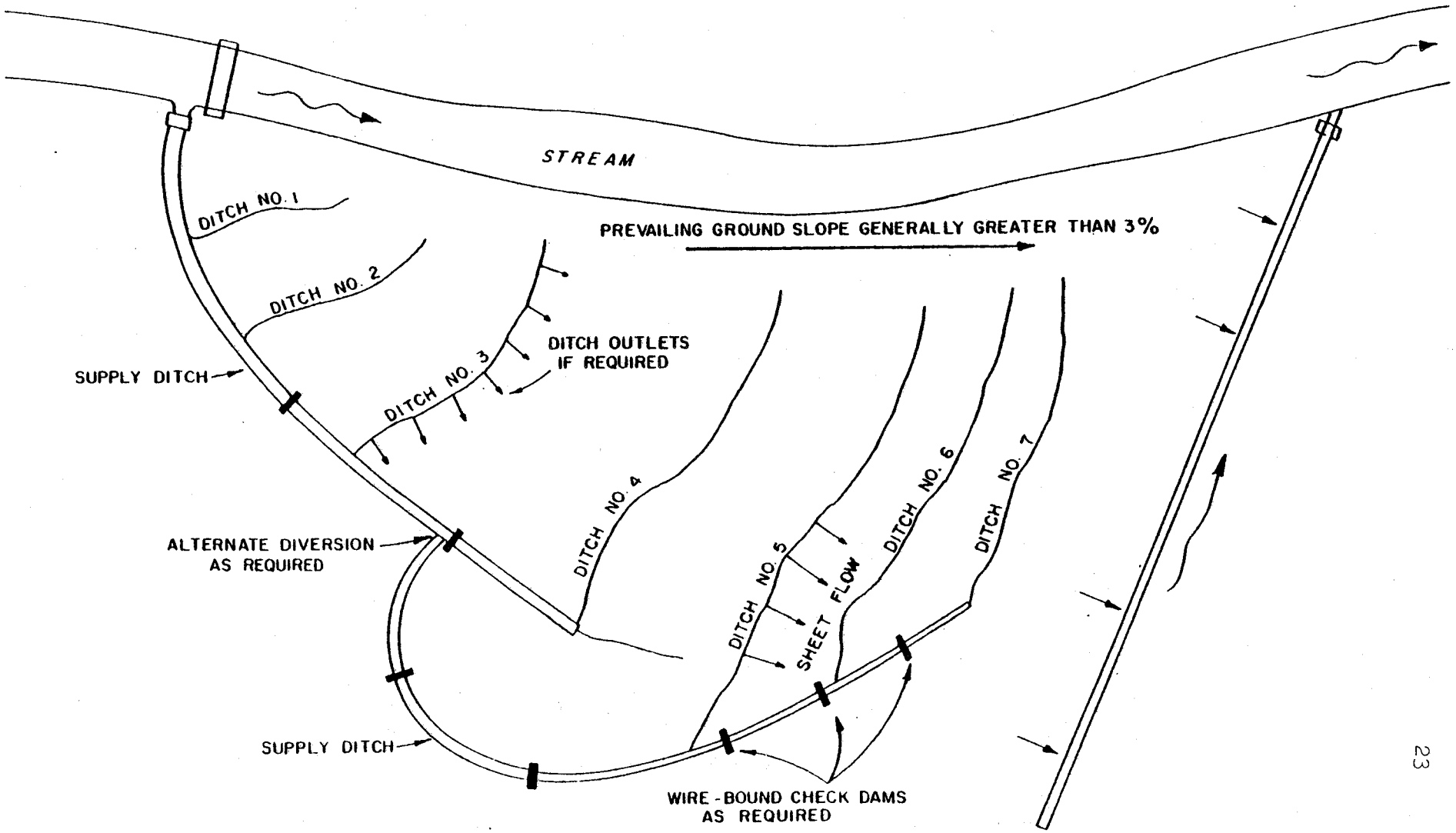
SPECIFIC METHODS

Water spreading methods include controlled surface flooding, basins, ditches and canals, modified channel, and overirrigation.

Flooding is a simple, effective method for water spreading involving the passage of water over the land surface in a thin sheet. A schematic representation of an off-channel flooding operation is shown as Figure 1. This figure illustrates appurtenant structures, including diversion works, flow metering devices, supply and lateral ditches, and a return flow ditch. If the land slope is sufficiently great, the flow velocity through the spreading grounds will be great enough to move clay and silt-size particles through the area, thus minimizing clogging.

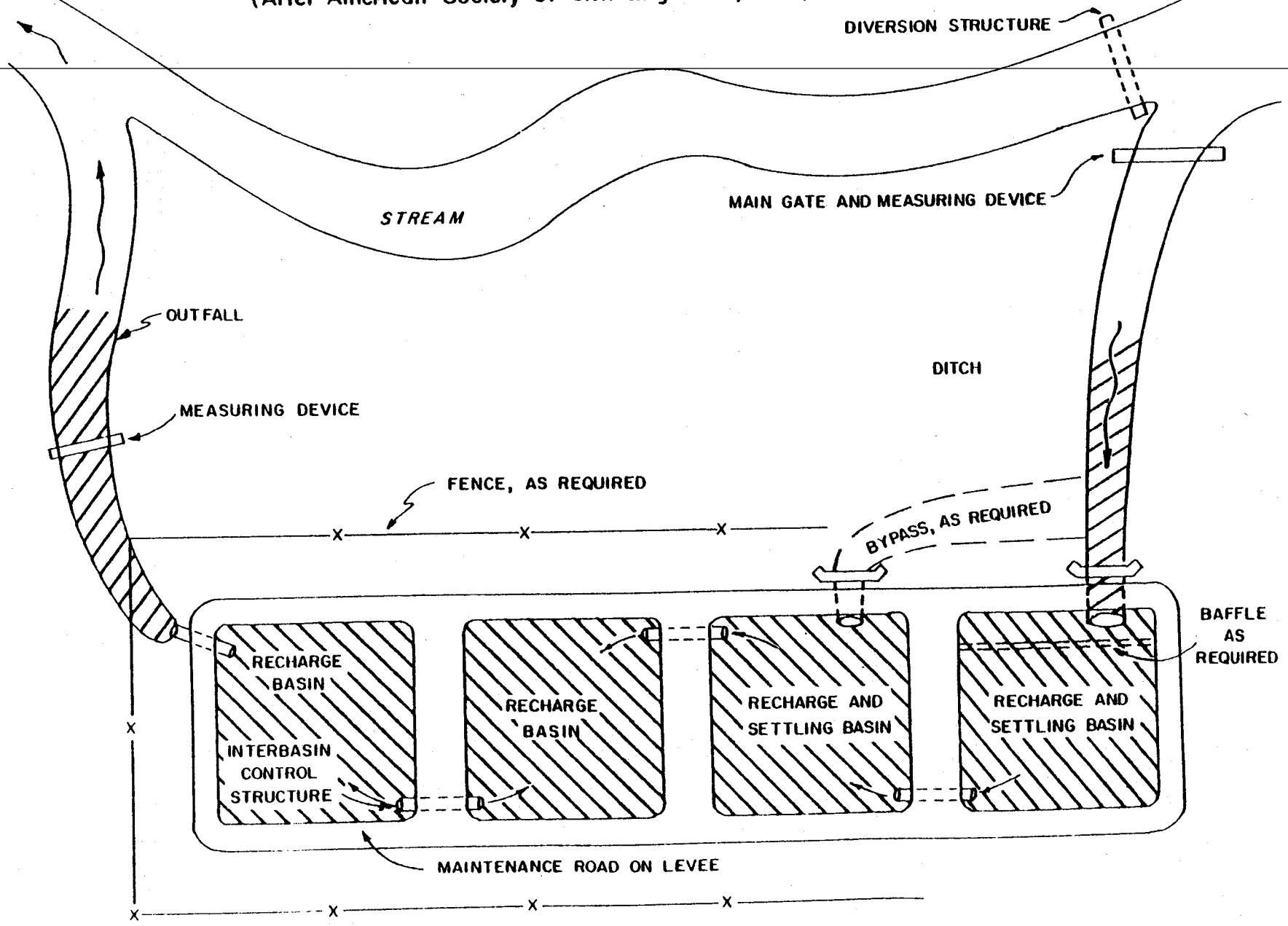
In the basin method, recharge water is introduced into spreading areas bounded by levees. The purpose of basin type operations is to obtain the maximum ratio of wetted area to gross land area; as high as 90% in some urban

TYPICAL PLAN OF DITCH AND FLOODING TYPE RECHARGE PROJECT
(After American Society of Civil Engineers, 1961)



TYPICAL PLAN OF BASIN TYPE RECHARGE PROJECT

(After American Society of Civil Engineers, 1961)



areas (American Society of Civil Engineers, 1961). Long and narrow basins are more efficient than basins for which the length is small relative to the total area. Long-narrow ponds generate a greater lateral movement of water in the vadose zone, reducing the effect of mounds on intake rates. Figure 2 is a schmatic representation for basin-type operation, together with appurtenances. Frequently, the first basin and possibly the second basin of a sequence are larger in area and depth than the other basins to promote settlement of fines from the recharge source.

Flocculents are frequently added at the headworks to promote settling. Commonly, basins are operated in parallel to allow some basins to be dried while others are flooded, thus permitting renovation.

The ditch method uses unlined ditches to transport water through the spreading grounds to increase the opportunity for recharge. An advantage of ditches is that velocities can be adjusted by controlling the slope, to reduce clogging. A disadvantage is that the ratio of wetted to gross area is low. Elsewhere in these transactions, Marsh presents a description of a conceptualized ditch method for Butler Valley. Seepage losses in canals also may promote recharge. According to Ambroggi (1978): "Seepage from irrigation canals is one of the best techniques for artificially recharging ground-water reservoirs on a large scale".

Experience in the west has shown that natural stream channels are generally highly efficient recharge units. Consequently, the water spreading methods discussed in previous paragraphs could be installed in such channels. A noteworthy example of an in-channel operation is that operated by the Orange County Water District in the Santa Ana River. The river is divided in half longitudinally by a levee. A sequence of spreading basins is located on one side of the levee while water on the other side moves through a maze of cross-channel dikes (U.S. Army Corps of Engineers, 1984). These cross-channel barriers slow down the river, allowing for greater contact time.

Application of water in irrigated areas during off season also promotes artificial recharge. A danger with this method is that excessive salt and fertilizer loads may be introduced into ground water together with pesticides.

In a paper elsewhere in these proceedings Priestaf reviews additional examples of spreading methods for specific locations in California and elsewhere.

RECHARGE PITS

Recharge pits are excavated to greater depths than basins used in water

spreading operations. According to Milne (1975) the selection of a pit over water-spreading facilities is based on the following considerations:

1. In areas of low permeability, the storage capacity of a pit provides a means of retaining a greater quantity of water for replenishment.
2. Deep pits can be constructed to penetrate tight surface strata in order to provide access into deeper, more permeable formations.
3. In areas where problems of rights of way are critical, a pit requires less land to accomplish the same amount of replenishment under certain hydrogeological operating conditions.

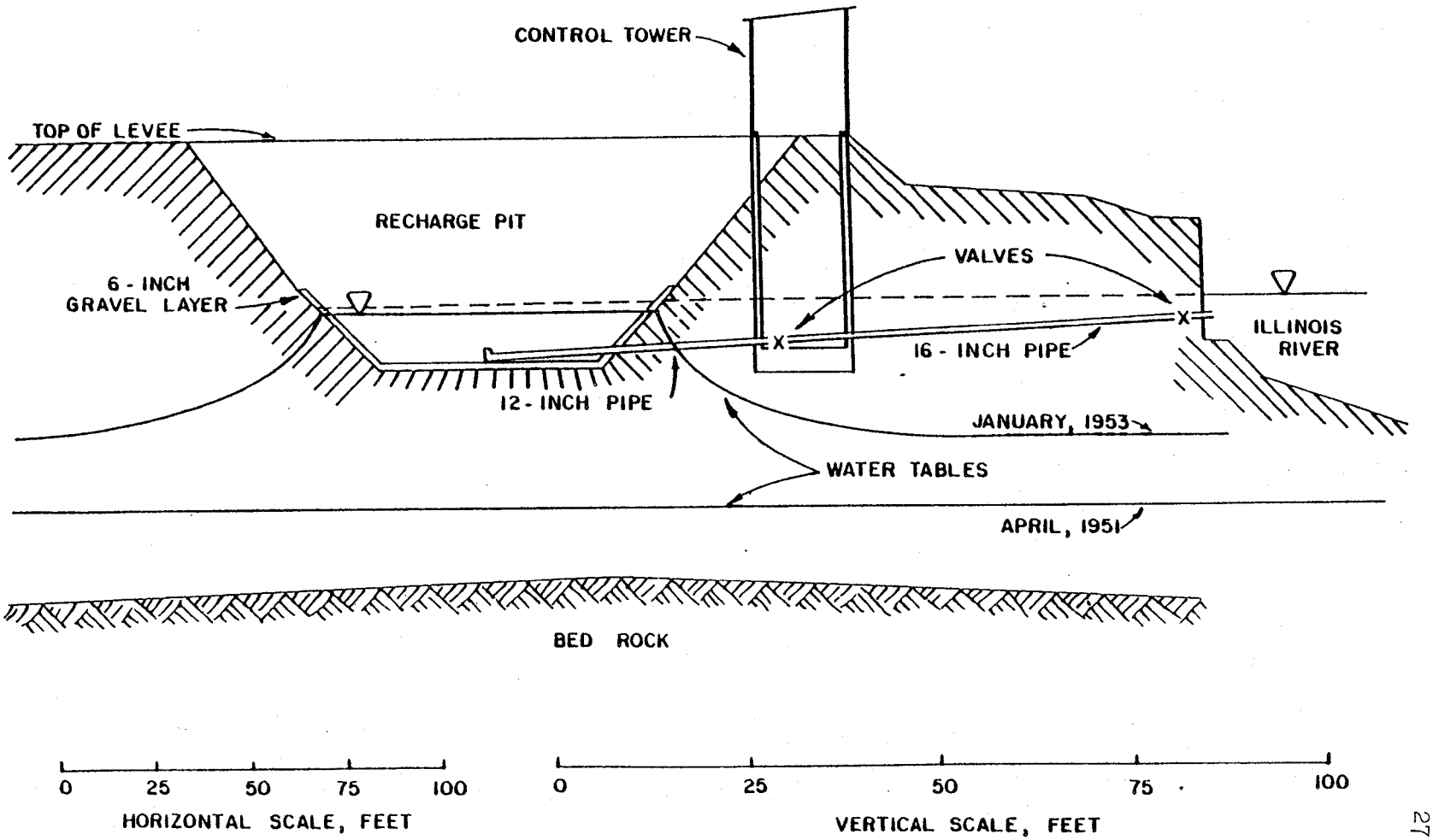
Recharge pits may either consist of existing excavations, such as gravel pits, or specifically constructed cavities. Abandoned pits may require modification or earth moving to remove fine sediment and trash and to permit installing inlet facilities. Side slopes are important in sustaining favorable intake rates. Specifically, because sediment accumulation is restricted on steep slopes, the intake rates through the sides of a pit remain high (Scalmanini and Scott, 1979). Total depth of ponds depends on the thickness of impeding overburden. Depths of 50 to 70 feet are reported for pits in Orange County (Scalmanini and Scott, 1979). Greater depths were felt to improve intake rates (greater head) and also it was found that midge flies were eliminated when water depths exceed eight feet. As pointed out by Priestaf elsewhere in this document, deep basins also minimize evaporation rates and wave-induced erosion and sedimentation.

Figure 3 is a cross-section of a recharge pit operated in Peoria, Illinois. The purpose of the pit was to recharge cool water from the clogged Illinois River during the winter months for recovery as cooling water in the subsequent summer. Studies on methods for controlling surface clogging by sediment and microorganisms during recharge operations on this pit were reported by Suter (1956) and Scalmanini and Scott (1979). For this pit, a pea-gravel filter on the sides and bottom of the pit reduced the effect of clogging by sediment. Chlorination controlled the effects of biological clogging. In some cases it may be necessary to use a sequence of pits in series, with the initial pits used for sedimentation.

BORE-HOLE RECHARGE

Three types of bore-hole recharge methods are reviewed; namely, recharge wells, injection wells, and recharge shafts ("dry wells"). Recharge wells are

CROSS-SECTION OF RECHARGE PIT AT PEORIA, ILLINOIS
(After Todd, 1963)



defined as a bore hole through which water is released by gravity into an unconfined aquifer. An injection well is a well through which water is forced into an aquifer (generally confined). A recharge shaft is a bore hole terminating in porous layers within the vadose zone. Recharge wells and injection wells are generally used for any or all of the following conditions: (1) deep water tables, (2) confined aquifers, (3) vadose zone consisting of fine-grained alluvium, or with fine layers, (4) limited land availability, and (5) clean (sediment free) water. With well recharge the filtering and possibly cleansing effect of passing recharge water through the vadose zone is bypassed. The potential recharged volume is less than for spreading methods. However, the possibility of leaching undesirable native constituents into the water table is diminished and the opportunity for recovering a greater fraction of recharged water is enhanced.

Scalmanini and Scott (1979) reviewed important aspects of recharge well construction, operation and maintenance, based primarily on experience in Southern California. Although all three of the common well construction methods have been used for installing recharge and injection wells, reverse rotary appears to be most suitable. Cable tool construction offers a clean borehole, but is limited in depth and selection of casing material and also is slower. The rotary method introduces a mud cake from the drilling fluid which clogs the formation. Reverse rotary requires no drilling fluid, offers flexibility in casing material, and may be gravel packed (Scalmanini and Scott, 1979).

Factors in the design of a well include depth, diameter, casing material, perforations, gravel pack, and water conduction facilities. The interested reader should consult the report of Scalmanini and Scott (1979) for details. In general, however, the construction and development of a recharge well are similar to the requirements of a producing well. Construction of injection wells is more complicated in that separate injection zones must be isolated by appropriate packing techniques.

Figure 4 is a cross-section through a pilot recharge well constructed at El Paso, Texas for recharging wastewater which has received advanced treatment to meet drinking water standards. This well employs two small diameter conductor pipes to introduce water below the water table. Other wells have used conductor pipes with foot valves to maintain a positive pressure on the incoming water (see Brown, et al., 1978). Introducing water directly through a pump column may result in negative pressure in the water column, causing cavitation (bubble formation) and severe aquifer plugging.

To facilitate redevelopment, recharge and injection rates are normally maintained at values less than the corresponding pumping rates of a well.

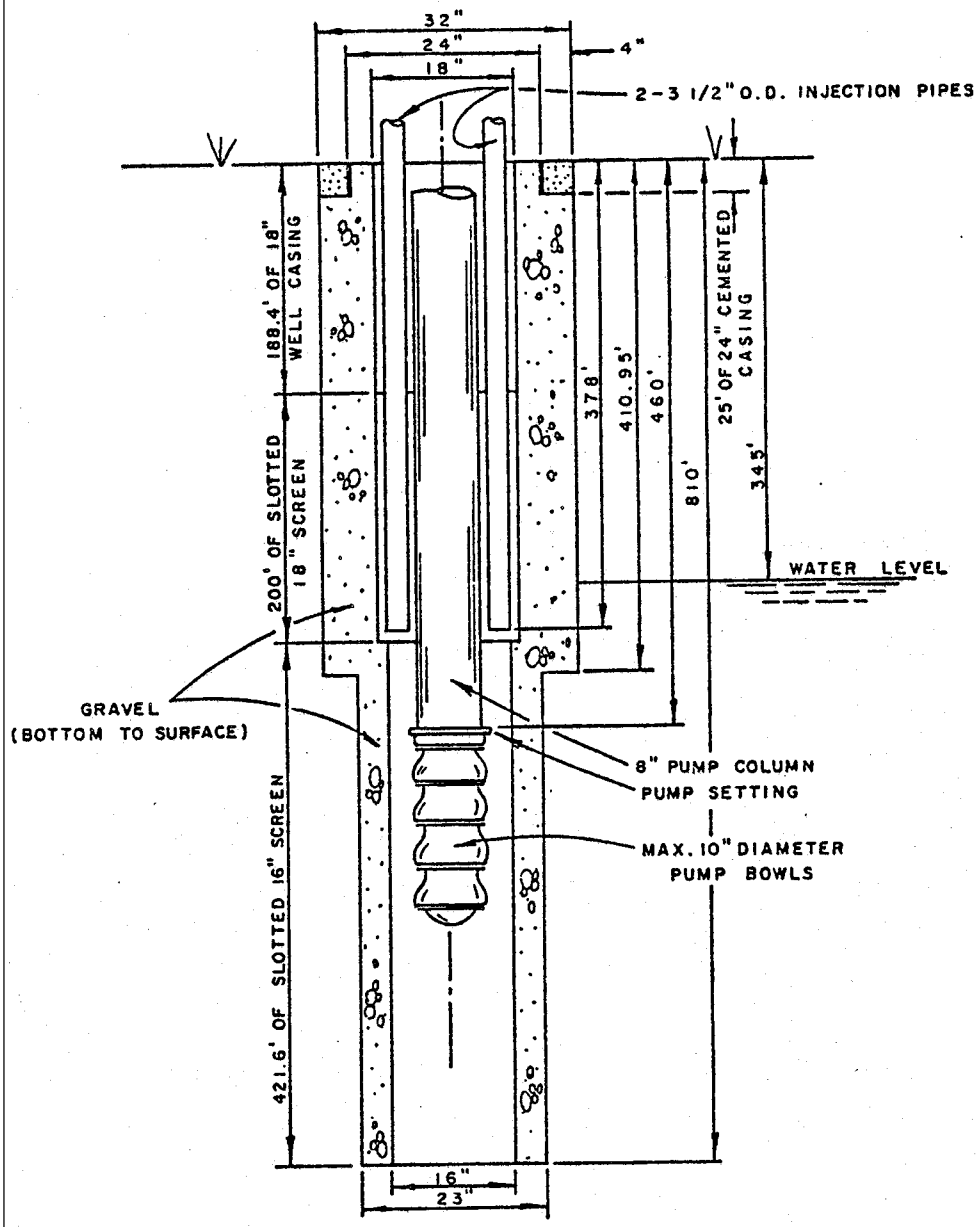
In addition, renovation should be started before clogging becomes too severe (Harpaz, 1970).

Figure 5 is a cross-section through a recharge shaft or "dry well". Such wells are constructed through flow-impeding layers into permeable sediments above the water table. Although recharge shafts have been used specifically for artificial-recharge purposes (see Pettyjohn, 1968; and Signor et al., 1968), the principal usage of these structures in Arizona is for disposal of urban runoff.

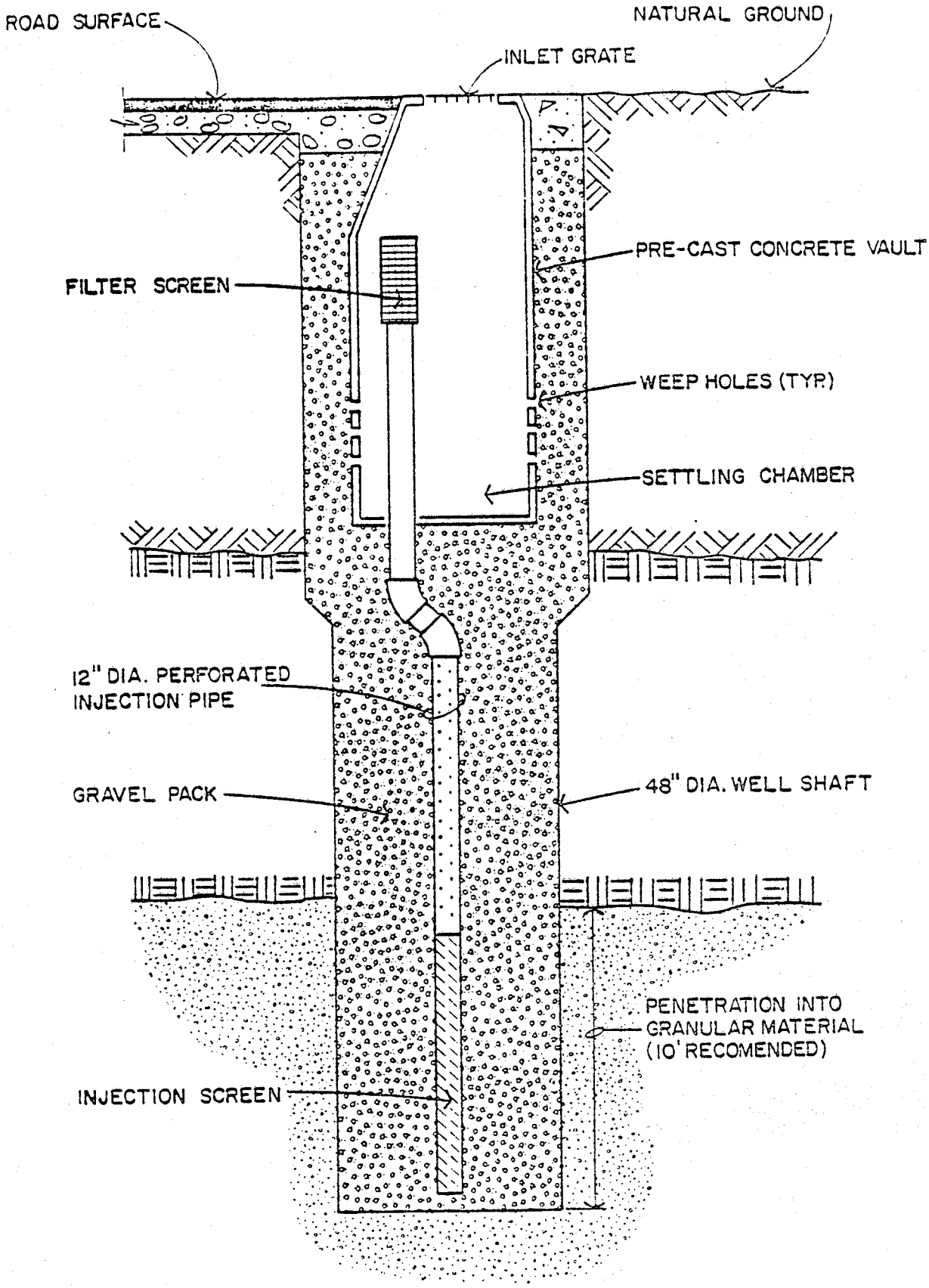
MANAGEMENT PROBLEMS IN ARTIFICIAL RECHARGE

A basic goal of all recharge operations is to maintain high intake rates in order to maximize loading rates. Consequently, factors promoting a reduction in such rates reduce the efficiency of the overall operation. Intake rates naturally decline in all facilities because of the loss in energy required to overcome viscous forces as the wetting front advances. Other factors which affect intake rates include sediment, microorganisms, air, temperature, and water quality. Clogging as a consequence of entrained sediment is caused mainly by two factors, namely sedimentation and filtration (Scalmanini and Scott, 1979; Bouwer, 1978). Sedimentation relates to the settling out of fine particulate matter on the soil surface of a spreading facility or pit. Straining of the fine particles also occurs as water and sediment move into the soil pores. Accumulation of such filtered sediment eventually clogs the soil pores. As pointed out by Bouwer (1978) the clogging materials have a lesser permeability than the soil itself, and intake rates decrease to low values; i.e., the clogged layer becomes a "bottleneck" in the infiltration process. Filtration also occurs during bore-hole recharge as sediment moves into the gravel pack and aquifer formations. The effects of sedimentation are reduced by lowering the incoming sediment concentrations using settling basins, coupled with flocculents, and grass filters. Wet-dry cycling is used on spreading facilities to offset clogging, with the land surface being renovated by scraping using heavy equipment while the soil is dry. Redevelopment is necessary to overcome the effects of sedimentation in recharge and injection wells.

Dead organisms settling on the bottom of a spreading facility may clog the surface by sedimentation-type action. The byproducts of microbial activity (eg. polysaccharides) also clog pores. In addition, pH changes in standing water because of algal activity may result in the precipitation of carbonates, possibly clogging soil pores (Bouwer, Personal Communication, 1979). However,



Pilot injection well construction
(Courtesy, Cliett, 1985)



TYPICAL DRYWELL DESIGN (After Camp Dresser & McKee, Inc.)

NO SCALE

algal mats on the soil surface may break loose, opening up the soil surface and temporarily increasing intake rates. In wells, organic slime build up occurs in the well perforations and gravel pack, reducing intake rates. Control of microbial activity on spreading grounds requires imposing wet-dry cycles to allow surface renovation. For well recharge methods, sand filtration and chlorination of the recharge source may be necessary.

Air may affect intake rates in water spreading areas and pits in two ways, namely as entrained or as confined air. Entrained air tends to block soil pores, reducing intake rates. A more severe problem is that of confined air ahead of wetting front, causing a back-pressure. Confined air occurs in large spreading areas underlain by shallow water tables or tight lenses. Venting may be necessary for spreading operations to reduce air compression. Air binding is a common problem in well recharge, as the pores in the gravel pack and aquifer become blocked. Control of water temperature is important in well methods to prevent the formation of air bubbles. Similarly, negative pressures should be prevented in the water column within a well to prevent cavitation and air bubble formation.

In their water spreading studies in Fresno, Bianchi et al (1978) observed that ponded water temperature was the most significant ambient factor influencing overall performance. For example, intake rates in the leaky acre project varied from 40 acre feet/day in winter to 58 acre feet/day in summer. Higher rates related to the lower viscosity of the warmer water recharged in the summer. Water temperature also affects viscosity of water recharged into a well, but a more important effect probably relates to air release: if recharge water is much cooler than the ground water, air will come out of solution as the recharge water warms up, leading to air bubble formation.

The chemical composition of the recharge source may lead to dispersion of clays in the surface soils of a spreading grounds, causing reduced intake rates. (In another paper in these transactions, Vandemoer discusses the possibility of clay formation by interactions between recharging water and the vadose zone matrix, possibly leading to clogging.) Similarly, in recharge wells, precipitates of chemical compounds such as carbonates, hydroxides, orthophosphates and sulfides may block conducting pores. Precipitation of calcium and magnesium carbonate may be the most important of these reactions (Warner and Doty, 1967). Possible measures for avoiding chemical reactions include pretreatment of the recharge

source, e.g. by pH adjustment, and recharging non-reactive water between recharge water and native ground water. According to Wood (1980) plugging by dispersion of clays is likely to be more severe than plugging by mineral precipitation.

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WATER QUALITY IMPACTS OF RECHARGING CAP SUPPLIES

Catherine Vandemoer

Introduction

Water management in Arizona is entering a new era. At a time when all of the water supplies in major population centers were thought to have been fully developed, water managers are now faced with two primary tasks: (1) making better use of existing supplies, for example through recharge strategies, and (2) integrating, within this context a new source of water--the Colorado River. In areas where ground water may be considered a "sole source" supply, such as the Tucson Basin (U.S. Environmental Protection Agency, 1984), the integration and effective management of water supplies is even more critical, as existing ground water quality must also be protected. The importation of Colorado River water, in this context, may pose water managers with some of the most serious long-term water quality challenges to be faced in decades.

Central Arizona Project water has most recently been viewed by water managers as a potential source of recharge. Theoretically, the water could be stored underground until it is needed, enhancing the conjunctive management of surface and ground water resources as well as reducing the region's chronic ground water overdraft. However, on a mass balance basis, the net import of salt to central and southern Arizona may limit potential recharge strategies, and underscores the necessity of effective management of this vital resource.

In the management effort, basin water managers are fortunate to have the opportunity to integrate a vast amount of existing hydrogeologic and hydrochemical information in the formation of water policies that effectively and carefully utilize the CAP. A physical and chemical framework of the water resource system, upon which predictions can be made regarding the effects of disturbances to that system, is vital to the management effort. One such chemical framework for understanding the water resources in the Tucson area is presented here. This hydrogeochemical approach is based on the principles of chemical equilibrium between water and the minerals of the aquifer, and is applied as a predictive tool in assessing the ground water quality and aquifer matrix impacts of recharging Central Arizona Project supplies.

Framework

'Hydrogeochemistry' describes the relation of the chemical character of ground water to its environment. The term 'environment' designates the atmospheric conditions, soil chemistry and physics, the mineralogy and lithology of the geologic framework which contribute solutes to ground water, and the flow characteristics of the environment (Back, 1965, Stumm and Morgan, 1981). In ground water systems, mineral solubility controls to a great extent the chemical character of water (Garrels, 1965). Several studies have demonstrated the influence of rock mineralogy on the chemical composition of the waters contained therein (Bricker, 1967, Garrels, 1967 and Norton, 1974). For example, rain water undergoes drastic chemical change as it reacts with the rock material it falls on; further chemical change can be noted as that water reemerges as spring or base flow, having further contact with the rock (Laney, 1972). The hydrogeochemical approach to understanding ground water chemistry describes the reactions occurring between earth materials and water, the solid and

aqueous reaction products, and defines the controlling processes by which ground water attains its observed chemical character. With a generic understanding of the processes controlling ground water chemical evolution, we can begin to predict the changes in the chemical character of water over space and time that result from the natural functioning of the hydrologic system, or from disturbances such as artificial recharge.

Chemical equilibrium studies are fundamentally based on the laws of thermodynamics, which describe the energy changes in a system as it moves from one state to another by chemical reaction. As a predictive tool, thermodynamics has its greatest usefulness in closed, carefully controlled systems of the chemical laboratory; however, the principles of thermodynamics are useful in setting limits on what is possible in a natural system (Drever, 1981, Krauskopf, 1979). Several quantities, such as the Gibbs Free Energy, the equilibrium constant, the activity, and the reaction quotient chemical potential relate the thermodynamic properties of solids, liquids and gases, and are used to describe how far a given reaction is from equilibrium, whether it will react, and how far the reaction will proceed.

The saturation state of natural waters may also be evaluated with respect to a mineral or suite of minerals by comparing the solubility product with the ion activity product of the species under consideration. For example, consider the evaluation of a natural water with respect to the mineral, gypsum ($CaSO_4 \cdot 2H_2O$):

The reaction:

$$CaSO_4 \cdot 2H_2O = Ca^{2+} + SO_4^{2-} + 2H_2O \qquad (1)$$

The equilibrium constant:

$$K_{eq} = (aCa^{2+})\ (aSO_4^{2-})\ (a^2H_2O)/(aCaSO_4 \cdot 2H_2O) \qquad (2)$$

The solubility product:

$$K_{sp} = (aCa^{2+})\ (aSO_4^{2-}) = K_{eq} \qquad (3)$$

The Gibbs Free Energy for the reaction:

$$\Delta G_r = \Sigma \Delta G^o_p - \Sigma \Delta G_R \qquad (4)$$

$$\Delta G_r = 6.29 \qquad (5)$$

A numerical value for the equilibrium constant:

$$\log K_{eq} = -\Delta G_r/1.364 \ @\ 25^oC \qquad (6)$$

$$K_{eq} = 10^{-4.61} = K_{sp} \qquad (7)$$

Comparing the ion activity product of gypsum, $aCa^{2+} \cdot aSO_4^{2-}$, with the solubility product (equation 7), it is possible to determine whether the water is saturated or undersaturated with respect to the mineral. Using values for calcium and sulfate in the Tucson Basin ground waters,

$$\text{Ion Activity Product}/K_{sp} = Q \qquad (8)$$

$$(8.51\text{x}10^{-4})\ (4.18\text{x}10^{-4})\ 10^{-4.61} = .014 \qquad (9)$$

By convention, the value is less than 1 which indicates the solution is undersaturated with respect to gypsum. If any gypsum were present in this area, it would be dissolving, releasing calcium and sulfate to the water. In the previous calculations, "a" designates activity, and the values for the Gibbs Free Energy of products (ΔG_p°) and reactants (ΔG_R°) were obtained from Drever (1981).

Finally, the volume of formation of the solid reaction products may be used to calculate the porosity change in a porous medium as a result of the production or destruction of aquifer minerals through chemical reaction. For example, in a reference volume consider the alteration of potassium feldspar ($KAl_3Si_3O_8$) in a ground water system where an intermediate reaction product, kaolinite ($Al_2Si_2O_5(OH)_4$) reacts with the feldspar and water to form muscovite ($KAl_3Si_3O_{10}(OH)_2$) and quartz (SiO_2):

$$KAlSi_3O_8 + Al_2Si_2O_5(OH)_4 + H_2O = KAl_3Si_3O_{10}(OH)_2 + 2SiO_2 \qquad (10)$$

The partial molar volume change of the reaction, ΔV_r^{o} (cc/mole) can be calculated by (Garrels and Christ, 1965):

$$\Delta V_r = \sum \Delta V_f^{\circ} \text{ products} - \sum \Delta V_f^{\circ} \text{ reactants} \qquad (11)$$

Using the values of the molar volumes for reactants and products obtained from the standard state thermodynamic data base of Helgeson (1970), the change in volume in this reaction is 22.22 cc/mole per kilogram of water. If, for example, 3 moles of muscovite were produced over a period of time in which several kilograms of water passed through the reference volume, the volume of product minerals added to the system from this reaction is 66.75 cm^3. If the initial porosity of the medium, as defined by:

$$n = V_v/V_t \qquad (12)$$

(where V_v is the volume of voids and V_t is the total volume) was .30, the production of .06m^3 of product mineral in a 1m^3 reference volume would reduce the volume of voids to .24 m^3 and the corresponding porosity of the reference volume would decrease from .30 to .24. Similar porosity change calculations have been made in explaining changes in the circulation of waters in geothermal fields.

A final extension of the hydrogeochemical framework involves the use of a mineral stability diagram, a convenient graphical tool which permits the identification of reaction paths for water as it reacts with a geologic medium.

Major Chemical Changes Associated with Recharge

Recharge involves the mixing of two or more chemically distinct waters and also the injection or percolation of water into geologically and geochemically distinct aquifer materials. Consequently, there will be both quality changes to the recharged water as well as aquifer matrix changes as the recharged water reacts with the geologic material.

The quality of the recharged water changes as a result of its interaction with the soil and aquifer material, soil gases and organic matter and existing soil moisture. There may or may not be a net increase in the dissolved constitutents in the recharged water, depending on the chemical condition of this water with respect to the mineralogy of the aquifer. There is further chemical change as the altered recharge water encounters ambient ground water. The recharged water may have a different dissolved load than existing ground water; either dilution or concentration of the resulting solution is the result. In addition, the specific chemical elements--calcium, sodium, sulfate, for example--and their ratios determine the aqueous complexes formed and subsequently affect the water's use for domestic, agricultural and industrial operations.

The matrix changes are as a result of the destruction and production of solid reaction products. The continual application of recharge water to the geologic medium essentially furthers the subsurface weathering process. From the standpoint of recharge strategies, the mineral products of weathering are critical. For example, the production of expanding clay minerals (montmorillonite) versus non-expanding clay minerals (kaolinite) may affect the permeability of the medium, particularly after the application of sodium-rich waters to the area in question. The potential formation of calcite-or caliche- in layers or as coatings on sand grains also affects the permeability of the medium and the long-term utility of the recharge site.

The management implications of both quality change processes have relevance for the location of recharge projects, the method of recharge, the timing and distribution of recharge events, and the control of the chemistry of the recharged water through mixing strategies.

Tucson Basin Ground Waters and the Central Arizona Project

The Tucson Basin is a north-north west trending basin in the basin and range physiographic province and is located in Southern Arizona (figure 1). The aquifer material is comprised of a thick sequence of sedimentary deposits derived from the erosion of surrounding igneous, metamorphic and sedimentary rocks. The subsurface stratigraphy, as delineated by well cuttings analysis, is extremely complex and reflects the conditions of deposition of the sediments. Aquifer material ranges from fine, silty sediment to coarse-grained sediment, slightly to moderately cemented with calcite or silica occurring as coatings on sand grains or as thick patches.

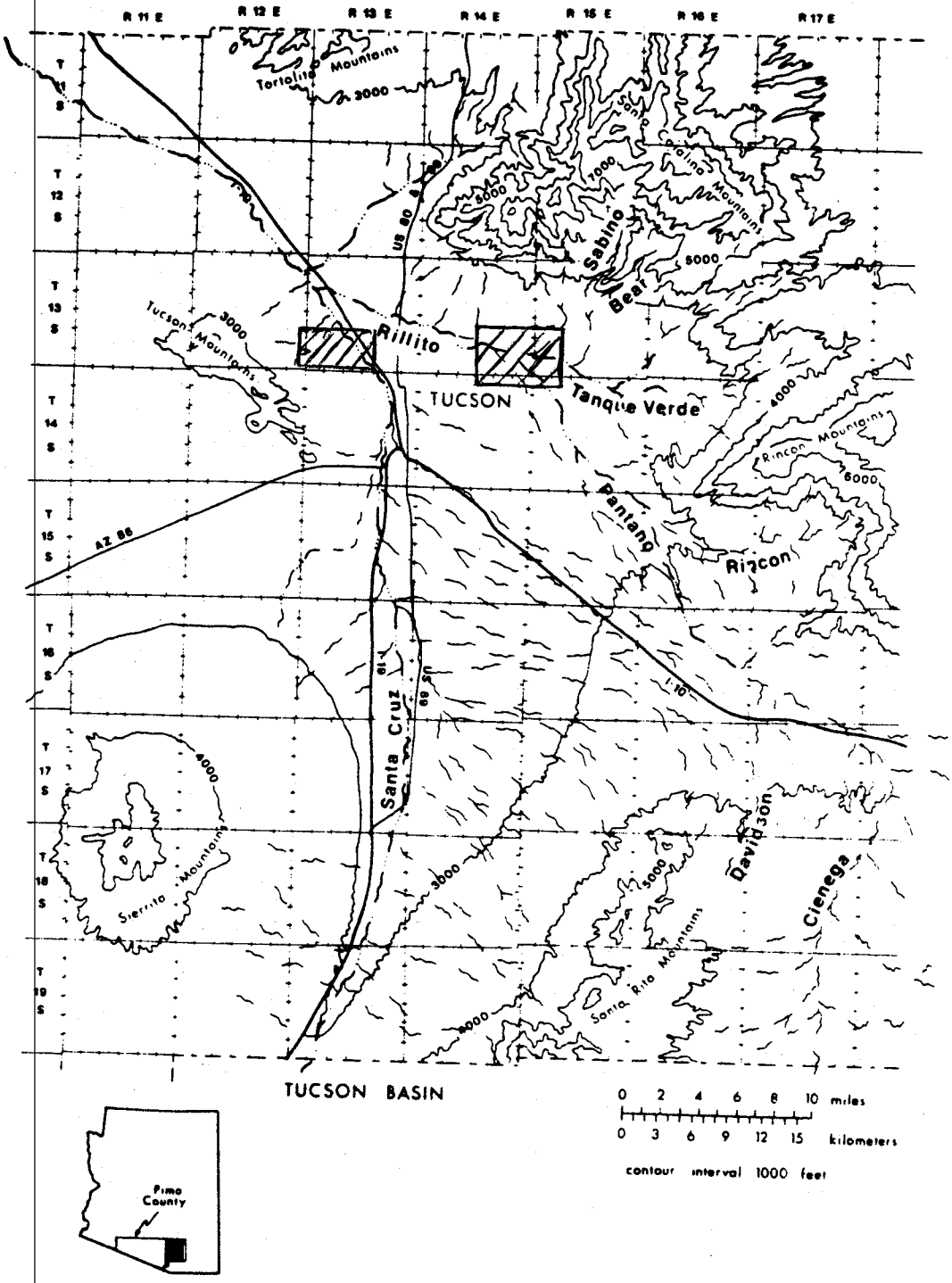


FIGURE 1. Location of study area. Boxes are sites considered in this report. (after Keith, 1981)

Mineralogically, the sediments reflect the source and thus relative dominance of the mafic versus felsic rocks and minerals in the aquifer. The ground waters contained in these rocks also reflect the distinction: substantial differences in concentrations of calcium, sodium, sulfate, chloride and pH values can be observed between the eastern and western parts of the basin. Based on the major differences in ion concentration in the ground waters of the basin, Laney (1972) distinguised seven chemical types of water in the Tucson Basin. A Piper diagram, presented in figure 2, generally characterizes these waters.

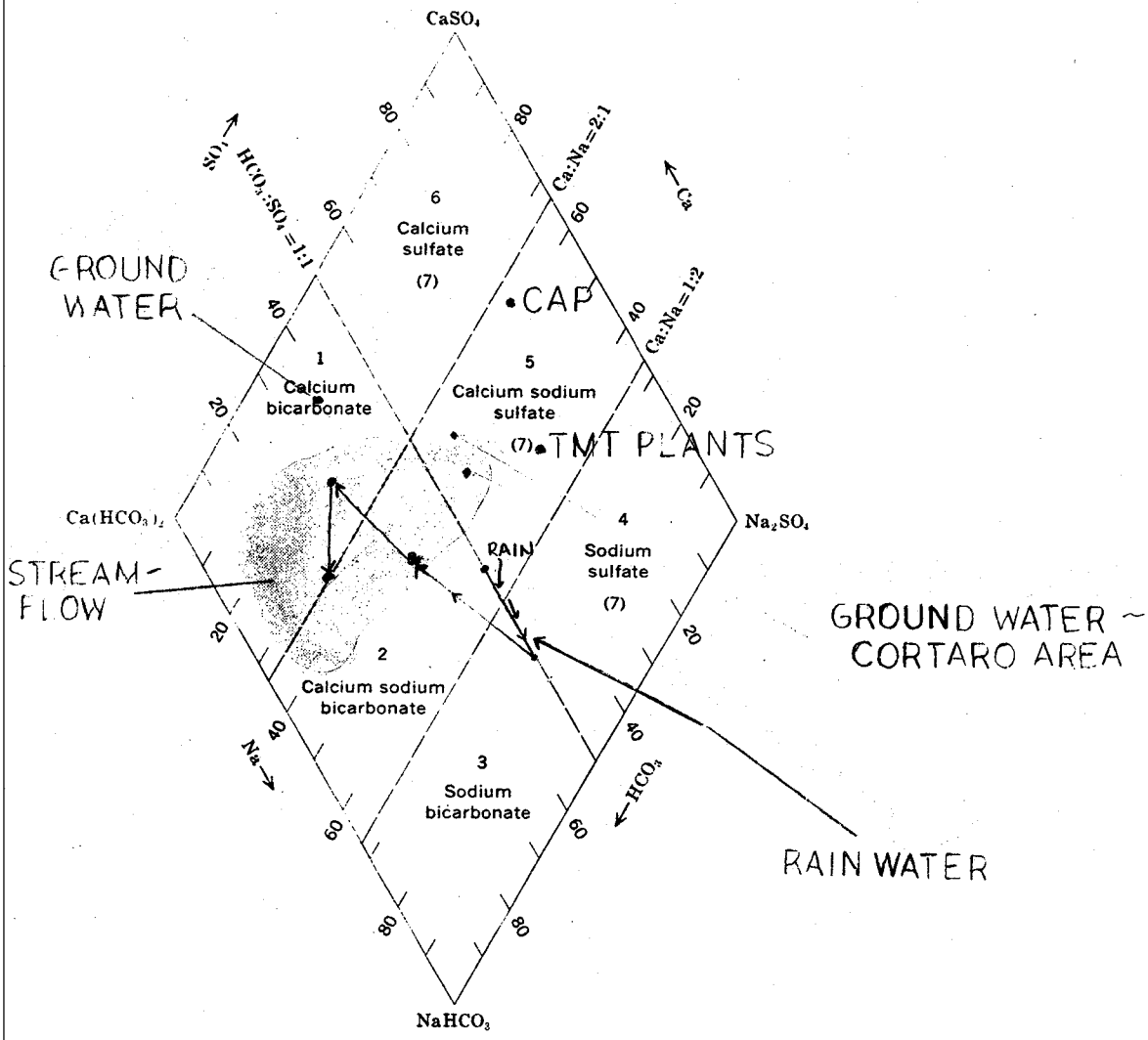
Approximately 75% of the basin's shallow ground water is of calcium-sodium-bicarbonate composition. Major surface streams are of the calcium-bicarbonate type. Ground water in a north-central part of the basin, the Cortaro area, as well as the treatment plant waters are calcium-sodium-sulfate waters and presumably reflect both anthropogenic activities as well as the stratigraphic interfingering of sediments from the Tucson and Santa Catalina mountains (Laney, 1972, Wilson, et al 1983). Note that the Central Arizona Project water plots close to calcium-sulfate water type, and is quite different in its natural condition than other basin waters. Although not immediately apparent from figure 2, the change in rainwater composition shown is a clue to the geochemical processes in the basin which control the evolution of recharge waters.

The specific study areas chosen for analysis in this paper are shown in Figure 1, and consist of rain water, spring and baseflow samples, and ground water analyses along a presumed flow path for both recharge and ground water. Chemical analyses of ground water, steam flow and Central Arizona Project water are presented in Table 1, and further illustrate general differences in Tucson's water sources.

Analysis of the data on a mineral stability, or activity, diagram yields additional information concerning the geochemical processes controlling ground water chemical evolution (Figure 3). The logarithm of the activity ratios of calcium to hydrogen is plotted against the activity of silicic acid. The change in the activity ratios of the water along the flow path chart a reaction path. Note that the spring waters plot in the kaolinite mineral stability field. As the solution moves along the flow path and becomes ground water, additional calcium is added and the composition of the fluid moves toward the montmorillonite field. Note also in the diagram the narrow range of concentration of silica. The diagram suggests that the concentration of silica may be controlled by equilibrium between the two clay minerals and not by the dissolution of quartz (Garrels, 1967).

A mineral stability diagram for the system involving sodium is presented in Figure 4. Note the same general trend in the reaction path and the similar narrow range in silica concentration. As illustrated in the diagram, the reaction path is theoretically consistent with the reaction of a carbon dioxide-charged rain water with a sodium feldspar (Garrels, 1967, Laney, 1972).

The chemical evolution of the basin's recharge waters is shown in Figure 5, where the activity ratios of calcium and sodium are plotted against each other. The samples included on this diagram are rain water, stream flow and ground water immediately beneath the stream channels along a flow path on the eastern side of the basin. The ground water samples have been labeled 'piedmont' wells because physiographically they are found in the piedmont region of the basin.



EXPLANATION

3
Major water type that contains less than 50 mg/l of chloride
Number corresponds to types in table 6

(7)
Major water type that contains more than 50 mg/l of chloride
Number corresponds to type in table 6

Chemical composition of streamflow (recharge water) in Santa Cruz River, Rillito Creek, and Pantano Wash

FIGURE 2 —Classification of major water types using ratios of calcium to sodium and bicarbonate to sulfate and absolute amount of chloride.

Source: Laney 1972, Chemical Quality of the Water in the Tucson Basin, U.S.G.S. Water Supply Paper 1979

Table 1. Selected water quality analyses of the major sources of water in the Tucson basin. All values are in milligrams per liter except as otherwise noted.

	Tucson Basin Ground Water [a]	Santa Cruz River [b]	Central Arizona Project [c] I	Central Arizona Project [c] II
Ca^{2+}	37	25	85	100
Na^{+}	19	20	107	120
Mg^{2+}	7.2	2	31	40
K^{+}	1	.95	5.2	6.8
Cl^{-}	6	7.9	94	140
HCO_3^{-}	117	98	128	210
SO_4^{2-}	36	9	309	380
F^{-}	.25	.4	.5	.9
$NO_3^{=}$	1.6	--	.2	.4
SiO_3	30.1	.6	9.3	100
TDS	224	102	718	690
pH	7.4	7.0	7.95	8.8
SAR	1.25	1.05	2.6	2.8

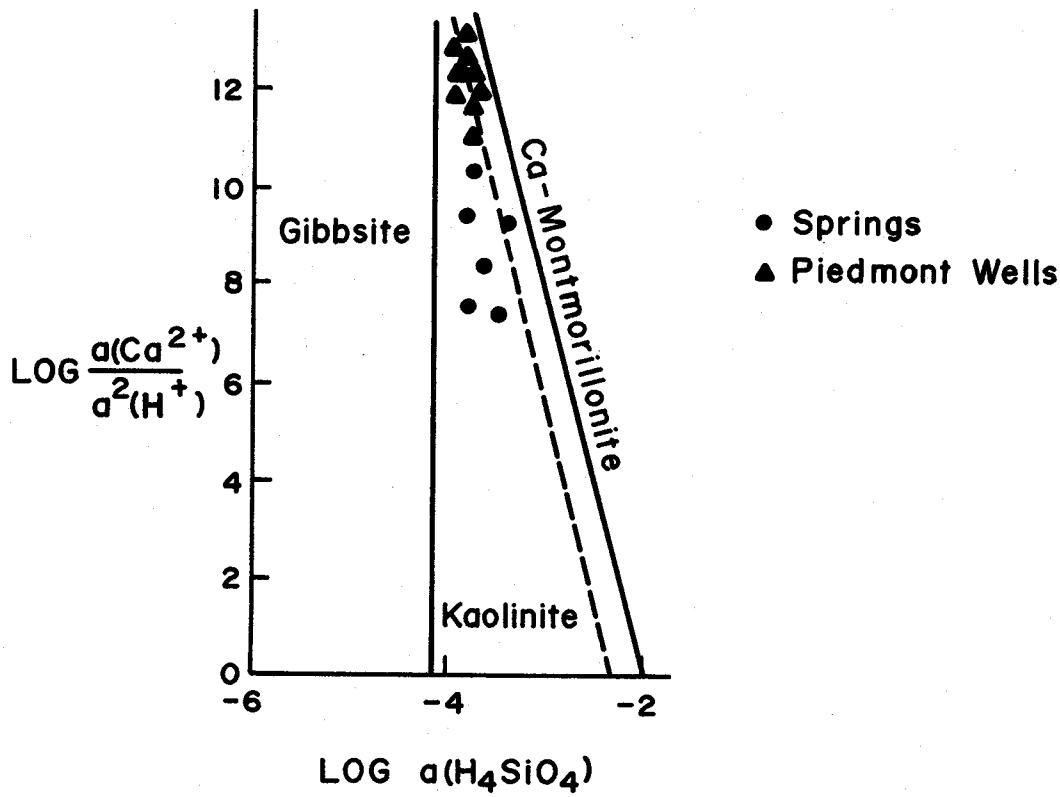
a. Location: T13S R14E, section 26 averages, University of Arizona, 1977.

b. Laney, R. L., 1972, U.S.G.S. Water Supply Paper 1979.

c. I: Colorado River below Parker Dam, EPA Storet Data Retrieval System.

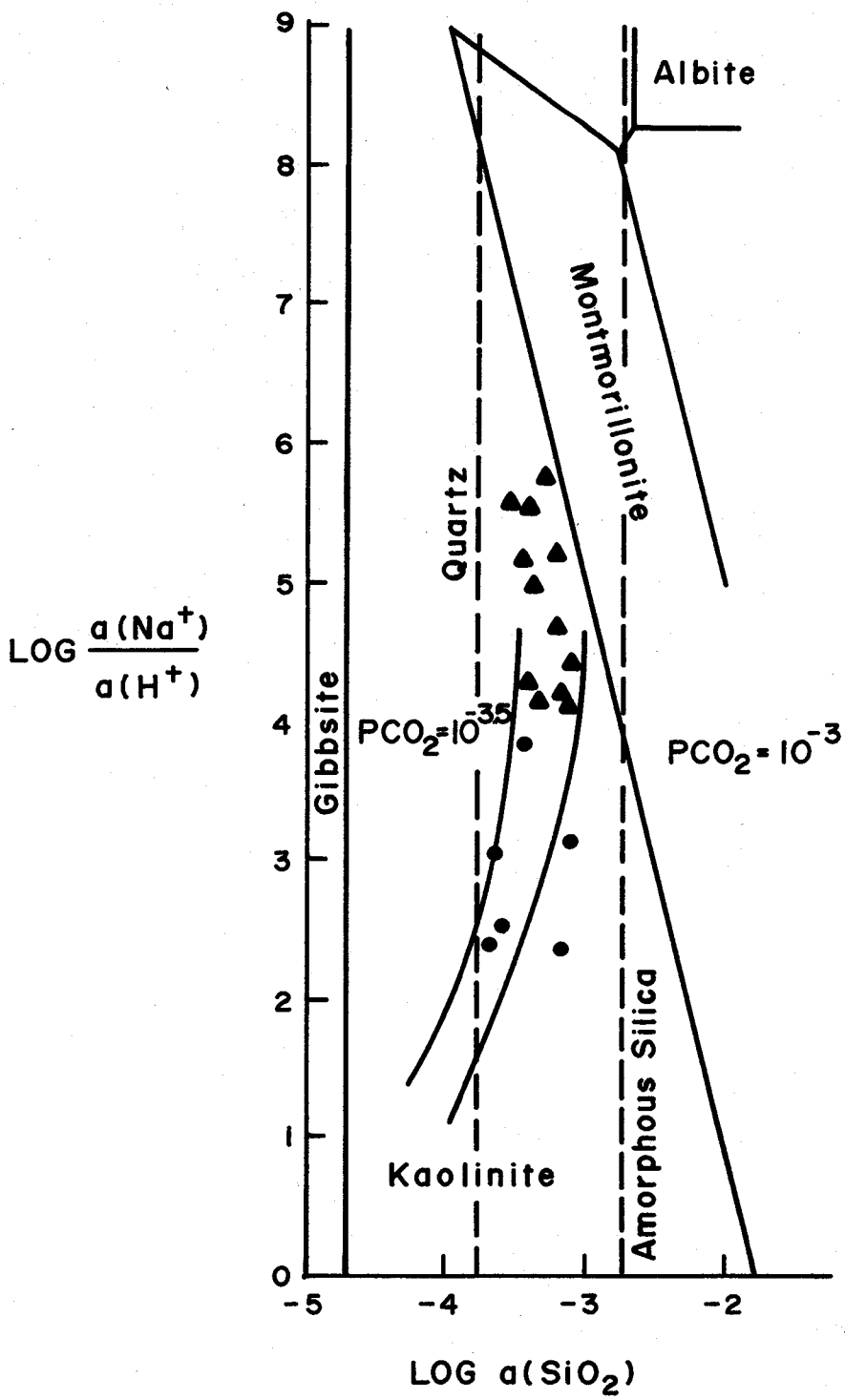
II: Colorado River with influence of Bill Williams River. Solution represents composition of 50% Bill Williams and 50% Colorado River water. From CH2M Hill, 1984.

In the lower left part of the figure, rain water plots in the kaolinite stability field and is essentially an acid, dilute water. Mineral-water interaction is shown as the spring flow, direct runoff and baseflow samples are plotted on the diagram. Calcium and sodium are both released as a result of the reaction, and the pH of the solution rises.



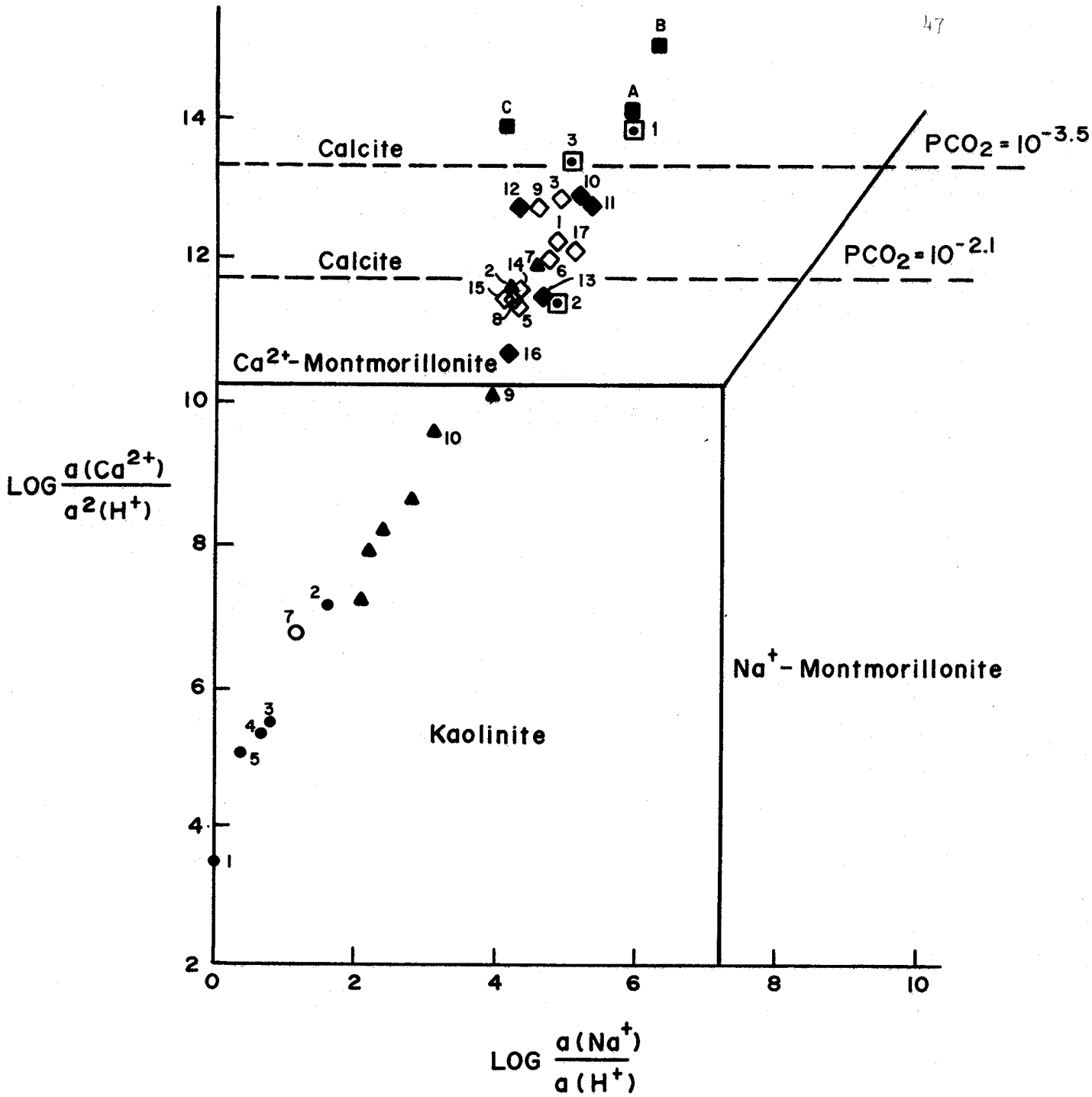
Activity Diagram for system Al_2O_3-CaO-SiO_2-H_2O at 25°C and 1 bar, unit water activity. Stability fields calculated from data in Helgeson (1969). Solution compositions for water samples were used to calculate activity ratios. Dashed line parallel to Ca-Montmorillonite field is position of the Kaolinite-Ca-Montmorillonite suggested by this study.

FIGURE 3



Activity Diagram for the system $NaO-SiO_2-Al_2O_3-H_2O$ at 1 bar and 25°C. The circles represent spring waters or the Santa Catalina Mountains and the triangles represent foothill and piedmont ground water samples.

FIGURE 4



Activity Diagram for the system $NaO - CaO - Al_2O_3 - SiO_2 - H_2O$, Garrels (1967) showing evolution of Tucson Basin ground waters.

FIGURE 5

KEY

- ●1 Rain
- ○4 Direct Runoff
- △10 Base Runoff
- ◇17 Piedmont Wells
- ◆10 Wells not on flow path
- A □ GS-1, A=116-475, B=480-600, C=605-700
- ⊡ CAP, 1-Untreated, 2-Treated, Levl 1, 3-Treated, Levl 7

The piedmont wells, illustrated as the solid triangles, all plot in the expanding clay mineral field, montmorillonite. Note also that at different values of carbon dioxide in the ground water system, the ground water is either saturated, supersaturated or undersaturated with respect to calcite. This means that calcite should be precipitating in some places in the aquifer and forming cement, a conclusion that has been verified by well cuttings analysis. The clustering of ground water samples around the calcite saturation surfaces suggests that calcite dissolution and precipitation keeps ground waters in this area and that further chemical change involves the sodium and calcium concentrations of the solution. The feldspars, which form the primary reactant minerals of the basin, are not shown on this diagram but would plot in the upper portions of the figure. Because the carbonate system seems to encourage the clustering of ground water samples in one field, however, it is probable that the basin waters will never reach equilibrium with its reactants. Continual weathering of these minerals, and consequent release of calcium and sodium is the result in the near surface waters.

There are specific points in the basin at which it is possible to see the formation of non-expanding versus expanding clay minerals in the ground water environment. The sampling points suggest that ground waters close to the Catalina foothills northeast of the Rillito River are in equilibrium with kaolinite. Further southwest of the Rillito, an into the piedmont area, the ground waters are in equilibrium with the expanding clay, montmorillonite. The addition of a sodium-rich water such as the CAP in areas where this mineral is forming may cause further swelling within the aquifer matrix.

Note the position of the Central Arizona Project water in the figure. Saturated with respect to calcite, gypsum and anhydrite*, the CAP also plots in the montmorillonite field. A mixture of CAP with water from both the piedmont and base flow areas would drag the fluid composition closer to the montmorillonite and calcite fields. If a supersaturated condition results, these minerals will tend to precipitate. Water analyses for treated CAP are also shown on the diagram. Among other things, the treatment process involves a change in the major ion ratios as well as an adjustment of pH. Interestingly enough, the most expensive treatment (level 7) does little in the way of reducing the potential for expanding clay mineral development.

Ground water samples along a flow path from the Tucson mountains to the Santa Cruz river in the western side of the basin are presented in Figure 6. The diagram has the same axes as the previous figure. Note that the ground waters plot in the same general area as the piedmont wells of the eastern side of the basin. However, the reaction path for these waters is in the opposite direction from wells in the eastern part of the basin, as indicated by the arrow.

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*obtained by comparing the ion activity product with the solubility product, as illustrated earlier in this paper.

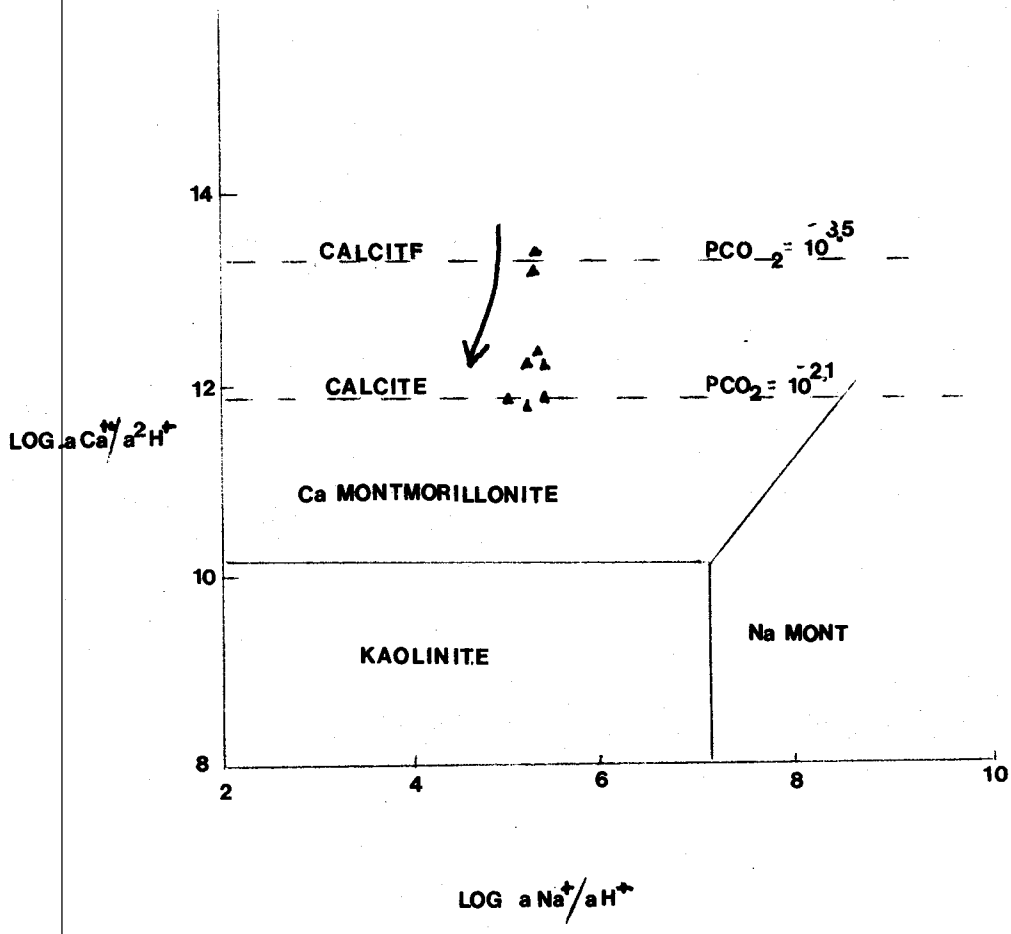
Initially, waters in the Tucson mountains are higher in dissolved solids than waters in the Santa Catalinas. As water moves along the flow path to the Santa Cruz river, the pH decreases as does the concentration of calcium. Sodium activity remains fairly constant. At the same time, the waters become undersaturated with respect to calcite and move toward the kaolinite stability field. The source of acid in this case, which would lower the activity ratios, could be the oxidation of sulfide minerals in the aquifer or could indicate a mixing of different types of waters in the area, perhaps the recharging Santa Cruz river water. Mixing is possible in this case as a hydrograph of a well along this flow path close to the river showed the influence of several large flow events on the Santa Cruz during the winter of 1985 (Tucson Water, personal communication, 1985). The reaction trend, if continued, would make kaolinite from montmorillonite. This suggests that natural recharge events may serve to dilute concentrated artificially recharged waters and reduce the deleterious effects of clay mineral formation.

In summarizing the base case for ground water in the Tucson Basin, note that the natural processes of diagenesis are leading to the formation of expanding clay minerals, silica and calcite cement, gypsum and anhydrite within the aquifer. The actual flow conditions within the aquifer will in part determine whether the mineral precipitation pattern will occur as thick layers or as coatings. The overall effect is the growth of secondary minerals into existing pore space within the matrix. The gradual formation of these minerals over time may be the reason why many ground water flow models in the basin overpredict the rate of ground water movement.

Continued reaction of ground water with the aquifer material gradually increases the concentration of major ions which contribute dissolved solids to the ground water. Near surface waters controlled by the carbonate system may never reach equilibrium with the basin reacting minerals and will continue to deliver ions to ground water.

Finally, natural recharge events do affect ground water quality through lateral migration of recharge water. There are also natural recharge areas which tend to produce the non-expanding clay minerals and also do not produce calcite at specific points in the basin.

The Central Arizona Project, water when superimposed upon existing geochemical conditions, hastens the process of clay mineral formation and will increase the dissolved solids content of ground water.



Chemical profile along flow path-Tucson Mts. to Santa Cruz river.

FIGURE 6

Management Implications

The utility of a hydrogeochemical framework as applied to the interpretation of ground water chemistry has been demonstrated by constructing a generic view of the processes controlling ground water chemistry in the Tucson Basin. The processes are clues to the types of quality changes to be expected from artificial recharge projects in the basin. Within this context, it is possible to sketch broadly several management implications for recharge strategies involving CAP:

(1) Location of Recharge Sites: recharge areas should be located where the mineralogy, existing ground water quality, dissolved carbon dioxide content, and flow conditions are conducive to the formation of non-expanding clay minerals. At the same time, locating recharge projects in these areas will degrade existing ground water quality.

(2) Chemistry of the recharge water: the activity ratios of the recharged water, and not just the pH, should be controlled so that the initial composition of the recharged water plots in the kaolinite stability field. This could be accomplished by some type of pretreatment strategy or by mixing waters.

(3) Timing of Recharge Strategies: recharge strategies should be timed with natural recharge events on the various stream reaches to take advantage of the low pH and relatively smaller concentration of dissolved solids contained in the stream flow. This would assist in dilution of recharged waters. Also, the time allowed for reaction between CAP water and the aquifer matrix should be shortened.

(4) Monitoring Existing Recharge Projects: Inasmuch as the time involved in the formation of secondary minerals is critical to the utility of the porous medium, careful monitoring of the aquifer matrix material as well as water quality would assist in delineating the magnitude of impact of artificial recharge strategies.

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GROUNDWATER RECHARGE WITH SEWAGE EFFLUENT [1/]

Herman Bouwer [2/]

INTRODUCTION

Sewage effluent is a dependable and often increasing water source for artificial recharge of groundwater. Primary and secondary effluent can be used for recharge via infiltration basins or other spreading system. Direct injection with wells into potable aquifers requires advanced wastewater treatment so that the effluent essentially meets drinking water quality standards before it is injected into the well. This is expensive.

When primary or secondary effluent as such is used for groundwater recharge, the main objective of the recharge system often is quality improvement of the effluent as it filters through the vadose zone and aquifer to become "renovated" water. As discussed later in this paper, this quality improvement consists of essentially complete removal of suspended solids, biodegradable organic compounds, microorganisms, and phosphate, and of significant removal of nitrogen and heavy metals. This quality improvement normally is adequate to meet the requirements for unrestricted irrigation and unrestricted recreation. Where the renovated water is to be used for drinking, it will have to undergo additional treatment after it is pumped from the aquifer. This posttreatment normally would consist of activated carbon filtration, disinfection, and possibly reverse osmosis. Groundwater recharge systems using sewage effluent or similar wastewater should utilize the optimum combination of pretreatment of the wastewater before recharge, quality improvement obtained in the soil and aquifer system, and posttreatment of the renovated water after it is collected from the aquifer. Also, high quality native groundwater resources should be protected against encroachment by the lower quality renovated water from the recharge system.

SOIL-AQUIFER TREATMENT

To take full advantage of the treatment capability of vadose zones and aquifers for sewage effluent without contaminating native groundwater, it is best to design and manage the recharge system so that all the water that infiltrates in the soil as low quality water will be removed from the aquifer after it has traveled far enough and spent enough time underground for optimum "renovation." Where the groundwater is deep and has to be pumped from wells, such systems could consist of two parallel infiltration strips, or strips of basins, with a line of wells midway between the strips to pump the renovated water out of the aquifer (Fig. 1, top). A variation on this system would be a circle of infiltration basins with a single well

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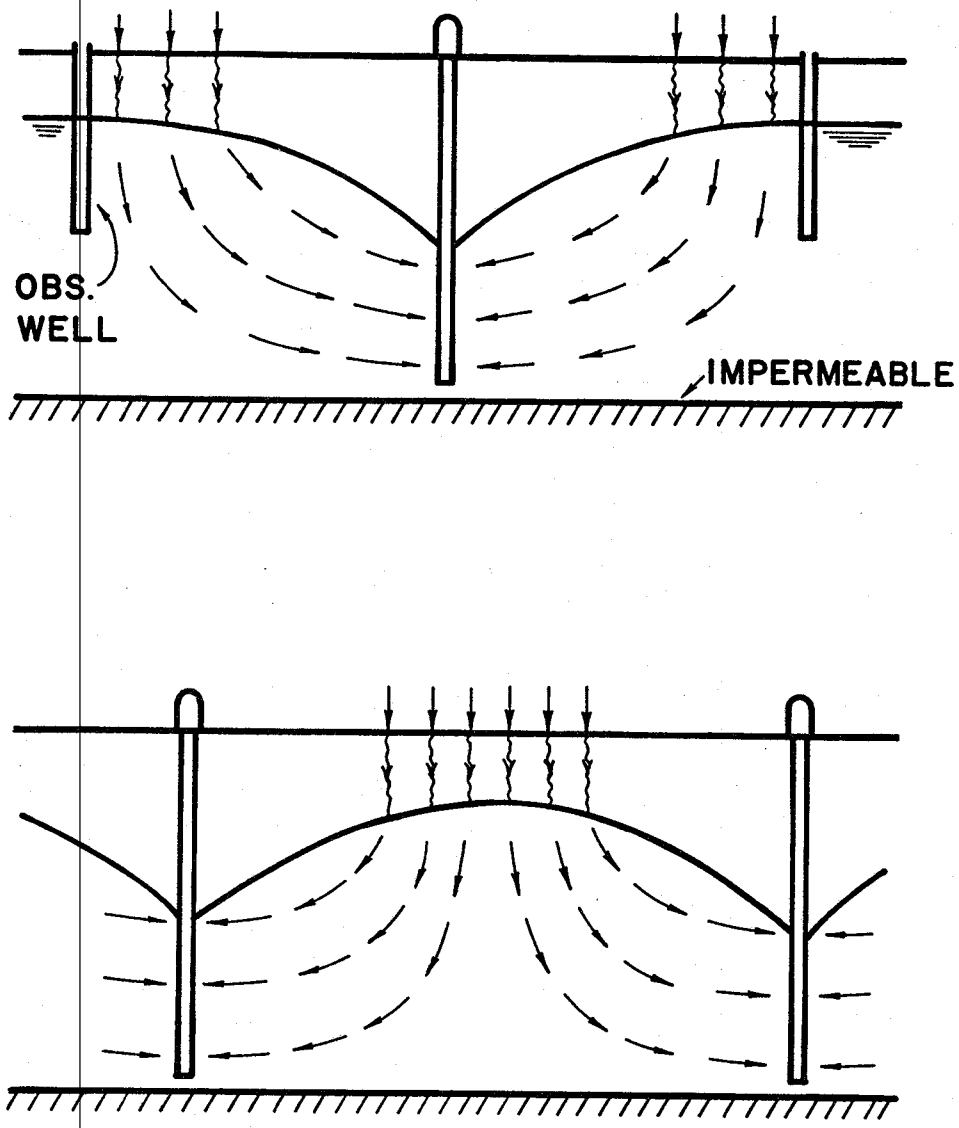

Figure 1. SAT systems with infiltration basins in two parallel strips with wells midway between strips for pumping renovated water (top), and infiltration basins in center surrounded by a circle of wells for pumping renovated water out of aquifer (bottom).

in the center. The latter system could primarily be used for relatively small sewage flows, because the total infiltration should not exceed the discharge from the well or wells in the center. Another possibility would be to arrange the infiltration basins closely together in a cluster and to surround the basins at a certain distance by a circle of wells to pump the water out of the aquifer again (Fig. 1, bottom). The systems of Fig. 1 prevent spread of renovated water into the aquifer outside the portion of the aquifer between the infiltration facilities and the interceptor wells. This portion of the aquifer thus is essentially dedicated to wastewater treatment. For this reason, systems as in Fig. 1 are called soil-aquifer treatment (SAT) systems, rather than groundwater recharge systems.

The system of Fig. 1, top, should be managed so that the groundwater level below the outside of the infiltration strips remains at the same elevation as the groundwater level in the aquifer outside the infiltration areas. When this is achieved, there is no flow from the SAT system to the outside aquifer or vice versa, and the wells discharge essentially one hundred percent renovated wastewater. This is advantageous where there are legal restrictions on pumping native groundwater, or where the renovated water needs to undergo further treatment (for drinking, for example). The treatment plant's capacity would then be based on the flow of wastewater only, without dilution by native groundwater. In contrast, the wells in the SAT system of Fig. 1, bottom, yield a mixture of renovated water and native groundwater, unless the renovated water is allowed to move for considerable distance beyond the circle of wells. If this is not permitted, the capacity of any posttreatment plant must be larger than the flow of renovated wastewater only.

The SAT systems as in Fig. 1 enable use of the optimum combination of pre-, soil-aquifer, and posttreatment of the water. For municipal sewage effluent, a good sequence would be primary treatment (followed by lime precipitation, settling, or lagooning if necessary to remove suspended solids), lagooning, or oxidation ditch treatment before infiltration. After infiltration, SAT would remove almost all suspended solids, microorganisms, biodegradable carbon, and phosphorus, while significantly reducing the concentrations of nitrogen and heavy metals. The renovated water pumped from the wells could then be directly used for unrestricted irrigation (disinfection may be necessary in some cases) or unrestricted recreation, while potable use would require additional treatment (activated carbon adsorption, disinfection, and possibly reverse osmosis). Such treatment, however, would be much cheaper and much more effective after SAT than before SAT. Thus, there is an advantage to letting the soil-aquifer treatment system do the dirty work first before using advanced water treatment technologies to purify the water to drinking quality. However, the trend in California seems to be toward more treatment before SAT, so that SAT is used only as a polishing treatment, and the water from the wells is used directly for drinking. This could be the preferred course of action if groundwater recharge with sewage effluent is initiated in an established urban area with many wells already pumping drinking water from the aquifer. In that case, construction of an SAT system as in Fig. 1, and the associated posttreatment plant and water distribution system may be more expensive

than treatment of the sewage effluent to essentially drinking water quality standards prior to infiltration.

WATER QUALITY REQUIREMENTS FOR IRRIGATION

Where urban areas are in irrigated regions, it is logical to use the water of the best quality for municipal use, while using lower quality water for irrigation (provided, of course, that the lower quality water meets the quality requirements for irrigation). This gives municipalities an opportunity to trade their sewage effluent for high quality water (surface water, groundwater, imported water) with nearby irrigation entities.

Where sewage effluent is used for irrigation, it should be treated so that it meets the public health, chemical, and aesthetic requirements of irrigation water. The quality requirements from a public health standpoint depend on the crops that are irrigated and how they are consumed by humans. If only non-edible crops are grown (fiber and seed crops, for example), primary treatment may suffice. At the other extreme, if the sewage effluent is used for general irrigation including vegetables consumed raw by people or crops brought raw into the kitchen where they can contaminate other food, the effluent must be treated to remove all disease-causing organisms (bacteria, viruses, protozoa, amoebae, and eggs of parasitic worms). This usually requires primary and secondary treatment of the effluent, followed by filtration and disinfection. An example of the various classes of crops or plants that can be irrigated with sewage effluent and the corresponding water quality requirements for public health considerations is shown in Table 1. Where sewage treatment is limited and only non-edible crops (fiber, seed, or forage crops) can be irrigated, a strict program of inspection and enforcement is necessary to make sure that the sewage effluent is not used to grow some vegetable crops on the side.

The chemical quality requirements for using sewage effluent for irrigation are the same as those for regular irrigation water. These requirements are formulated to avoid adverse effects on the soil (primarily deflocculation of clay and decline of soil structure as caused by excessive sodium concentrations) and on the plant (salinity effects, excessive nitrogen, and specific ion toxicities, particularly of trace elements). Examples of chemical quality requirements of irrigation water are shown in Tables 2 and 3. Most sewage effluents will meet these requirements. If the salinity of the effluent is high, salt-tolerant crops should be grown and special management techniques (adequate leaching, use of high quality water for germination of the crop, planting on the side of the ridges instead of on top of the ridges in furrow-irrigated crops, etc.) should be used to avoid undesirable effects due to salinity. Excessive concentrations of certain trace elements are usually due to industrial waste discharges in the sewer system. These can be reduced by proper source control. Blending with other water is also a possibility. The nitrogen concentration requirements in Table 2 are for general crop irrigation in warm, dry climates where water applications may be on the order of 3 to 6 ft per season or per year. For cooler climates or supplemental irrigation, or where only grasses or other forage crops are grown, much higher nitrogen concentrations can be allowed.

Table 1. Standards for irrigation with reclaimed wastewater in Arizona (from Matters, 1981).

	Crop and Land Use Category							
	A	B	C	D	E	F	G	H
pH	4.5-9	4.5-9	4.5-9	6.5-9	4.5-9	4.5-9	4.5-9	4.5-9
Fecal coliforms (CFU/100 mℓ)								
Geometric mean (5-sample minimum)	1,000	1,000	1,000	1,000	1,000	200	25	2.2
Single sample not to exceed	4,000	4,000	4,000	4,000	2,500	1,000	75	25
Turbidity (NTU)	-	-	-	-	-	-	5	1
Enteric virus (PFU/40 ℓ)	-	-	-	-	-	-	125	1
Entamoeba hystolytica	-	-	-	-	-	-	-	N.D.
Ascaris lumbricoides (roundworm eggs)	-	-	-	-	-	-	N.D.	N.D.
Common Large Tapeworm	-	-	N.D.	N.D.	-	-	-	-

CFU - colony-forming unit
NTU - nephelometer turbidity units
PFU - plaque-forming units
N.D. - none detectable, using correct samples and methods and qualified personnel

A. Orchards
B. Fiber, seed, and forage crops
C. Pastures
D. Livestock watering
E. Processed food crops
F. Landscaped areas, restricted access
G. Landscaped areas, open access
H. Crops to be consumed raw

Table 2. Guidelines for interpretation of water quality for irrigation.

Problems and quality parameters	No problems	Increasing problems	Severe problems
Salinity effects on crop yield:			
Total dissolved-solids concentration (mg/ℓ)	< 480	480-1920	> 1920
Deflocculation of clay and reduction in K and infiltration rate:			
Total dissolved-solids concentration (mg/ℓ)	> 320	< 320	< 128
Adjusted sodium adsorption ratio (SAR)	< 6	6-9	> 9
Specific ion toxicity:			
Boron (mg/ℓ)	< 0.5	0.5-2	2-10
Sodium (as adjusted SAR) if water is absorbed by roots only	< 3	3-9	> 9
Sodium (mg/ℓ) if water is also absorbed by leaves	< 69	> 69	
Chloride (mg/ℓ) if water is absorbed by roots only	< 142	142-355	> 355
Chloride (mg/ℓ) if water is also absorbed by leaves	< 106	> 106	
Quality effects:			
Nitrogen in mg/ℓ (excess N may delay harvest time and adversely affect yield or quality of sugar beets, grapes, citrus, avacados, apricots, etc.)	< 5	5-30	> 30
Bicarbonate as HCO_3 in mg/ℓ (when water is applied with sprinklers, bicarbonate may cause white carbonate deposits on fruits and leaves)	< 90	90-520	> 520

From: Ayers, 1975

Table 3. Recommended maximum limits in milligrams per liter for trace elements in irrigation water.

	Permanent irrigation of all soils	Up to 20 yr irrigation of fine-textured neutral to alkaline soils (pH 6-8.5)
Aluminum	5	20
Arsenic	0.1	2
Beryllium	0.1	0.5
Boron-sensitive crops	0.75	2
semitolerant crops	1	
tolerant crops	2	
Cadmium	0.01	0.05
Chromium	0.1	1
Cobalt	0.05	5
Copper	0.2	5
Fluoride	1	15
Iron	5	20
Lead	5	10
Lithium: citrus	0.075	0.075
other crops	2.5	2.5
Manganese	0.2	10
Molybdenum	0.01	0.05*
Nickel	0.2	2
Selenium	0.02	0.02
Vanadium	0.1	1
Zinc	2	10

* For acid soils only

From: Water Quality Criteria, National Academy of Sciences and National Academy of Engineering, 1972.

The aesthetic aspects of irrigation with sewage effluent are of most concern in densely populated areas, but they are also important for the farmers and the workers handling the effluent water. The aesthetic aspects involve the appearance of the effluent and its odor. Thus, the concentrations of suspended solids and of biodegradable organic matter should be minimized so that the water looks clear and does not smell.

Where sewage effluent is to be used for unrestricted irrigation (category H in Table 1), a fairly intensive treatment technology is required to meet the quality requirements. Typically, the treatment would have to consist of primary (settling) treatment, secondary (biological) treatment, coagulation, sedimentation, sand filtration, and chlorination. The primary and secondary treatment steps could be replaced by lagooning or oxidation ditch treatment (carousel systems). Where hydrogeologic conditions are favorable for groundwater recharge with infiltration basins, however, the necessary purification beyond conventional treatment can very simply be obtained with an SAT system (Fig. 1). SAT systems require surface soils that are fine enough to give good purification of the sewage water, coarse enough to give high infiltration rates, and deep enough to give good treatment of the water before it enters the aquifer or other coarse-textured formations. Sandy loams to loamy sands several meters deep are very good soil profiles for wastewater renovation by SAT.

PHOENIX PLANS

The city of Phoenix is interested in renovating part of its sewage effluent by SAT and in exchanging the renovated water with a nearby irrigation district for high quality groundwater from that district that the city would then use to augment its municipal water supply. There are two major sewage treatment plants in the Phoenix area: The 91st Avenue treatment plant (activated sludge, chlorination, capacity about 120 mgd), and the 23rd Avenue treatment plant (activated sludge, chlorination, capacity about 40 mgd). The SAT system for the Phoenix area would consist of a series of infiltration basins arranged in two parallel strips with wells on a line midway between the strips (Fig. 1, top). The feasibility of SAT was studied with two experimental systems, a small test project installed in 1967, and a larger, demonstration project installed in 1975. The latter could be part of a future operational project (Fig. 2) that will have a basin area of 120 acres and a projected capacity of about 36,000 acre feet/year or 32 mgd. As an example of the hydraulic capacities and the treatment that can be obtained with SAT systems, the results of these two test projects will be summarized in the remainder of this paper.

RESULTS OF SAT TEST PROJECTS

Project descriptions and hydraulic loading rates

The first project was the Flushing Meadows project (Bouwer et al., 1974 and 1980). This was an experimental project installed in the Salt River bed in 1967. It consisted of six parallel, long, narrow infiltration basins of

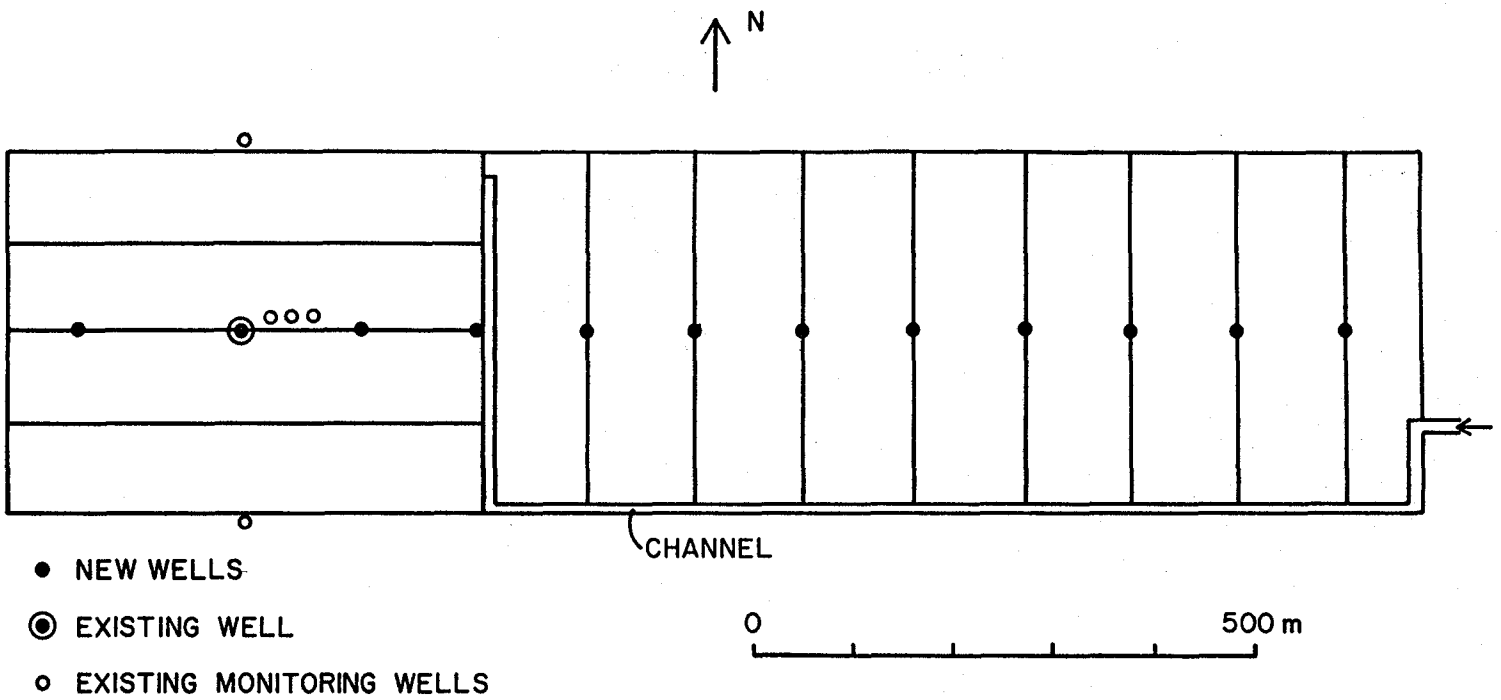

Figure 2. Sketch of 23rd Avenue project with 40-acre lagoon (left) that was split into four infiltration basins and 80-acre lagoon (right) that can be split into nine infiltration basins to increase capacity of system to that of plant outflow. The twelve wells for pumping renovated water are shown as dots. Also shown is the bypass-supply channel.

about 0.3 acre each. The soil consisted of about 3 ft of loamy sand underlain by sand and gravel layers. The groundwater table was at a depth of around 10 ft. Monitoring wells 20 to 30 ft deep were installed at various points between the basins and away from the basins. This made it possible to sample renovated wastewater from the aquifer below the basins and after the water had moved laterally for some distance through the aquifer.

The second project was the 23rd Avenue project (Bouwer and Rice, 1984). This is a demonstration and future operational project installed in 1975 on the north side of the Salt River bed. It consists of a 40-acre lagoon split lengthwise into four infiltration basins of 10 acres each (Fig. 2). The soil lacks the loamy sand top layer of the Flushing Meadows project. Thus, the soil profile consists mostly of sand and gravel layers. The water table depth in the study period ranged between 15 and 75 ft and was mostly around 50 ft. Monitoring wells for sampling renovated wastewater were installed in the center of the project at depths of 60, 80, and 100 ft and on the north and south side of the basin complex at depths of 75 ft (Fig. 2). In addition, a large production well (capacity about 2000 gpm) was drilled in the center of the project with the casing perforated from 100 to 180 ft depth.

Flooding and drying schedules were mostly 9 days flooding-12 days drying at the Flushing Meadows project and 14 days flooding-14 days drying at the 23rd Avenue project. Water depths in the basins were about 6 to 8 inches. During flooding, infiltration rates typically were between 1 and 2 ft/day, yielding a total infiltration or hydraulic loading of between 200 and 400 ft/year for Flushing Meadows and about 300 ft/year at the 23rd Avenue project. For the 23rd Avenue project, the effluent from the treatment plant initially flowed through an 80-acre lagoon (Fig. 2) before it entered the infiltration basins. This gave problems of soil clogging in the infiltration basins due to heavy growth of algae in the lagoon, especially in the summer. The unicellular algae Carteria klebsii were particularly troublesome. In addition to forming a "filter cake" on the bottom of the infiltration basin, the algae removed CO_2 from the wastewater for photosynthesis which raised the pH and, in turn, caused precipitation of $CaCO_3$, which further aggravated the soil clogging. Algae growth and resulting soil clogging were avoided by constructing a bypass canal around the 80-acre lagoon (Fig. 2), reducing the detention time of the effluent from a few days to about one-half hour. After the bypass channel was put into operation, hydraulic loading rates for the infiltration basins increased from 70 ft/year to almost 300 ft/year.

At a hydraulic loading rate of 300 ft/year, 1 acre of infiltration basin can handle 300 acre feet of wastewater per year or 0.27 mgd. Thus, the 40 mgd of effluent from the 23rd Avenue wastewater treatment plant would require 150 acres of infiltration basins. Almost all of this area can be obtained by also converting the 80-acre lagoon east of the present infiltration system into infiltration basins (Fig. 2). This would give a total basin area of about 120 acres. The wells for pumping the renovated water from the aquifer could be located on the centerline through the project (Fig. 2). At a capacity of about 2,000 gpm per well, twelve wells would be needed to pump renovated water out of the aquifer at the same rate as it

infiltrates as wastewater in the basins, thus creating an equilibrium situation.

For both projects, most of the quality improvement of the wastewater occurred in the vadose zone (i.e., the zone between soil surface and the groundwater table). The quality improvements for these projects will be summarized in the following paragraphs. For additional details, reference is made to H. Bouwer et al. (1974, 1980, and 1984) and to E. J. Bouwer et al. (1984).

Suspended solids

The suspended solids content of the renovated water at the Flushing Meadows project was less than 1 mg/l. For the 23rd Avenue project, it averaged about 1 mg/l for the large production well. Most of these solids probably were fine aquifer particles that entered the well through the perforations in the casing. The suspended solids content of the secondary effluent at the 23rd Avenue project averaged about 11 mg/l.

Total dissolved solids

The total salt content of the water increased slightly as it moved through the SAT system (from 750 to 790 mg/l at the 23rd Avenue project). Evaporation from the basins (including from the soil during drying) should increase the TDS content by about 2 percent. The rest of the increase probably was due to mobilization of calcium carbonate due to a pH drop from 8 to 7 as the effluent moved through the vadose zone.

Nitrogen

At the Flushing Meadows project, nitrogen removal from the effluent water as it seeped through the vadose zone to become renovated water was about 30 percent at maximum hydraulic loading (300-360 ft/year), but 65 percent if the loading rate was reduced to about 210 ft/year by using 9-day flooding and 12-day drying cycles and by reducing the water depths in the basins from 1 to 0.5 ft. The form and concentration of nitrogen in the renovated water sampled from the aquifer below the basins were slow to respond to the reduction in hydraulic loading (Bouwer et al., 1980). In the tenth year of operation (1977), the renovated water contained 2.8 mg/l of ammonium nitrogen, 6.25 mg/l nitrate nitrogen, and 0.58 mg/l organic nitrogen, for a total nitrogen content of 9.6 mg/l. This was 65 percent less than the total nitrogen of the secondary sewage effluent, which averaged 27.4 mg/l (mostly as ammonium) in that year. At the 23rd Avenue project, the total N content in the secondary sewage effluent averaged about 18 mg/l, of which 16 mg/l was as ammonium. The 2-week flooding and drying cycles must have been conducive to denitrification in the vadose zone, because the total N content of the renovated water from the large center well averaged about 5.6 mg/l of which 5.3 mg/l was as nitrate, 0.1 mg/l as ammonium, 0.1 mg/l as organic, and 0.02 mg/l as nitrite. The nitrogen removal thus was about 70 percent. This removal was the same before and after the secondary effluent was chlorinated, indicating that the low residual chlorine of the effluent by the time it infiltrated into the

ground apparently had no effect on the nitrogen transformations in the soil.

The flooding and drying sequence that maximizes denitrification in the vadose zone depends on various factors and must be evaluated for each particular system. Pertinent factors include the ammonium and carbon contents of the effluent entering the soil, infiltration rates, cation-exchange capacity of soil, exchangeable ammonium percentage, depth of oxygen penetration in the soil during drying, and temperature. The combined laboratory and field data from the Flushing Meadows experiments showed that to achieve high nitrogen removal percentages, the amount of ammonium nitrogen applied during flooding must be balanced against the amount of oxygen entering the soil during drying. Flooding periods must be long enough to develop anaerobic conditions in the soil. Infiltration rates must be controlled to the appropriate level for the particular effluent, soil, and climate at a given site. Most of the nitrogen transformations in the Flushing Meadows studies occurred in the upper 2 ft of the vadose zone.

Phosphate

Phosphate removal increased with increasing distance of underground movement of the sewage water. After 10 ft of downward movement through the vadose zone and 20 ft through the aquifer, phosphate removal at the Flushing Meadows project was about 40 percent at high hydraulic loading and 80 percent at reduced hydraulic loading. Additional lateral movement of 200 ft through the aquifer increased the removal to 95 percent (i.e., to a concentration of 0.51 mg/l phosphate phosphorus vs. 7.9 mg/l in the effluent). After ten years of operation and a total infiltration of 2474 ft of secondary effluent, there were no signs of a decrease in phosphate removal. At the 23rd Avenue project, phosphate phosphorus concentrations in the last few years of the research averaged 5.5 mg/l for the secondary effluent and 0.37 mg/l for the renovated water pumped from the center well. The shallower wells showed a higher phosphate content, indicating that precipitation of phosphate continued in the aquifer. For example, renovated water sampled from the 75-ft-deep north well showed phosphate phosphorus concentrations that averaged 1.5 mg/l. Most of the phosphate removal probably was due to precipitation of calcium phosphate.

Fluoride

Fluoride removal paralleled phosphate removal, indicating precipitation as calcium fluoride. At the Flushing Meadows project, fluoride concentrations in 1977 were 2.08 mg/l for the effluent, 1.66 mg/l for the water after it had moved 10 ft through the vadose zone and 10 to 20 ft through the aquifer, and 0.95 mg/l after it had moved an additional 100 ft through the aquifer. At the 23rd Avenue project, fluoride concentrations averaged 1.22 mg/l in the secondary effluent and 0.7 mg/l in the renovated water from the center well.

Boron

Boron was not removed in the vadose zone and the aquifer and was present at concentrations of 0.5 to 0.7 mg/l in both effluent and renovated water.

The lack of boron removal was due to absence of significant amounts of clay in the vadose zone and aquifer.

Metals

At the Flushing Meadows project, movement of the secondary effluent through 10 ft of vadose zone and 20 ft of aquifer reduced zinc from 193 to 35 μg/l, copper from 123 to 16 μg/l, cadmium from 7.7 to 7.2 μg/l, and lead from 82 to 66 μg/l (Bouwer et al., 1974). Cadmium thus appeared to be the most mobile metal.

Fecal coliforms

The secondary effluent at the Flushing Meadows project was not chlorinated and contained 10^5 to 10^6 fecal coliforms per 100 ml. Most of these were removed in the top meter of the vadose zone. Some penetrated to the aquifer, however, especially when a new flooding period was started. The deeper penetration of fecal coliforms at the beginning of a flooding period was attributed to less straining of bacteria at the soil surface because the clogged layer had not yet developed. Also, the activity of native soil bacteria at the end of a drying period was lower, producing a less antagonistic environment for the fecal coliforms in the soil when flooding was resumed. Fecal coliform concentrations in the water after 3 m of travel through the vadose zone and 6 m through the aquifer were 10 to 500 per 100 ml when the renovated water consisted of water that had infiltrated at the beginning of a flooding period, and between 0 and 1 per 100 ml after continued flooding. Additional lateral movement of about 300 ft through the aquifer was necessary to produce renovated water that was completely free from fecal coliforms at all times.

At the 23rd Avenue project, fecal coliform concentrations in the secondary sewage effluent entering the infiltration basins were 10,000/100 ml prior to November 1980 when the effluent was not yet chlorinated and was first passed through an 80-acre lagoon. This concentration increased to 1.8 x 10^6/100 ml when the unchlorinated effluent was bypassed around the lagoon and flowed directly into the infiltration basins. It then decreased to 3500/100 ml after the effluent was chlorinated and still bypassed around the lagoon. The corresponding fecal coliform concentrations in the water pumped from the large center well from a depth of 100 to 180 ft averaged 2.3, 22, and 0.27/100 ml, respectively. The corresponding ranges were 0 to 40, 0 to 160, and 0 to 3 per 100 ml, respectively. Considerable fecal coliform concentrations were observed in the renovated water from the shallower wells, especially when the fecal coliform concentration of the infiltrating effluent was 1.8 x 10^6/100 ml. At that time, water from the 60-ft-deep well showed coliform peaks after a new flooding period was started that regularly exceeded 1000/100 ml and at one time even reached 17,000/100 ml. Thus, a considerable number of fecal coliforms passed through the vadose zone. However, chlorination of the effluent and resulting reduction of the fecal coliform concentration to 3500/100 ml prior to infiltration, and additional movement of the water through the aquifer to the center well produced renovated water that was essentially free from fecal coliforms.

Viruses

At the Flushing Meadows project, the virus concentrations of nonchlorinated secondary effluent averaged 2118 plaque forming units (PFU)/100 liter average of six bimonthly samples taken for one year). They included polio, echo, coxsackie, and reoviruses. No viruses could be detected in renovated water sampled after 10 ft of movement through the vadose zone and 10 to 20 ft movement through the aquifer. At the 23rd Avenue project, virus concentrations in the renovated water from the center well averaged 1.3 PFU/100 liter before chlorination of the secondary effluent, and 0 PFU/100 liter after chlorination of the secondary effluent. The combined effects of chlorination and SAT thus apparently resulted in complete removal of the viruses.

Organic carbon

At the Flushing Meadows project, the biochemical oxygen demand (BOD) of the effluent water after moving 10 ft through the vadose zone and 20 ft through the aquifer was essentially zero, indicating that almost all biodegradable carbon was mineralized. However, the renovated water still contained about 5 mg/l total organic carbon (TOC), as compared to 10 to 20 mg/l of TOC in the secondary effluent. At the 23rd Avenue project, the TOC concentration of the secondary effluent averaged 12 mg/l where it entered the infiltration basins, and 14 mg/l at the opposite ends of the basins. This increase probably was due to biological activity in the water as it moved through the basins. The renovated water from the 60-ft well (intake about 15 ft below the bottom of the vadose zone) had a TOC content of 3.2 mg/l and that from the center well (which pumped from 100 to 180 ft depth) had a TOC content of 1.9 mg/l, indicating further removal of organic carbon as the water moved through the aquifer. The TOC removal in the SAT system was the same before and after chlorination of the secondary effluent, indicating that chlorination had no effect on the microbiological processes in the soil.

The concentration of organic carbon in the renovated water of 1.9 mg/l was higher than the 0.2 to 0.7 mg/l typically found in unpolluted groundwaters. The latter are mostly due to humic substances like fulvic and humic acids (Thurman, 1979). The renovated sewage water from the SAT process thus could contain a number of synthetic organic compounds, some of which could be carcinogenic or otherwise toxic.

Removal of trace organic compounds in the vadose zone

The nature and concentration of trace organics in the secondary sewage effluent and in the renovated water from the various wells of the 23rd Avenue project were determined by Stanford University's Environmental Engineering and Science Section, using gas chromatography and mass spectrometry. The studies were carried out for two months with nonchlorinated effluent, and then for three months with chlorinated effluent, taking weekly or biweekly samples. As could be expected, the results showed a wide variety of organic compounds, including priority pollutants (many in concentrations on the order of μg/l, see E. J. Bouwer et al., 1984; and H. Bouwer and Rice, 1984).

The chlorination had only a minor effect on the type and concentration of organic compounds in the sewage effluent. Of the volatile organic compounds, 30 to 70 percent were lost by volatilization from the infiltration basins. Soil percolation removed 50 to 99 percent of the nonhalogenated organic compounds, probably mostly by microbial decomposition. Concentrations of halogenated organic compounds decreased to a lesser extent with passage through the soil and aquifer. Thus, halogenated organic compounds (including the aliphatic compounds chloroform, carbon tetrachloride, trichloroethylene, and 1,1,1-tri-chloroethane, and the aromatic di- and trichlorobenzenes and chlorophenols) were more mobile and refractory in the underground environment than the nonhalogenated compounds, which included the aliphatic nonanes, hexanes, and octanes, and the aromatic xylenes, C_3-benzenes, styrene, phenanthrene, and diethylphthalate.

Other organic micropollutants

In addition to the aliphatic and aromatic compounds mentioned, other compounds tentatively identified in organic extracts of the samples of secondary sewage effluent and renovated water using gas chromatography-mass spectrometry were: fatty acids, resin acids, clofibric acid, alkylphenol polyethoxylate carboxylic acids (APECs), trimethylbenzene sulfonic acid, steroids, n-alkanes, caffeine, Diazinon, alkylphenol polyethoxylates (APEs), and trialkylphosphates. Several of the compounds were detected only in the secondary effluent and not in the renovated water. A few others, Diazinon, clofibric acid, and tributylphosphate, decreased in concentration with soil passage, but were still detected in the renovated water. The APEs appeared to undergo rather complex transformations during ground filtration. They appeared to be completely removed with soil percolation during the pre-chlorination period, but after chlorination two isomers were found following soil passage while others were removed.

The results of these studies showed that SAT is effective in reducing concentrations of a number of synthetic organic compounds in the sewage water, but that the renovated water still contains a wide spectrum of organic compounds, albeit at very low concentrations. Thus, while the renovated water is suitable as such for unrestricted irrigation and recreation, recycling it for drinking would require additional treatment such as carbon filtration to remove the remaining organic compounds. The water would also have to be disinfected and reverse osmosis may be desirable.

CONCLUSIONS AND FUTURE PLANS

The results of the Phoenix studies show that the renovated water from the SAT projects meets the public health, agronomic, and aesthetic requirements for unrestricted irrigation, including vegetable crops that are consumed raw (Bouwer, 1982). The water also meets the standards for lakes with primary contact recreation (Matters, 1981). Potable use of the renovated water will require additional treatment, for example, activated carbon adsorption, reverse osmosis, and disinfection. Such treatment, however, will be more effective and economical for renovated water from a soil-aquifer treatment system than for effluent from a conventional sewage treatment plant.

In the Phoenix studies, secondary effluent was used because that was what the treatment plants provided. The secondary (biological) treatment step, however, is not necessary because the SAT system can handle relatively large amounts of organic carbon. Thus, where sewage effluent is to be used for a rapid-infiltration system, primary treatment may suffice (Carlson et al., 1982; Lance et al., 1980; Leach et al., 1980; Rice and Gilbert, 1978; Rice and Bouwer, 1983). Some additional clarification or lime precipitation of the primary effluent may be desirable, however, to reduce suspended solids and to improve the quality of the primary effluent. Also, chlorination or other disinfection would be much more effective after SAT than before.

The cost of putting partially treated wastewater underground and pumping it from wells as renovated water is relatively low, and SAT systems do not require highly trained operators. Thus, where land availability and hydrogeological conditions are favorable for groundwater recharge by surface spreading of wastewater, SAT can play an important role in the reuse and recycling of municipal wastewater.

The 40-acre system of the 23rd Avenue project could be expanded to 120 acres by also splitting the 80-acre lagoon east of the present 4-basin infiltration system into infiltration basins (the expansion is shown as the nine infiltration basins in Fig. 2). About twelve wells, located on the centerline through the entire project, would be necessary to pump renovated water at the same rate as the combined infiltration rate of sewage effluent in the basins. The capacity of the 120-acre system would be about 36,000 acre feet/year or about 32 mgd. The renovated water would be pumped into the nearby canal of the Roosevelt Irrigation District (RID), which, in turn, would let the city of Phoenix pump high quality groundwater from RID wells in the western part of the Salt River valley. This water would be discharged into the Grand Canal of the Salt River Project, which, in turn, would allow the city of Phoenix to divert an equal amount of water from the Arizona Canal through the Phoenix water treatment plants located on that canal. The water would then be used by the city of Phoenix for its expanding urban areas north of the Salt River Project. Compared to other alternatives, this would be the least expensive way for the city of Phoenix to get additional water (Bouwer and Chase, 1984). Realization of this project is being delayed by legal complications, including clarification of the legal status of sewage effluent and how the Groundwater Management Act affects pumping rights of renovated water from aquifers in Active Management Areas.

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Recharge Programs: A California Overview

Iris Priestaf, Ph.D.
David Keith Todd Consulting Engineers

Artificial recharge as a means of managing groundwater resources has been practiced in California since the late nineteenth century. The scope of artificial recharge, however, was not documented until the 1950's, when the California Department of Water Resources (DWR) conducted a comprehensive inventory of all artificial recharge activities in the state. The DWR identified 54 agencies involved in artificial recharge, and located 276 projects, concentrated in the San Francisco Bay Area, San Joaquin Valley, and Southern California (Richter and Chun, 1959; Richter, 1958). No recent surveys have been attempted that are comparable in scope. However, review of recent (post-1970) literature suggests that the practice of artificial recharge has expanded significantly since the 1950's to include more than 70 agencies and hundreds of projects.

The variety of recharge projects in California frustrates attempts at generalization; however, examination of selected recharge programs and the most prevalent methods (deep basins, shallow basins, and channel recharge) yields insight into some of the technical and environmental aspects of artificial recharge as now practiced in the state. Mention is made of multiple use of recharge facilities.

Deep Basins

Deep basins are widely used for recharge, particularly

in urban areas such as the Los Angeles metropolitan and San Francisco Bay areas where land for recharge is limited. Most deep basins, developed originally as gravel quarries, have a considerable capacity to store water, so many of the pits are also used for floodwater detention. The multiple use of deep basins--as sources of gravel, flood detention basins, and recharge basins--is advantageous, but at times the experience with deep basins has been problematic.

One aspect of most deep basins is their steep-sided form, typically not designed for artificial recharge, but inherited from their prior use. Research in the Santa Clara Valley suggests that steep side slopes maintain high infiltration rates (Scott, et al., 1974); however such slopes are subject to caving and erosion, and often must be recontoured or stabilized.

Maintenance of infiltration rates in deep basins has been a major problem. Infiltration rates have been high initially, but tend to deteriorate rapidly as organic debris and sediment (both from influent floodwater and erosion of basin sides) build up on the basin bottom and lower slopes.

To maintain or restore infiltration rates, several means have been used. Mechanical removal of sediment has had limited success--limited largely because access by earth-moving equipment is hampered by steep slopes and by standing water in the basin bottoms. Anaheim Lake, operated by the Orange County Water District (OCWD), is an exception. The lake recharges imported water and floodwater that has been routed through settling ponds. Despite relatively

clean inflow, initial infiltration rates of about six feet/day declined to two feet/day, largely because of wave erosion of basin side slopes and subsequent silt deposition. However, the basin's relatively low slopes allow regular scraping, which restores infiltration rates to a long-term average of three feet/day.

Nevertheless, the foremost practice to maintain infiltration is limitation of inflow to relatively silt-free water, either through bypassing turbid flows, filtration or settling. For example, the Alameda County Water District (ACWD) bypasses water exceeding about 500 mg/l, but is now installing filter galleries in the Alameda Creek channel in order to capture and recharge some of this water. Similarly, the Los Angeles Flood Control District (LAFCD) uses coagulants in the feeder channels to their deep basins wherever possible.

Shallow Basins

Shallow basins probably are the most frequently used means of artificial recharge in California, with extensive application wherever surface infiltration rates permit. Their use is common not only in urban settings, but particularly in rural areas where large parcels of land can be devoted to recharge.

An established principle of basin design is that basins should be arranged in series, to allow use of the uppermost basin for settling and to allow for rotating use. Beyond that, the ideal design of shallow basins is not a subject of

agreement. Given the limitations of the shape and slope of a suitable land parcel, most recharge basins are roughly square, to maximize the ratio of the wetted to gross area. Such ponds rely primarily on infiltration through the basin bottom despite concomitant problems with sedimentation. An alternative design maximizes the area of basin side slopes rather than simple wetted area (Scott, et al., 1974; Todd Engineers, 1984). In this design, basins are long and narrow, separated by berms, with minimal bottom area and maximal area in slopes. The ratio of wetted to gross area is lower, but this is compensated by higher long-term infiltration rates through the sloping basin sides.

In planning for artificial recharge of Colorado River water in the arid Coachella Valley, proposed recharge basins were designed to be relatively deep, to take advantage of the positive relationship between depth of water(hydraulic head) and infiltration rates. In addition, a deep basin has a small surface area, so evaporative losses and wind-generated waves are minimized. Control of wave action is considered to be particularly important, as infiltration tests at the site indicate that the primary source of clogging sediment is wave-induced erosion of basin sides (Tyley, 1973). The plan also suggested use of filter beds of pea gravel on the basin bottoms.

The LACFCD's Rio Hondo spreading grounds are a well-known example of a shallow basin facility, including 45 roughly rectangular basins arranged in series along the

lined Rio Hondo channel. The spreading grounds recharge imported water, treated wastewater, and local surface water diverted from the Rio Hondo channel.

As with deep basins, maintenance of recharge rates is the prime task. To reduce sedimentation, water diverted for recharge is not permitted to exceed a silt content of 500 mg/l. This quality of water is achieved primarily through treatment with flocculants in a settling basin; although other agencies reject flocculation as too expensive, the Los Angeles district considers it crucial, to the extent that almost all of their major facilities have flocculation stations.

In addition, the Rio Hondo basins are operated on a 21-day cycle of flooding, draining, and drying. The drying of the ponds maintains aerobic conditions, discourages proliferation of insects and algae, causes cracking and curling of clayey bottom sediments to improve permeability, and allows access by equipment for periodic silt removal. This operation and maintenance program results in a recharge rate of about 2 foot/day under wetted conditions.

Channel Recharge

Efforts to increase natural recharge from stream channels generally expand the wetted area, prolong the period of inundation, or enhance the infiltration. The means to accomplish such an increase in recharge can be relatively simple. For example, numerous rural water districts rely on dry-season releases from an existing

operating schedule, facility size, and the facility's ratio of land to water (Scott, 1974). Size and the land:water ratio are particularly important in determining whether recreation is water-based (for example, fishing and boating), or oriented toward land (picnicking and sports).

Anaheim Lake in Orange County is a successful multipurpose facility, combining artificial recharge with a water-based recreational use. The lake is leased by the OCWD to a private concessionaire for a "put and take" fishing operation that offers rainbow trout to more than 100,000 anglers a year (OCWD, 1983). Fishing is limited to a small shoreline area, and is restricted to the October-May season, allowing regular maintenance of the basin in the summer months. Accordingly, the recreational use interferes little with recharge operations; in fact, because of supervised public access, vandalism of the facility is minimal.

Development of the Alameda Creek quarry area exemplifies a joint artificial recharge and recreation project, where recreation is more than just incidental. The Alameda County Water District's deep basins and channel recharge facilities are clustered in an 800-acre site, which includes existing parkland. In many ways, the site is ideal for a range of recreational uses: it is large, with a relatively high land:water ratio, and includes a dozen ponds of varying size and shape, some of which are bordered by riparian woodland. The recharge ponds generally are operated at capacity, and are not often drawn down.

Currently, the area offers a variety of diversions, including fishing, model boating, picnicking, and sports.

In recognition of the area's regional recreation significance, the ACWD has agreed with local city and regional park district officials to develop further the quarry site as a joint artificial recharge facility and regional park, including improved land facilities, an increased fishery, and creation of a large recharge basin/sailing lake from several small existing pits.

The joint use agreement places certain restrictions on the ACWD (ACWD, 1975); namely, the ACWD must inform the park district of operations affecting the recreation, and will restrict use of heavy equipment to days other than weekends and holidays. Chemicals will not be used in the water without mutual consent. However, the ACWD is not limited in regulation of basin water levels, beyond giving the park district written notice and the opportunity to respond before acting. In turn, the ACWD enjoys tangible benefits; costs of acquiring land are shared, and the park district shoulders almost all responsibility for security, claims of liability, and property damage insurance.

The future holds the promise of continuing expansion of artificial recharge in California. Each agency mentioned above has definite plans for improvement or expansion of their artificial recharge programs. Both the Los Angeles and Orange County districts plan to acquire and adapt additional gravel quarries to recharge purposes; the

Alameda County Water District, which has reached the limits of available land, plans to install filter gallery and recharge well systems.

One ongoing change has been the increased involvement in artificial recharge of the California Department of Water Resources. One aspect of the State Water Project is the Groundwater Basin Storage Plan, involving conjunctive operation of surface water facilities (Lake Oroville and the California Aqueduct) and groundwater basins. The program involves storage of surplus project water in groundwater basins adjacent to the aqueduct, and subsequent recovery of stored water in drought years, when the State Water Project is otherwise unable to meet its contractual obligations. Thus far the program has moved through reconnaissance studies identifying 13 potential groundwater storage basins, to feasibility studies in seven selected basins, and two successful demonstration programs.

However, the Groundwater Basin Storage Plan was bound in a comprehensive water plan to the controversial Peripheral Canal; although the plan, as Senate Bill 200, won the approval of the state legislature in 1980, it met with resounding defeat in a popular referendum in 1982. As a consequence, water planners have retreated from "big" plans, so now the State Water Project is developing in increments, with an eventual goal of increasing the system's capacity to divert wet-season flows for storage in groundwater basins.

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LUNCHEON ADDRESS

City of Phoenix
Cave Creek Recharge
Project: Technical Aspects

BY

Mario R. Lluria
Senior Project Hydrologist
Cella Barr Associates

WELCOMING

Ladies and gentlemen, fellow hydrologists:

I want to welcome you and thank you for your attendance at this luncheon hosted by Cella Barr Associates.

For those of you that may not know, Cella Barr Associates is a multidisciplinary engineering firm which among other functions offers hydrological services.

Mr. Larry Onyskow, our chief groundwater hydrologist and project manager was not able to attend this meeting and asked me to address you about the City of Phoenix Cave Creek Recharge Project which CBA is designing.

INTRODUCTION

In January of 1984, the City of Phoenix contracted the services of Cella Barr Associates to investigate various techniques of recharging excess CAP water in a ten mile stretch between the Granite Reef Aqueduct and the Arizona Canal.

The availability of CAP water presented our municipality with the challenge of finding an appropriate means of storing the water until needed.

The space available for underground storage of the water was limited by the fact that the City of Phoenix wanted to retain primary access. This imposed a very difficult restriction.

There was also a time constraint, the City wanted to have an adequate recharging operating system within a period of two years, and the water was to be recharged during the period of low demand in the winter months to be recovered by pumping during the high demand period in summer.

Last, but not least, was the economic factor. The City needed a cost-effective system which would not impose an excessive cost burden for the supply and marketing of this water to its customers.

For all these reasons, the City determined to take an engineering approach to the recharge of the excess CAP water.

Cella Barr planned a systematic, step wise approach in solving the possible problems that could arise in the study and design of this recharge system.

Although, groundwater recharge has been practiced extensively both in the United States and abroad for agriculture, salinity control and urban supply, it has not been frequently used intensively or in the magnitude of that desired by the City of Phoenix. Present projections call for the injection of 55,000 acre-feet of CAP water to an aquifer system each year.

Local conditions are different for each region and area and these have to be addressed individually to accomplish an adequate and efficient recharge system.

The feasibility study completed in 1984 considered various influential factors.

We looked at the local geology in the Cave Creek area to try to establish the common and the unique physical characteristic of the various lithologic units which are pertinent to the behavior of the aquifer or aquifers of the system. This was accomplished by an examination of all the published and unpublished reports of this area and by a thorough compilation and examination of all the lithologic information available from the wells of the study area and its surrounding region.

We examined the local groundwater hydrology to try to determine the type of aquifer system that is present in the Cave Creek area and to evaluate its capacity potential and possible response to the additional CAP water. We investigated the types of aquifers: confined, semi-confined, unconfined, perched; that could be expected, and where in the stratigraphic section could they be located. The various aquifer parameters were estimated using several techniques in order to attempt to predict both the areal and local transmissive and storage properties of the different hydrogeologic units. The average yield of production wells in the area, as well as the water table declines were established by statistical data obtainable.

The possible contribution or influence of the surface run off for the recharge process was investigated.

The quality of the groundwater in this area was determined from available data and the mean and range of concentration of the major and influential components was established. This was important in order to determine the background, or baseline, concentrations for comparison with the injected CAP waters. It showed if any areas had any higher than standard permissible composition, and of which components; and defined regional concentration zonation patterns and gradients.

The various methods of recharge:

a) deep well injection

b) surface impoundment by using constructed infiltration basins or utilizing available stream channel space

c) and combination of all, were evaluated by using the local geologic and hydrologic conditions determined by this study and taking into account the time, space and economic limitations.

The surface land ownership as well as the location of landfills was examined to evaluate possible permissible site for infiltration basins.

The history of subsidence effects from the pumping of groundwater from this area was briefly surveyed to establish if major problems existed and if they did, could they pose a problem or a benefit to the infiltration basins.

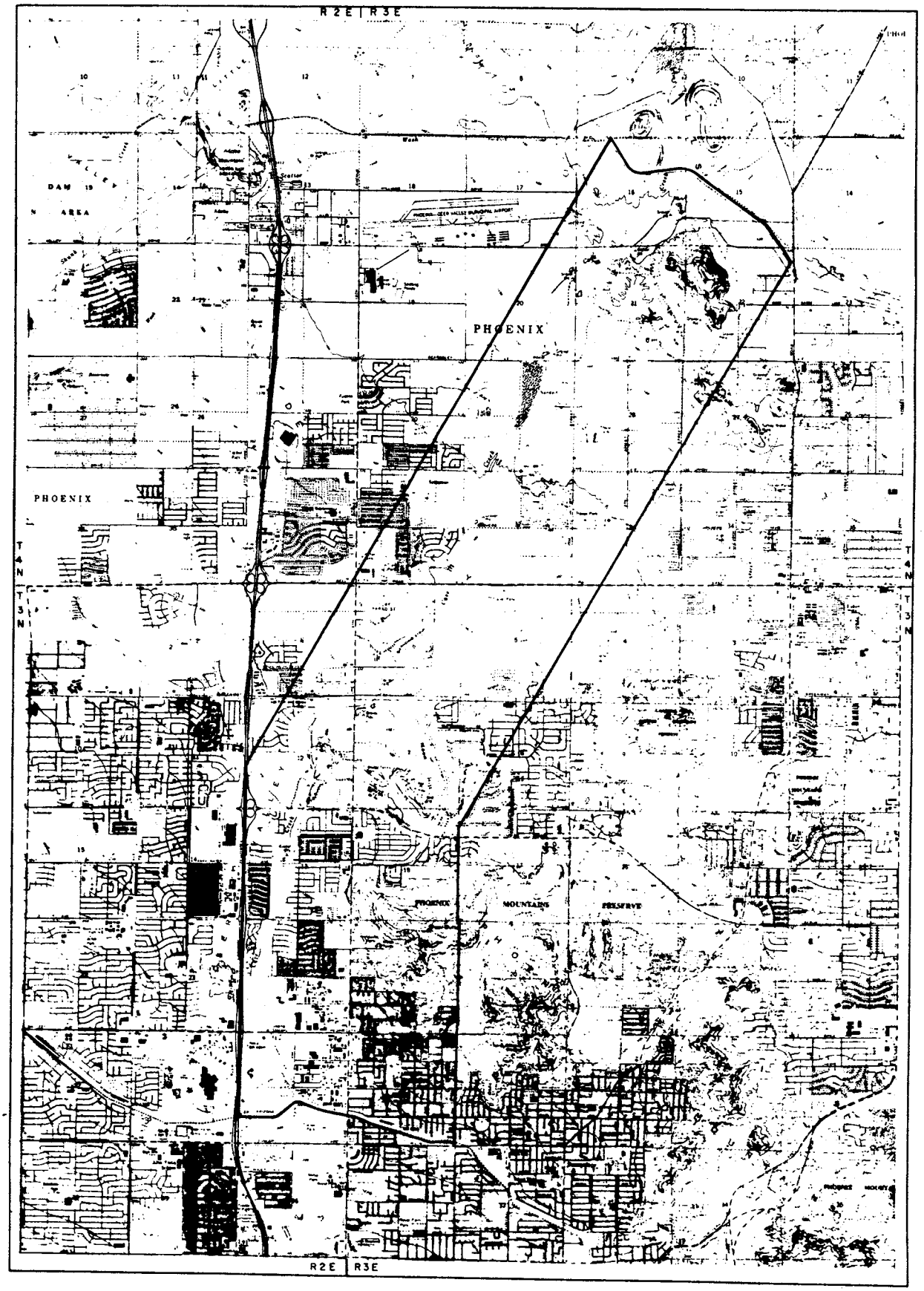
A case history survey of similar groundwater recharge projects in the United States was undertaken in order to examine the design and procedures used by others that may be applicable to the Cave Creek situation. As a result of this study members of the CBA technical team accompanied by Mr. Bill Chase of the City of Phoenix Managers Office inspected the facilities of the Hueco Bolson Recharge Project of the City of El Paso, Texas. Geologic and hydrologic conditions in the Cave Creek area are in many ways similar to those of the El Paso project.

LOCATION

The project area is located in the northern part of the City of Phoenix, just east of Interstate Highway 10 and occupies approximately 20 square miles (Figure 1).

During the initial stages of this project, it became apparent that, to provide an accurate picture of the local aquifer system, the area under investigation would have to be expanded.

This is the total area shown on this illustration and has a surface extension of approximately 90 square miles. We will refer to this as the "study area" or Cave Creek area.



EXPLANATION

—— Denotes study area boundary

1225 Contour interval is 5 feet and multiples thereof

FIGURE 1

Topographic Map of the Cave Creek Study Area

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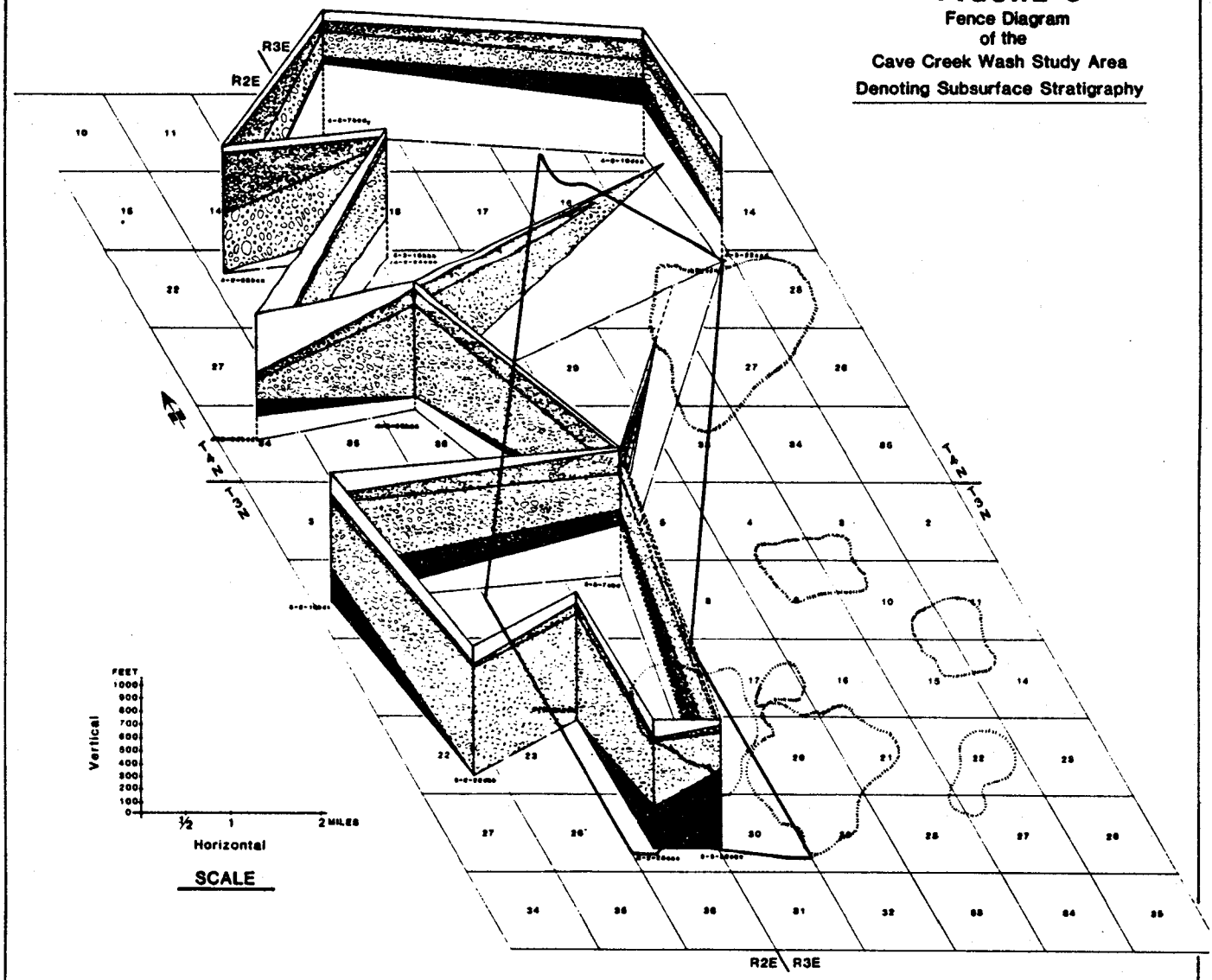
The aquifer system for the study area is hosted in three major units which reflect the three last phases of the Basin and Range tectonic event in this area. Up the section these are the Lower Conglomeratic Sand and Gravel Unit, the Middle Fine Grained Unit and the Upper Alluvial Unit. The areal distribution of these units is shown in Figure 3.

The age of these sediments is Late Miocene to Recent. In the study area the maximum thickness of this whole section is 1,600 feet.

The examination of 107 lithologic logs from the study area showed the principal geohydrologic characteristics of the three units. These are shown on Table I.

FIGURE 3

Fence Diagram of the Cave Creek Wash Study Area Denoting Subsurface Stratigraphy



EXPLANATION

- Denotes study area boundary
- Upper Sand and Gravel Unit
- Sticky Brown Clay Layer, Denotes Top of the Middle Fine-Grained Unit
- Middle Fine-Grained Unit
- Lower Conglomerate Unit
- Denotes correlation between units, dashed (——) where inferred
- Denotes generalized mountainous areas
- (example) Denotes legal description of well's location

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TABLE I

STRATIGRAPHIC UNITS HOSTING THE AQUIFERS OF THE CAVE CREEK AREA.

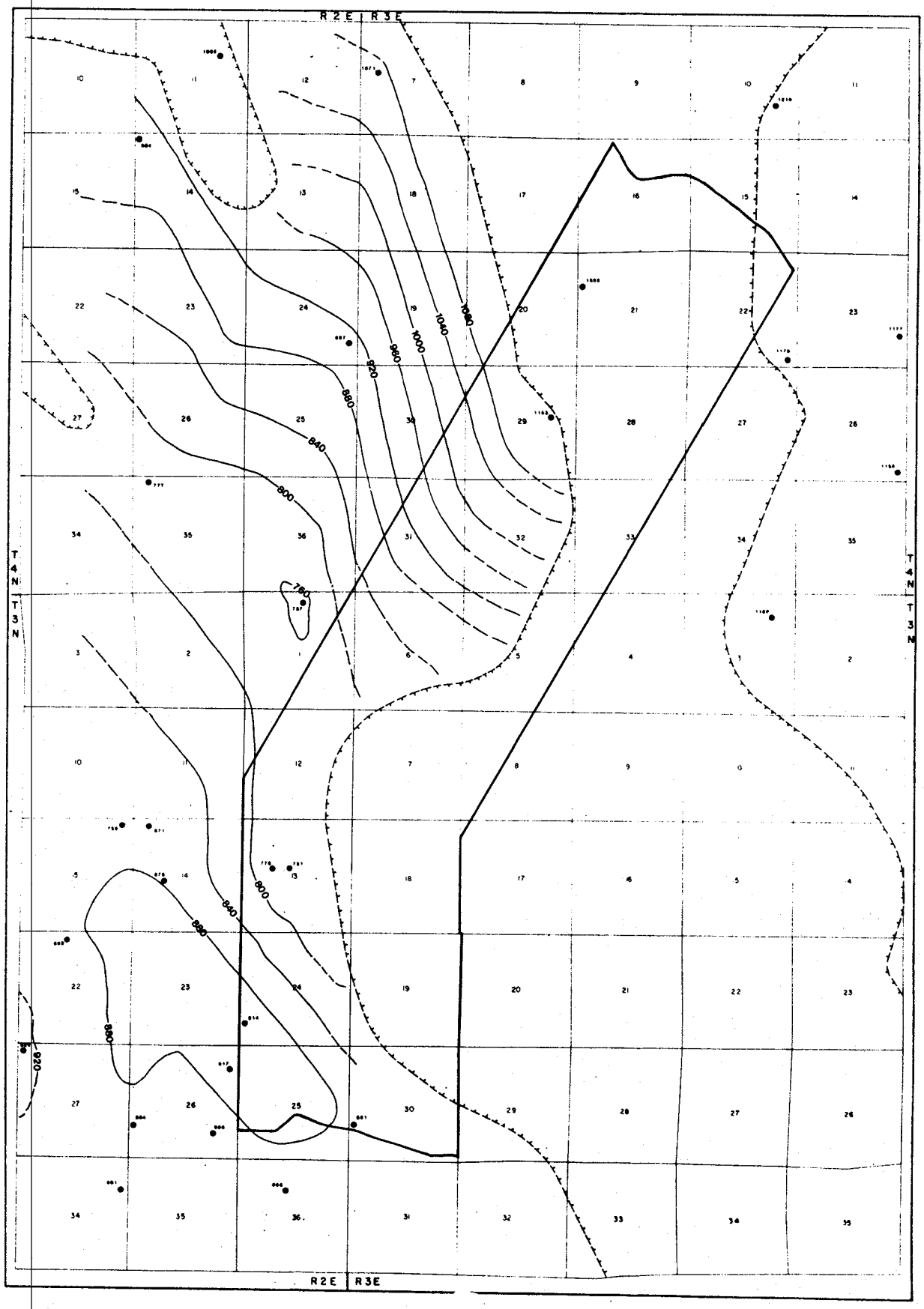
UNIT	PREDOMINANT LITHOLOGY	AGE	TYPE	MEAN THICKNESS(ft)	TYPES OF AQUIFERS
Upper Alluvial Unit	Unconsolidated sands and gravels	Pleistocene	Alluvial	130	Unconfined Perched
Middle Fine-Grained Unit	Clays, silts evaporites	Pliocene-Pleistocene	Lacustrine	590	Semi-confined to confined
Lower Conglomerate Sand and Gravel	consolidated sands and gravels, basalts in upper section	Miocene-Pliocene	Fanglomerate	Unknown	Confined

HYDROLOGY

Numerous wells have been drilled in this area and are in use for urban and industrial needs. The movement of groundwater in the study area is towards a trough in its central part, with a limited zone of outflow to the west (Figure 4).

Groundwater table decline averaged 4.9 ft/yr. from 1945 to 1983. The present rate is 1.9 ft/yr.

Mean and range values for the transmissivity, specific capacity and specific yields for the Cave Creek study area are shown in Table II.



EXPLANATION

——— Denotes study area boundary

—800— Water table elevation, contour interval is 40 feet (dashed where uncertain)

● 761 Well location, number indicates 1982-83 water level measurement

⊥⊥⊥ Denotes approximate boundary of aquifer

(Data obtained from ARIZONA DEPARTMENT of WATER RESOURCES/BASIC DATA and U.S. GEOLOGICAL SURVEY.)

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FIGURE 4

Water Table Elevation Contours for the Cave Creek Study Area

TABLE II

Aquifer Parameter	Mean	Range
STUDY AREA		
Transmissivity (gpd/ft)	30,000	5,000 - 100,000
Specific Capacity (gpm/ft)	17.8	0.7 - 72
Specific Yield	0.09	0.5 - 0.16
PROJECT AREA		
Transmissivity (gpd/ft)	68,000	5,400 - 144,000
Specific Capacity (gpm/ft)	34	2.6 - 72
Specific Yield	0.10	0.5 - 0.15

WATER QUALITY

The quality of the groundwater encountered at any location within the Salt River Basin depends primarily on the subsurface lithology and the physico chemical conditions prevalent in the aquifer in the immediate vicinity of the well. The most common problems encountered locally include large concentrations of fluoride and nitrate, hardness and total dissolved solids. Within the Cave Creek area, however, the overall quality consideratios center around high levels of nitrate and hardness.

The contribution of these two components to the groundwater produced can be reduced or even eliminated by isolating the donating aquifers in the wells. This is common practice in new City of Phoenix wells. We will be recharging into an aquifer that do not contain high concentration of either one.

The concentration mean and range for some of the more pertinent groundwater components of the study area and a comparison with the expected CAP water are contained in Table III.

TABLE III

CONCENTRATION OF SOME OF THE GROUNDWATER COMPONENTS OF THE CAVE CREEK AREA AND OF EXPECTED CAP WATER

(All concentrations are in mg/l)

Component	CAP Water	CAVE CREEK GROUNDWATER Concentration Mean	Concentration Range	Standard Deviation
Total Dissolved Solids	696	587	235- 1245	244
Nitrate	0.7	9.1	0.9- 19.0	5.3
Hardness	335	247	60- 548	123
Sulfate	310	56	8- 247	49
Sodium	110	60	30- 289	43
Turbidity*	2.0	0.15	0.08- 0.27	0.05
pH	7.8	8.0	7.7- 8.2	0.2

* In NTU Units

SELECTION OF RECHARGE METHOD

A detailed technical and economic examination of the three most commonly used methods of artificial recharge was undertaken to determine the favorability of using one or a combination of them. These methods are:

1) streambed recharge
2) infiltration basins (Figure 5)
3) injection wells

Of prime consideration was the problem of what will happen to the recharged water once it left the surface, that is the problem of control of the water. The time and cost of construction and operation were also important determinant factors.

A comparison of the major advantages and disadvantages of the three methodologies is shown on Table IV.

The results of the economic study indicated that the total cost per acre-foot recoverable for each of the methods was relatively close.

These are in 1984 dollars:

$115/acre-foot for the streambed recharge
$118/acre-foot for the infiltration basin
$116/acre-foot for the injection well

A decision on which method to employ was then based on technical considerations and land availability.

For the latter, and if we assume a realistic hydraulic loading rate of 245 feet/year, the area required for infiltration basins to recharge 55,000 acre-feet/year would be 225 acres. This would be land in a well developed urban area.

For the case of streambed recharge, a retaining structure such as a dam would have to be constructed on Cave Creek.

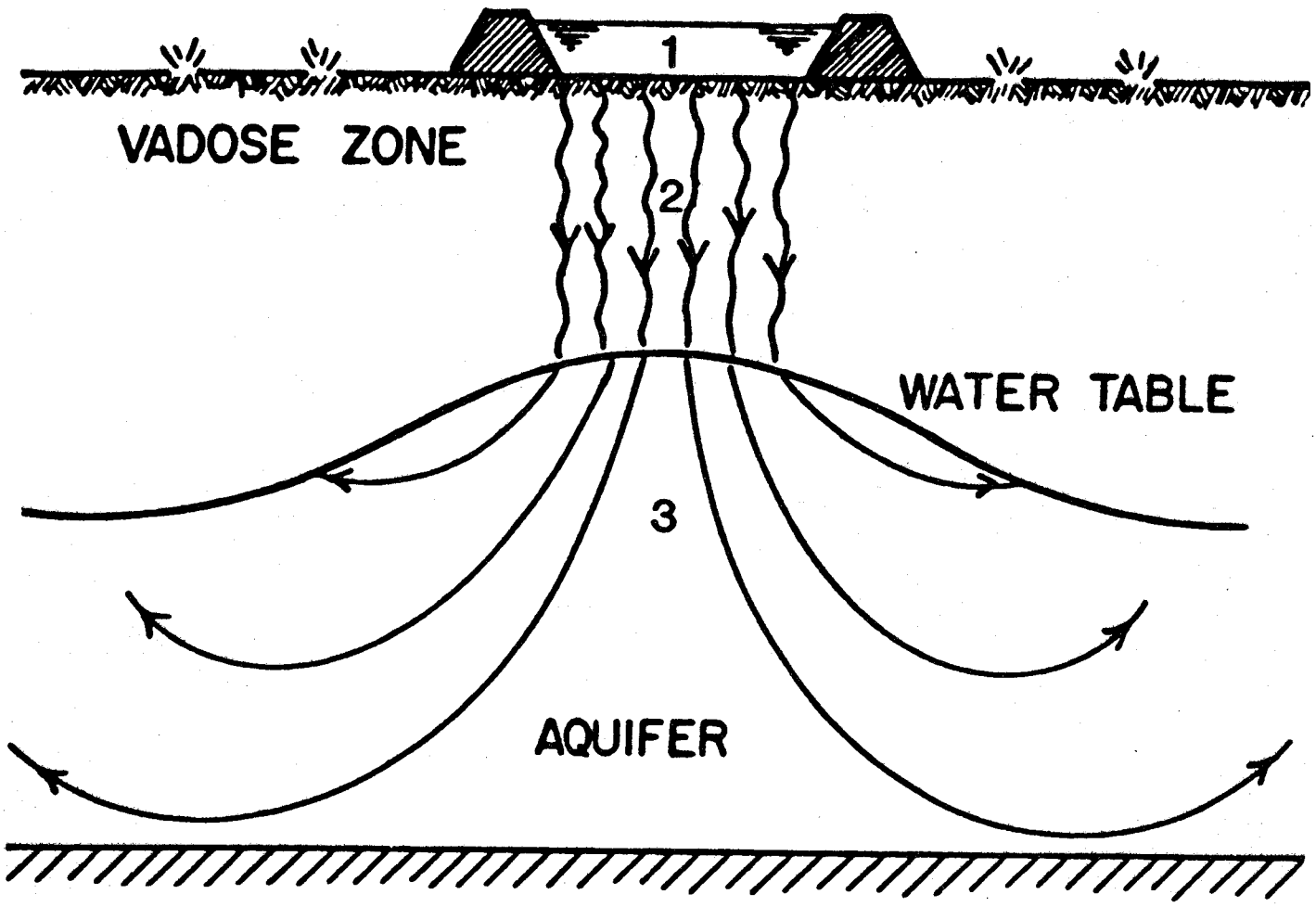
The rate of recharge using infiltration basins is considerably slow through the transmission zone and for both this method and the streambed recharge the water will go directly to the unconfined aquifer that in this area has the water quality problems previously mentioned. In addition, you loose control due to the presence of clay lenses in the lithologic sequence and permanent quantities are also lost to rewetting of clays and evapotranspiration.

By using injection wells the water can be recharged very rapidly and there is fairly good control of where the water is going. Most important the injection wells are also production wells.

After careful examination of all the local conditions, a decision was taken to use deep well injection.

A pilot study using one injection well in the project area was recommended and this phase is in progress at present.

The Three Processes Involved In Recharging Surface Water to the Groundwater System



(Taken from Bouwer, 1978)

Schematic of groundwater recharge system showing: 1) infiltration basin, 2) wetted zone, 3) groundwater mound and flow lines within the aquifer.

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Figure 5

TABLE IV

COMPARISON OF THE ADVANTAGES AND DISADVANTAGES OF THE THREE MOST COMMONLY USED METHODS OF ARTIFICIAL GROUND WATER RECHARGE, FOR THE CAVE CREEK AREA.

ADVANTAGES

Streambed Recharge	Infiltration Basins	Well Injection
1- Small capital investment	1- Low initial start-up costs	1- Water losses are low (90-95% recovery)
2- Minimal maintenance cost	2- Low maintenance costs	2- Very little property need be acquired
3- Lack of significant water quality problems	3- Loss severe water quality constraints	3- The recharge wells can be production wells.
	4- Recovery using shallow wells	4- The recharge wells can be constructed in urban areas.
		5- Cycling time to clean the wells is minimal

DISADVANTAGES

1- Loss of water to wetting of clays	1- Requires considerable land	1- The injected water must be of adequate quality
2- Environmental control problems	2- Basin clogging with fines	2- Organic slimes may clog the well.
3- Creating a shallow perched aquifer	3- Flooding of gravel operations	3- Air bublles may reduce effective permeability.
4- Increased seepage through landfills which would contaminate the recharge water.	4- Possible formation of perched aquifer	4- Chemical precipitates may obstruct.
5- Flooding of sand and gravel operations.	5- Insect infetation	
	6- Water losses to evaporation, transpiraton and clay absorbtion.	

THE PILOT STUDY

Geology

The recharge well to be used in the pilot study is City of Phoenix well number 274 located on Section 24 T3NR2E. For those of you from the Phoenix area or familiar with our city, it is located less than one mile northeast of the Metro Center Mall. It is in the floodplain of Cave Creek.

This well has been recently completed and equipped. An 18 inch pilot hole was drilled to 1,549 feet and the hole reamed to 28 inches to a depth of 1,390 feet. Screen has been set from 960 feet to 1,390 feet or a thickness of 430 feet. This interval hosts a confined aquifer as we shall see.

Figures 6 and 7 show the reverse circulation rig used in the drilling of well number 274.

The stratigraphy intersected by the drilling is as follows:

0 - 380'	The Upper Alluvial Unit: unconsolidated sand and gravels.
380' - 760'	The upper member of the Middle Fine Grained unit predominently clay, silt and silty sand with minor gravel.
760' - 960'	The lower member of the Middle Fine Grained unit: predominently clays, silt and evaporites.
960' - 1390'	Basalt, vesicular, fractured overlying andesite tuffs that grade into bentonitic clays down the section.
1390' - 1540'	Clays, bentonitic, that grade into a medium to coarse sand at the base.
1540' - 1549'	Pinal schist/Precambrian in age, mostly chloritic and the floor of the basin in this area.

The water table was intersected at 350 feet.

The aquifer to be recharged consists predominantly of fractured basalt in this area. The basalt which grades down section into andesites with some interbedded clays rests here in the clastic sediments of the Lower Conglomeratic Sandstone and Gravel Unit, but also laterally interfingers with the clastic sediments of this Lower Unit in other parts of the Cave Creek area. The basalt has adequate primary porosity and permeability, especially in the uppermost flow units where it is scoracious. Also, it's secondary or open fracture permeability is favorable for transmission.

Observation Well

To assist in determining the local aquifer parameters from a pumping test and principally to observe the transient effects of the injection an observation well will be constructed adjacent to the recharge well.

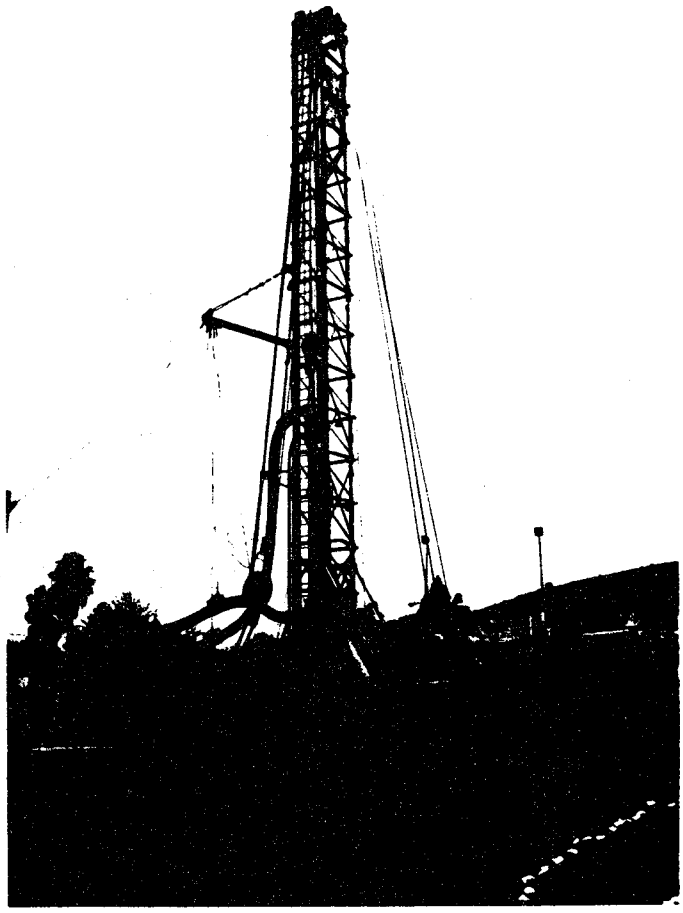


Figure 6 - Reverse circulation rig drilling. City of Phoenix Well Number 274 that will be used for recharge.

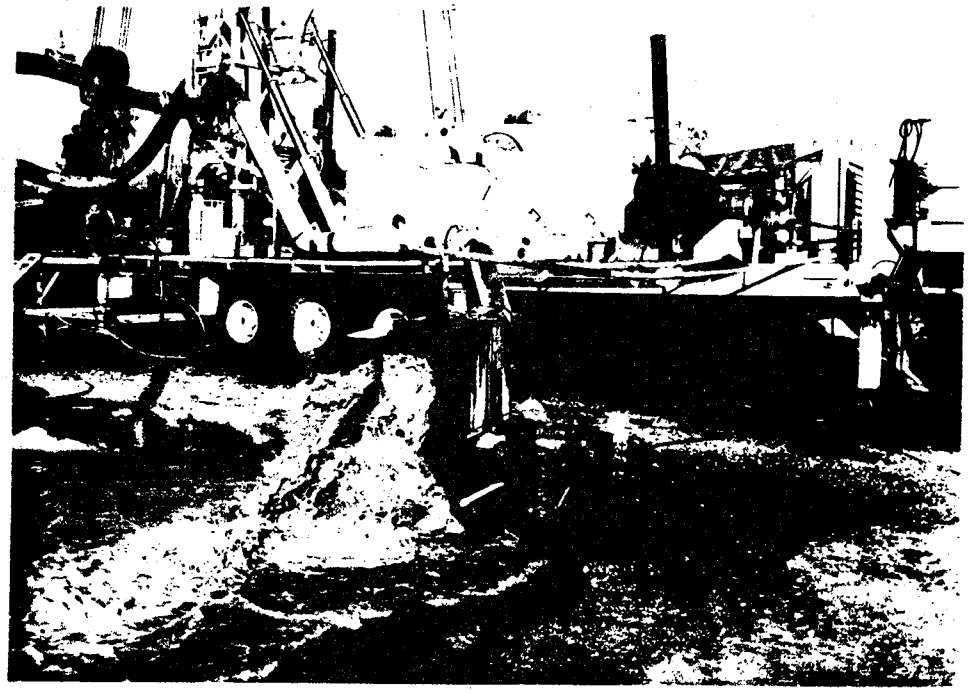


Figure 7 - Wedge sampler used to collect rotary cuttings for the City of Phoenix Well Number 274

The design of the observation well proceeded through several stages.

The first design consisted of several observation wells set radially from the injection well.

One alternative consisted of a "Cluster" of four wells, one fully screened well and three with piezometers set at three different depths.

Another design consisted of two wells one fully screened well, the other well with a set of "four nested" piezometers placed at various depths in the various hydrogeologic units.

Economic considerations did not permit the use of these multi-well design, so we first looked for alternate injection sites, where a usable City of Phoenix production well could be used for recharge and such that another well was located a reasonable distance away to be used as an observation well.

Such a setting appeared to be present at the Deer Valley Filtration Plant. However, on site inspection revealed that the separation between the possible recharge well and the well that could be used for observation was in excess of 1,000 feet (Figure 8).

A simple recharge time - well separation study was carried out using a simple Theis analysis.

Various magnitudes of the transmissivity and storativity used for these computations were based on lithologic analysis of the wells in the area. We considered a rise of 15 feet to be the minimum permissible deflection of the piezometric level that could be reliably detected over local background noise, due to seasonal fluctuation, changes in the pumping regimes, etc.

As you can see from Figures 9 and 10, it would take 1.8 years or 3.6 years to observe this deflection at 1,000 feet so the time involved in the injection would be excessive and the amount of water to be injected would be too costly.

A decision was then taken to use a single observation well located between 50 and 100 feet from City of Phoenix Well #274.

This will be sealed above the basalt and will be screened from 960 to 1,390 feet (Figure 11).

Pumping Test

A continuous recorder observation station will be installed in City of Phoenix well #274 to monitor the water level changes. This information will give background data of the local fluctuations to assist in interpreting the build-up during the recharge.

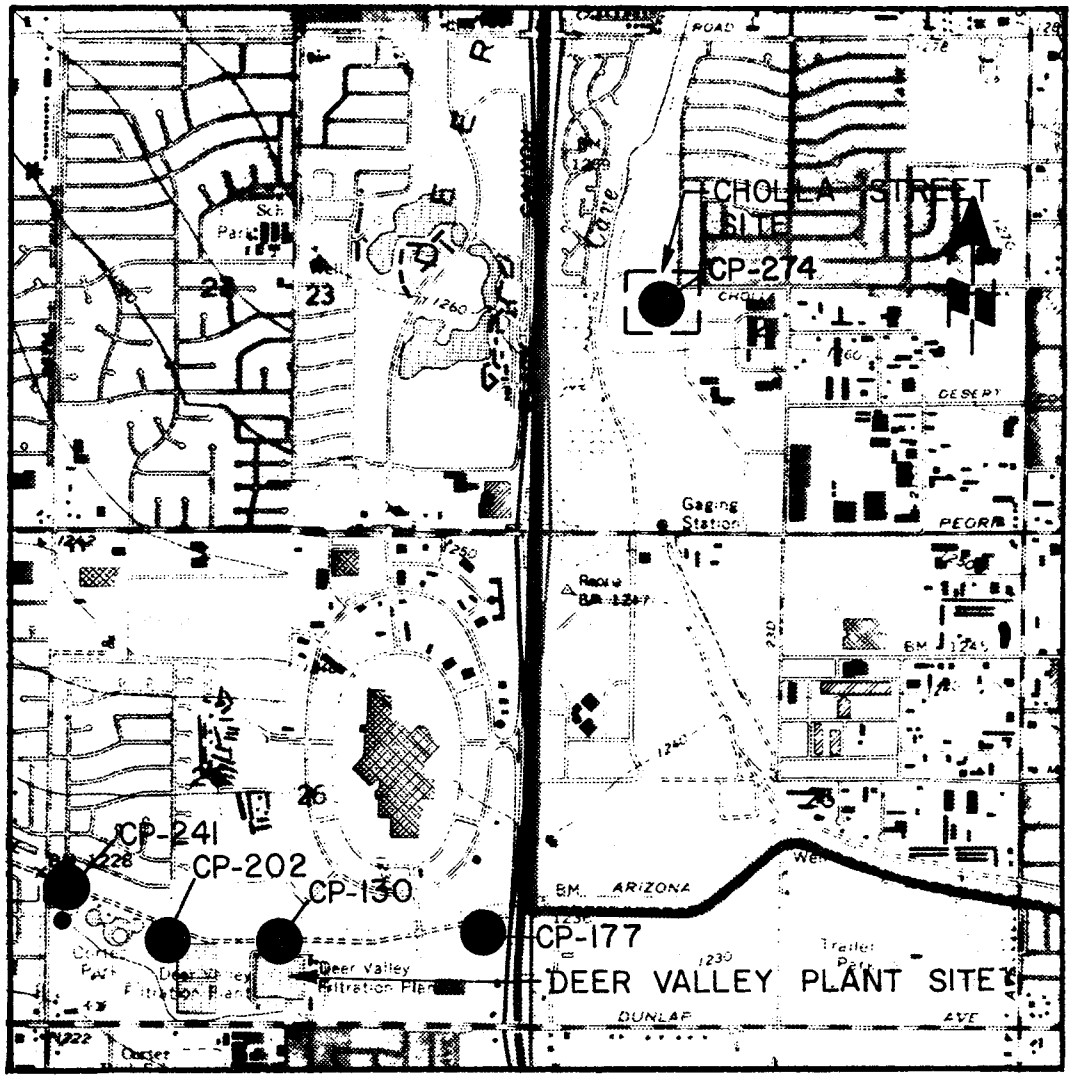
EXPLANATION

- ⊙ CITY OF PHOENIX WELL
- ● ABANDONED & BURIED WELL

SCALE: 1:24,000

Figure 8

LOCATION OF WELLS IN THE CHOLLA STREET AND DEER VALLEY PLANT SITES



CELLA BARR ASSOCIATES
5062 N. 19th Avenue,
Phoenix, Arizona 85015
(602) 242-2999

Figure 9

RECHARGE TIME VS. OBSERVATION WELL DISTANCE

CELLA BARR ASSOCIATES
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Phoenix, Arizona 85015
(602) 242-2999

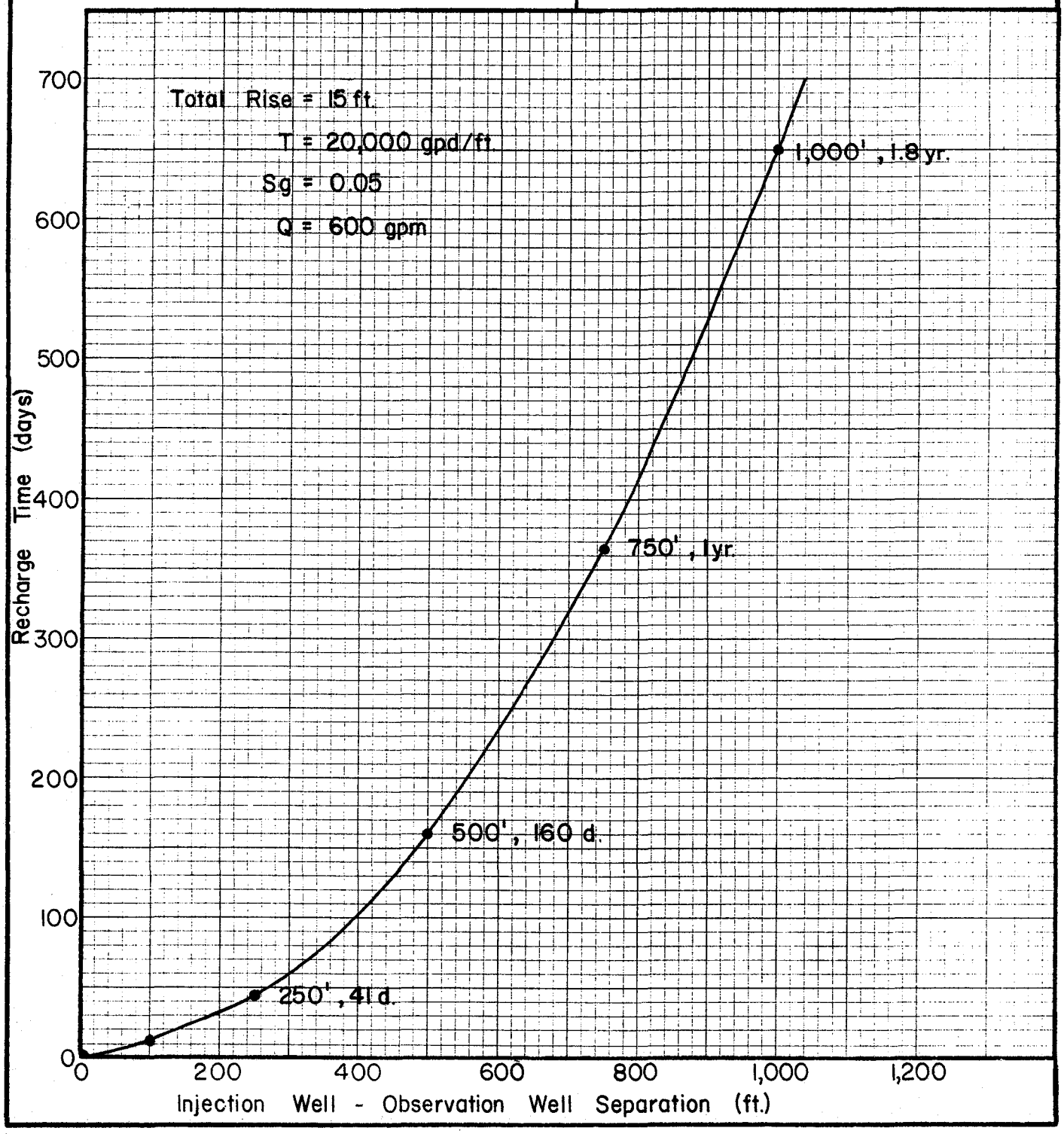


Figure 10

RECHARGE
TIME VS. OBSERVATION
WELL DISTANCE

CELLA BARR ASSOCIATES
5062 N. 19th Avenue,
Phoenix, Arizona 85015
(602) 242-2999

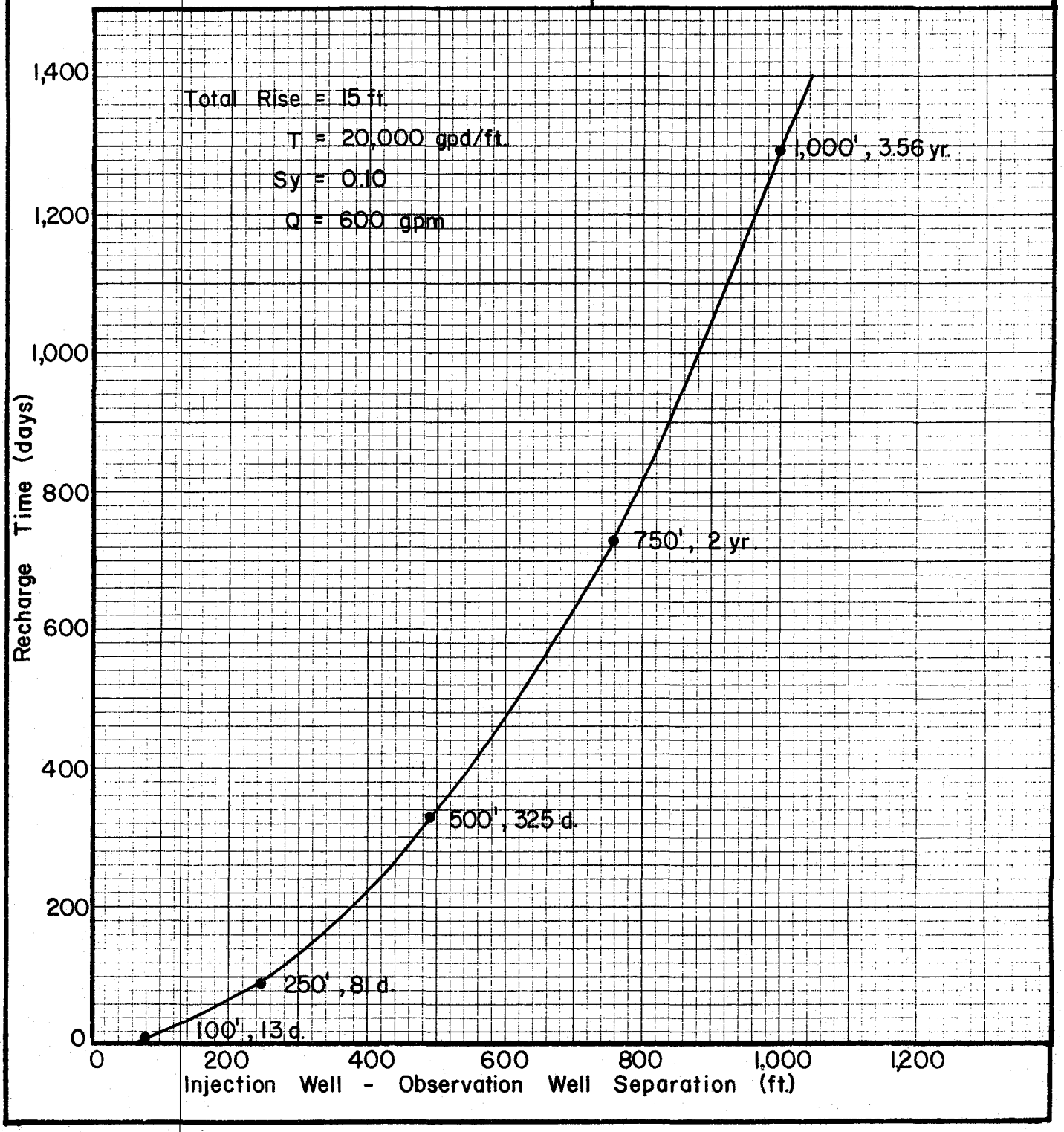
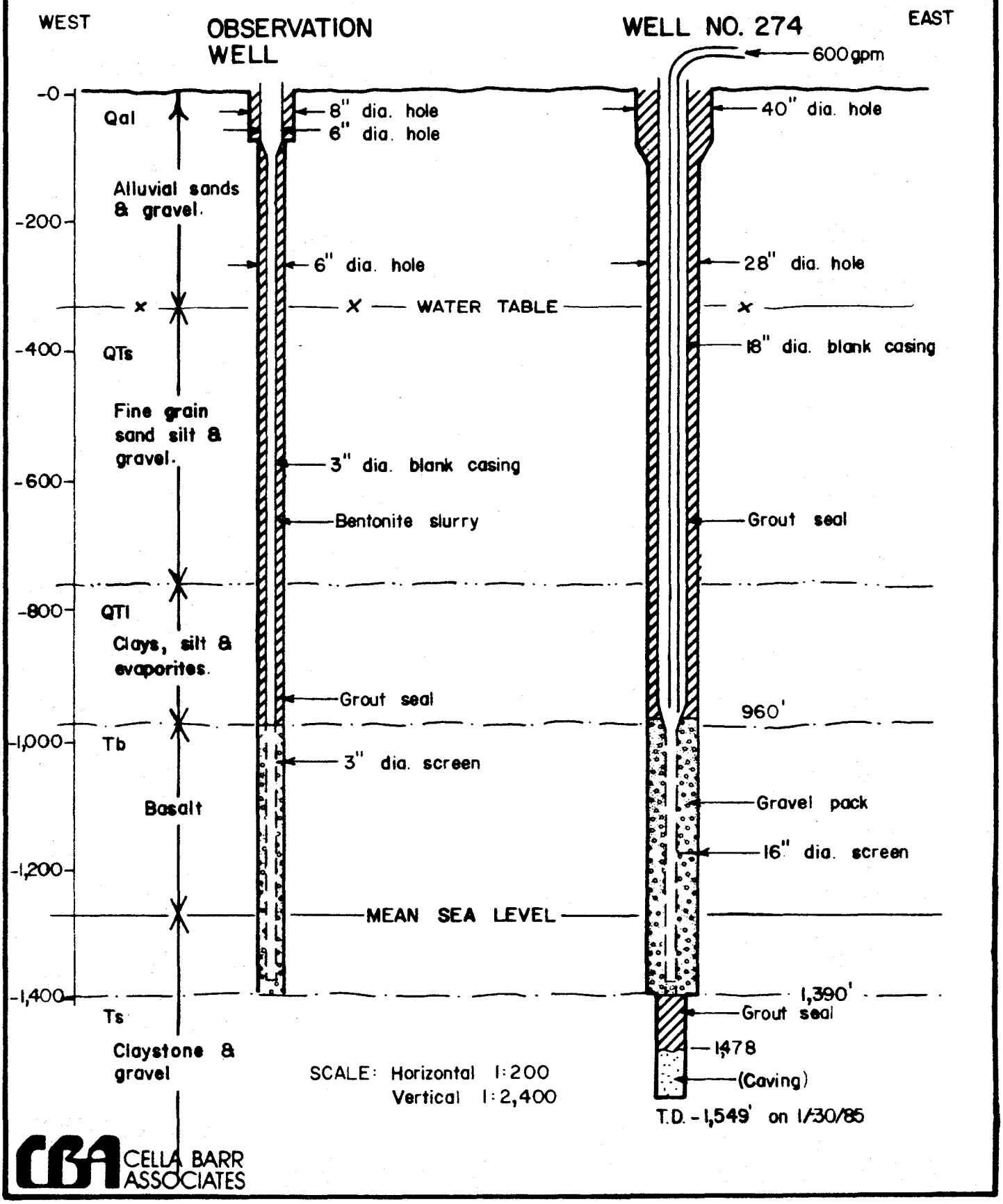


FIGURE: 11
CITY OF PHOENIX
CAVE CREEK RECHARGE PROJECT



A continuous rate pumping test will be carried out at the completion of the observation well to establish the local transmissivity and storativity values of the aquifer. This will also assist in estimating the rate of recharge, which in similar situations, like in the Hueco Bolson Project, should be about one half of the production rate of the well.

Water Quality Monitoring

A restricted groundwater sampling survey of wells in the vicinity of the recharge well will be undertaken before the recharge starts. This survey will establish the local background of the water quality in the area of influence of the injection.

Samples will also be taken during the period of recharge and during the recovery period to study any possible effects in the composition of the waters and of physico chemical parameters, such as the temperature, the pH, the Eh and conductivity.

Modeling

All the hydrologic and geologic data acquired to this point will be utilized for numerical model simulation to calculate the expected impacts on the local aquifer.

The results of the modeling will be useful for planning subsequent phases of the project and securing the necessary permits.

INJECTION TECHNIQUE

Since the main problem of artificial recharge by deep injection wells has been the generation of a zone of reduced permeability around the well due to:

a. introduction of fine particles into the formation,
b. introduction of organic matter and bacteria,
c. introduction of air.

Measures will be taken to avoid or minimize these:

The recharged water will be filtered, it will be treated, at least chlorinated, and the problem of air entrainment will be minimized by employing a system similar to that being used successfully in the City of El Paso recharge project.

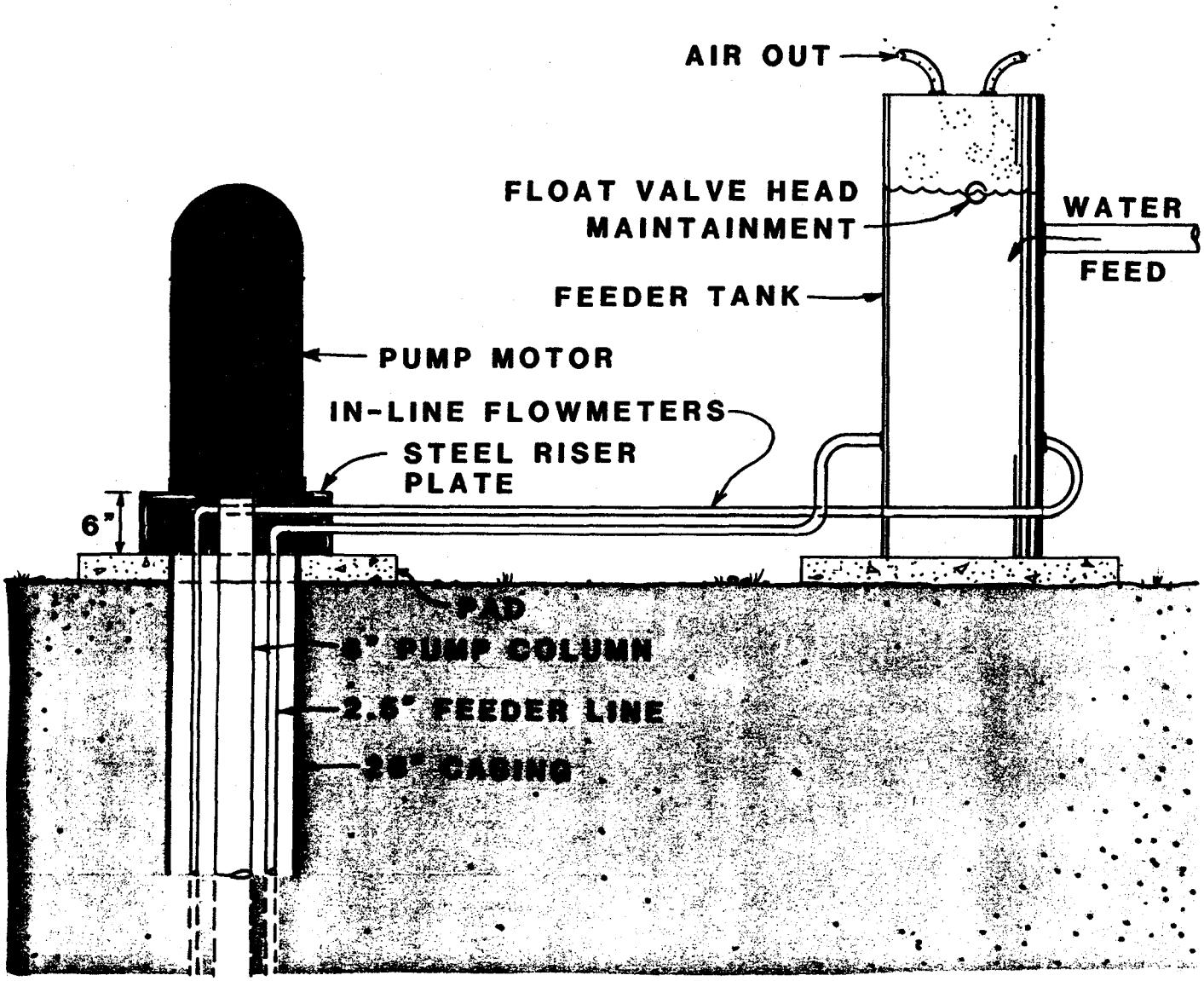
The main feature in this system is the double injection pipes with a maximum diameter of 2.5 inches (Figure 12).

The Recharge rate is now estimated at 600 gpm, but will be determined more accurately at the completion of the Pilot Phase.

CAVE CREEK RECHARGE PROJECT

CITY OF PHOENIX

TENTATIVE INJECTION SYSTEM DESIGN



Equip Well With A Piezomeric Water Level Sensor, Connected To A Recorder.

Figure 12

CELLA BARR ASSOCIATES

FINAL PHASE

If the pilot phase is successful the plan calls for the utilization of a well field consisting of 57 injection wells. Each well will recharge approximately 965 acre-feet per year for a total of 55,000 acre-feet. These injection rates take into account periodic maintenance and repairs.

CONCLUSION

I hope I have covered most of the technical aspects of the City of Phoenix Cave Creek Recharge Project. Mr. Bill Chase will cover the aspects of the economics and water management in his talk tomorrow.

Since this project is still in the experimental stages and the pilot recharge project is only in its early stages many questions still remain.

I will be glad to answer questions that you may have especially of a general geologic and hydrologic nature. However, many of the hydraulic aspects are still unknown.

ACKNOWLEDGEMENTS

I want to take this opportunity to thank the technical staff of the City of Phoenix, both of the City Managers Office and the Water and Wastewater Department to permit us to present this progress report to you.

I want to thank in particular Ken Schmidt who kindly supplied information on the recharge well and in other adjacent wells which he designed.

Finally thanks are due to my co-workers at Cella Barr Associates for their contributions, assistance and encouragement, in particular Mr. Larry Onyskow and Mr. Gene Cetwinski.

SESSION II: LEGAL AND INSTITUTIONAL ASPECTS OF RECHARGE

MODERATOR: MARYBETH CARLILE,
SOUTHERN ARIZONA
WATER RESOURCES ASSOCIATION

AN OVERVIEW OF INSTITUTIONAL CONSIDERATIONS IN ARTIFICIAL RECHARGE PROGRAMS

remarks by 1/
Michael Bradley

I want to start with some words about a policy that has been reiterated and accepted with relatively little hesitation; the policy that groundwater recharge is supply augmentation, and should be undertaken when and where feasible. Of course, the basic idea makes good engineering and economic sense. We are trying to extend the storage concept of surface water management, in which the surface waters of a river would be stored and surplus flows would be captured behind a dam or in a reservoir, and would be available for subsequent use during low flows or dry periods. Water that would otherwise escape would then be usable for future use and seasonal variations in precipitation and supply would be modified by storage. But dams are expensive to build and maintain. They are hazardous to downstream communities and cause environmental disruptions. The reservoirs preempt large areas of land for essentially a single use. The storage concept in application has costs as well as benefits. Nevertheless, we think we are on the verge of taking an old idea and brushing it to a new luster.

Why not store water underground as well as above ground? Underground water storage puts water in a aquifer rather than behind a dam, avoiding most but not all of the environmental consequences and some of the land dislocations. In addition, the underground storage has positive benefits. It reduces evaporation losses, and it can provide some natural filtration of the stored water. However, we have considerably less experience at managing groundwater storage systems than we have with managing surface water storage systems. Surface storage requires different technology than ground-water storage, and a different mix of skills, devices, and costs. But ground-water storage is more commonly practiced throughout the arid Southwest and it opens up a vast opportunity for us to learn as we develop these new systems.

We discuss water banking more and more frequently these days. Again the idea is simple. We put the water in an underground bank. The many analogies to having water in the ground and having money in a bank account become clear as you deal more closely with an underground system. Water underground is stored, saved, and available. It can earn interest in a physical as well as an economic sense. And its value increases in proportion to our ability

1/ Edited from taped transcript

to create and vision future alternatives for the water stored underground.

I want to discuss with you the one recharge system in Arizona. My experience has been limited to an interesting year as co-principal investigator of what is called the Butler Valley Project at the University of Arizona. Let me give you some background on the Butler Valley Project. The Butler Valley is approximately 7 miles south of Alamo Lake on the Bill Williams River and at its southern end one mile north of the Central Arizona Project (CAP) Aqueduct. It is a pristine, desert valley with no private land holdings of importance: a few old mine claims, some small irrigation leaseholds, very few wells and an aquifer that can store water. We had the opportunity to do a conjunctive use study on the Butler Valley. In large part the project's success is because of the efforts of my co-investigator, Gray Wilson, a well-known expert in this field, and by two officials in the State Land Department, Dr. Bill Allen and Don Young. I want to recognize their contributions. These people visioned the Butler Valley Project. They saw its potential. They took the initiative. They contacted us. They took us into the field. They bounced around in four-wheel drive vehicles. They worked hard to get land swaps between the land in State holdings and in Federal holdings, including some land that the Federal Government wanted near the Navajo Indian Reservation.

We developed the Butler Valley Project as a demonstration project; that is, we wanted to demonstrate the feasibility of conjunctive surface and underground management in a small scale. This small area, a relatively protected site, is an excellent experimental site, and we think the things learned here can be of great benefit to the State of Arizona. It is also a modest research project. We think it has great potential to contribute creatively and rationally to the on-going debate about how to store and manage water underground.

The Butler Valley is small, approximately 160 square miles in area, with rainfall of about 7 inches a year. The transmissivity is about 55,000 gallons per day per foot and the specific yield is 15% to 20% although the hydrologic characteristics are important, we think that the policy aspects of this project are also of considerable interest. The economic and institutional aspects of the Butler Valley Project are the specialty of my part of the study and it's the ideas that we are developing in public policy that I will share with you this afternoon.

A further fundamental assumption of the Butler Valley Project put a design in the project that we think is nearly unique. We started with a geophysical research team in the field and we also started on the same date with policy and economic studies. So the studies run concurrently and learn from each other. Commonly the geology studies are done, and then the engineering feasibility studies are completed, and then our economics cost-benefit analysis is finished on the last day, and the last hour, the researchers ask questions about what policy implications all this has or if we need legislation to implement the project. The policy and institutional studies of the Butler Valley Project are proceeding along with the physical and hydrological studies and we consider both areas of research of equal significance.

Although equally important, the policy and institutional studies have a curious sense about them. We have learned what a policy analyst does in a study like this; that is, you ask more questions than we answer. Over the last year we have been busy asking the important questions of public policy in a conjunctive use water management study. By the way, I am sorry that I can't give you complete, comprehensive answers to all of these questions. Most of them are more complex than we first thought but we continue to think about them. We would like to share them with you so you can think about them as well.

The first question we ask about the Butler Valley Project was an instituional one. Who owns the land? The land was owned in combination by the U.S. Bureau of Land Management and the Arizona State Land Department with some small mining claims in the foothills. No land was in private ownership so no private water rights to the groundwater exist in the Butler Valley. The leaseholders who irrigate acreages in the southern part of the Valley have wells to provide their water but their land is leased and their water rights were not a privately held water right. By the land trade mentioned earlier and legislation the Governor signed into law, control over most of the land of the Butler Valley has been given to the Arizona State Land Department. In return, the federal government received a piece of land they wanted near an Indian Reservation.

The second question we asked was, if we are going to have a conjunctive use water storage project, where will the water come from? To store water underground, of course, requires water. We found three alternatives. I will detail them in historic importance, the ones we considered first, were forced

to reject, and the final one we determined to be the most significant alternative.

The first alternative was the Alamo Dam and Lake 8 miles away on the Bill Williams River. After floods there seemed to be a lot of water there, it seems to be relatively unused, it seems like a good source of water. We started talking as if the Bill Williams River and the Alamo Lake might be a source of water to recharge into the Butler Valley and immediately mired ourselves in questions about this tributary flow to the Colorado River, which is allocated by contract with seven States and by treaty with Mexico. It didn't take us long to back away from the notion that Alamo Lake and the Bill Williams River would be a possible quick and easy source of water to recharge the Butler Valley. There are some other reasons as well. The lift cost would be roughly comparable to the lift out of the Colorado River across the Buckskin Mountains into the CAP, or about an 800 foot lift over hills just as it is up the Buckskin Mountains. You will notice out of those two alternatives only one has the pump and the pipe to lift the water. That is the CAP. Also the Bill Williams River and the Alamo Lake are not part of the CAP Project directly. There is no management institution in place such as the Central Arizona Water Conservation District (CAWCD). It would take research and legislation to somehow develop either a district or a jurisdictional scheme to manage the waters from the Lake into the Butler Valley. We thought these impediments were severe, so we looked at our second alternative, the natural rainfall in the Butler Valley.

Those of you familiar with the State know that between 7 and 8 inches a year falls in the Butler Valley, which would be a marginal addition to the supply if it were recharged but certainly not enough to make the Project worthwhile. Also the rainfall occurs with spatial and time variability. That means it comes, at certain times of the year and lands on, certain places in the Valley. These problems do not make recharge easy. While we haven't completely eliminated rainfall as a possible supply, we think that its management would be expensive compared to the amount available. We considered rainfall running off the foothills as a source of a marginal addition to supply, it can be recharged naturally; that is, little dams and weirs across the tributary channels might allow that rainfall to infiltrate into the groundwater.

But the third source of water seemed by far the most likely candidate for recharge. That was CAP water. After all, the canal is about a mile south

of the Butler Valley and the water would be available all year. The water will be coming to Phoenix soon. Those of us who live in Tucson still carry concerns deep in our heart about the water getting all the way down to Tucson. The more we thought about this problem, the more we thought that maybe here is a guiding force behind the Butler Valley Project. If the water could be run past the lower end of the Butler Valley and if engineering structures could be built that would allow the water to be piped up into the Butler Valley, it might be possible to do a number of things. It began to look as if the Butler Valley was a feasible ground-water recharge project. Technical feasibility then gave us policy questions to ask. If you can recharge water, then what operational rules will guide the recharge operation. I will present to you a couple of operational rules we are trying to clarify. These rules assume a program of conjunctive use management in the Butler Valley.

The first operational rule is that we should begin recharging water that comes along the CAP channel for the benefit of Arizona users, especially if it would otherwise go to California as surplus water. Even though the CAP project is not complete and even if the water doesn't reach Tucson immediately, we thought that there was a strong argument for recharging the water as soon as it came into the canal. Recharge means that Arizona could begin to do what it hasn't been able to do since 1928; that is, take a full allotment out of the Colorado River the way that allotment had been guaranteed to us by the Colorado River Compact. We could store this water for future use, making the Butler Valley a water bank. Now, as an ex-Californian I know full well what this means. This means screams of rage from the West. We will be forcing California to begin to do something that they haven't done for about 20 years, which is live under the conditions of their own self-limitation act, which limits them to a 4.4 million acre-feet share of the Colorado River water. When you live in California, as I have for a number of years, this sounds terrible. Californians talk of cutbacks and limitations and declining economies. When you live in Arizona, it doesn't sound so bad. The California self-limitation act has been in effect since the 1940s, but there has always been surplus for them to take because Arizona has never been able to accept its water. We begin to vision the Butler Valley as a way that Arizona could accept its full entitlement and store it in a bank account for use when and where it is needed in the Central and Southern Arizona region.

We also realize that storing water underground is not as efficient in many ways as storing it above ground. There is some loss to what was called this morning-"the investment"-and the fact that the water tends to hang up in the rocks. You don't get out the same amount of water you put in. However, we convinced ourselves that it is better to have 70 to 80% of our allotment here in Arizona than to have a 100% loss of our allotment to California simply because we had no facilities to take the water and to store it.

Operational Rule No. 2 is another simple and straight forward one. We see the Butler Valley as something different than what Governor Babbitt sees. We are distressed when Governor Babbitt talks about the Butler Valley as an aquifer to mine. Those of us who are sensitive to words realize the connotation of a "mined" aquifer is not positive. In contrast, we consider the Butler Valley to be a straight-forward conjunctive use storage project. The aquifer will be mined only in a limited sense. Water will be taken out of the ground. But, by taking water out you also produce something of value called storage in the aquifer-storage is valuable because you can also put water back in. We believe it is important to realize that the Butler Valley is a storage project, a planned recharge and pumping facility which uses the storage capacity of the aquifer. It would not detract from the cost, and it would not be a temporary or expensive project. Rather, we like to think of it as a serious off-line storage opportunity, and a project integral to the future of the State's water supplies.

Operational Rule No. 3 is probably not as well defined but maybe the more important one. We are beginning to realize that if water can be stored for future use in the Butler Valley that water is more than just water. That water now assumes a different aura, a different role. That water has become strategic water. Let me explain to you my concept of strategic water. Suppose we could take CAP water and store it off-line near the river in this natural bank account. For tactical purposes, you have added to the traditional uses a whole complex of possible uses for this water. Let me explain that carefully. CAP water is for traditional uses: irrigation, municipal and industrial uses. Traditional users have entered into contracts for CAP water and Butler Valley storage could also be for traditional uses. Water stored off-line could be used for low flow augmentation, quality dilution, for example, perhaps there is higher saline levels in the Colorado River at some time during the year

and you might be able to dilute the water in the channel with the Butler Valley water, or even emergency uses. But we are unsatisfied with only traditional uses, we think that Butler Valley water is far more important than just these traditional uses. It has a strategic sense about it. The Butler Valley water, we think, could be valuable whether delivered to users or not. Those of you who have been involved in the design of the CAP know that there has been some real questions about whether there would be capacity in the CAP to deliver additional water stored off-line. Those of you who work for cities or irrigation districts are well aware of the fact that most cities of necessity in the past have confined themselves mostly to dealing with what they call "firm supplies". That is water actually in existence in a reservoir or underground beneath your feet within the city limits. It is yours to command and control. Districts have dealt most effectively in the past with guaranteed contract allotments, waters for which you have a contract and a firm delivery agreement, whether they are off-line waters or out of basin waters. We think the Butler Valley water will be valuable, because it is stored in the Butler Valley in a strategic location upstream from most of the future users. Once we establish the rights to it, the water can be used for any purposes. It can be strategically used; that is, it can be negotiated with, it can be swapped, it can be traded, it can be leased, it can be sold. We vision a whole complex of opportunity arising because users have a valuable resource stored for them whether or not they take actual physical delivery of the water. We are interested in developing the tactical opportunities that Butler Valley storage would open up to the members of the CAP system. In effect, what we are envisioning is how a total loss to California can be turned into a stored liquid asset in Arizona, if you will forgive the play on words, for the participants in the CAP system.

That brings us to a few of the other questions to be asked. Suppose there is a Butler Valley Project, who will manage it? We immediately thought of a regulatory agency, some combination of State, or Federal, agencies, or some combination of local and state agencies. In discussion with Sam Steiger, a former U.S. Congressman from Arizona, we considered another idea, a marketing agency. Water in the Butler Valley could be sold as a commodity. Mr. Steiger

envisions a private enterprise organization selling the water in a market. We put our eggs in the basket as some combination of an existing agency and a modified market scheme. Supposedly the nearest existing agency that would have the management capability to handle the Butler Valley was the CAWCD. We think that limited regulation and a directed market is a combination that will happen through something like the CAWCD.

The next question we asked is what are the project economics? We are now developing the cost economics of the project. The early indications are that the cost economics on the scale of this project are quite reasonable. Not quite what was presented here this morning in another paper and not $60.00 per acre-foot, but still relatively reasonable.

We are also thinking about the management structure, about how a management agency would deliver the water stored here. We see two types of possible management designs: either a public management agency with strong public control that would deliver the water in some sense of equitable apportionment or a marketing agency. Under the public management scheme those who participate in the CAP would have storage rights in some sense roughly proportional to their participation in the project. Public management would create a great political benefit, the concensus decision-making process that goes along with equitable distributions. Everyone gets a chance to participate and feel like part of the system. We have not entirely discounted management by private enterprise in which the recovered water would be allocated by pricing and marketing mechanisms. Commonly, the schemes have a private corporation that manages the project. We understand that those could be efficient, but they do carry with them political difficulties. For instance, increased economic efficiencies often lead to increased political divisions, especially in a state where cities and irrigators are still in conflict over the available supply. Some people have asked us tough questions about marketing schemes, and whether contracting private institutions would not be given great subsidies if they were somehow allowed to market the water at a profit. Another person asked me the other day whether or not this water had already been paid for in the contracts? Why would you then market the water at an additional price to the contract price? I am thinking about this; I don't have the answer to that one yet. There are also some real issues with power rates: who gets the cheap power? It is still unsettled

whether CAWCD would get that power. It is quite unsettled whether or not a private operator would get cheap power rates from the Hoover Dam. As I say, we have no answers to these yet but we are thinking hard.

There are other on-going institutional activities in the State. There are legislative proposals. There were two last year, one from the Arizona Municipal Water Users Association, and one from the CAWCD. They dealt with establishing systems of water rights that would help allocate the water and with granting powers to the CAWCD that would help it manage the aquifer. Both failed, but we look forward to further admission of proposals in the next legislature.

It was mentioned before that we have a lot to learn from California, especially institutionally. They have developed a set of rights that give certain agencies the right to store water under the ground to protect it from interference, to pump it back out, and to use it. We would like to point out that we are much happier in Arizona having these discussions take place in the legislature. In California, these opinions came down from the courts. And those of you who are familiar with the City of San Fernando vs. City of Los Angeles opinion know that these opinions in effect give extraordinary legal rights, such as public servitudes, to cities over and above irrigators. We think that would be politically disruptive in Arizona. So we are most pleased that this discussion is taking place in the legislature where at least these concerns can be discussed in a political atmosphere, not just a legal one.

I want to conclude by indicating what I learned about the politics of groundwater storage. I did some early work with how a hydrologist can participate more effectively in the legal system as an expert witness and a special master. This has led me to realize that if we are going to have a sophisticated management system, as sophisticated as the physical problem of managing a ground and surface water conjunctive project, we should be training our future managers, our future hydrologists, and our future engineers in sophisticated management techniques. I am not saying that modern techniques such as systems analysis, linear program and computer simulation are in any sense unsophisticated. My personal opinion is they are not all there is to managing. I am developing my own thought in the area of negotiating techniques. Those of you who have been graduate hydrologists or engineers and are now in the

real world probably are finding out the hard way that many models are not tools for easy negotiation and in fact, many decisions are made by negotiation processes not modelling. I am taking my students next semester through a seminar exercise in negotiating solutions over complex environmental and water-right issues where we will, through simulation, bargain and negotiate solutions. All this seems to be news to hydrologists who seem to think that data is infallible and that models are precious in some way. Policy makers know that data is negotiable and a model can be accepted or rejected according to the rules that you are negotiating by. This and other lessons need to be made available to our future technical managers by using case study materials from problems such as the Butler Valley Project.

Dr. Michael Bradley received a Ph.D. in Natural Resources Conservation from the University of Michigan and is currently an Associate Professor of Hydrology at the University of Arizona.

THE PRESENT LEGAL FRAMEWORK FOR ARTIFICIAL RECHARGE IN ARIZONA

remarks by 1/
Kathy Ferris

Arizona's present legal framework is very unclear and in many areas largely non-existent. This is because there are no Arizona statutes or Arizona court cases that directly address the issues of artificial recharge. So that when courts in Arizona and when the Department of Water Resources are called upon to decide issues in this area, they will have to extrapolate their answers from existing relevant statutes and from court cases from other states. Today I am going to talk briefly about the Arizona water statutes that are administered by the Department of Water Resources that are applicable to artificial recharge. I am also going to talk about some of the issues involved in artificial recharge that aren't addressed by those statutes. And finally, I would like to summarize the concepts that the Department of Water Resources believes must be addressed by any artificial recharge legislation.

I think the legal framework for artificial recharge can be roughly divided into three phases. The first phase would be spreading or infiltration. The second phase would be maintaining the recharge water in the basin. The third phase would be recapturing the recharged water. The most obvious question in the first phase is where do you get the water? As you all probably know under Arizona water law you must have the right to use water before you may divert it or withdraw it. Surface water in Arizona is defined to include all waters flowing in streams, canyons, ravines, or other natural channels or intermittent, flood, waste or surplus water. In order to use surface water, a person must obtain a permit from the Department of Water Resources. Before granting a permit, the Department must determine that the proposed use would not conflict with vested water rights, is not a menace to public safety and is not against the interest and welfare of the public. Permits are granted for a specific amount, for use at a specific location. So that before a person seeking to artificially recharge surface water can do so, that person must have a permit or a certificate allowing that person to so use the water. Furthermore, a person having a surface water right must obtain the Department's approval prior to changing the use to which the water is put or changing the location of the use.

Two commonly considered sources of water for recharge projects in Arizona are CAP water and effluent. Now as many of you may be aware, the legal status of effluent at the present time is extremely unclear. In fact, the legal

1/ Edited from taped transcript

status of effluent is the subject of a complicated law suit which is going on in Federal Court. That is a lawsuit filed by John F. Long against the Phoenix Valley cities - here in this Valley - that operate the 91st Avenue Treatment Plant and against Arizona Public Service (APS) and Salt River Project (SRP). Long alleges in his law suit among other things, that effluent is either surface water or its groundwater and it is not a commodity that is owned by the cities that they can dispose of as they please. He, therefore, claims that the contract between the Valley cities and those entities that operate the Palo Verde Nuclear Generating Station under which the cities will sell their effluent to those entities is void. APS and SRP countered the Long lawsuit by filing an action in State court. In that action, they are seeking a declaration that effluent is neither surface water nor groundwater and that it is a commodity which the cities may use or dispose of unilaterally. Until these law suits are decided or until the legislature addresses the legal character of effluent, the ability of persons to use effluent as a water source for artificial recharge is clouded.

There are other questions that have to be answered in the first phase. One of these is who has the right to operate an artificial recharge project? Here, Arizona statutes provide little guidance. The question then becomes, can anyone who has a source of water, an excess to land, develop and implement a project or are prospective operators limited to public agencies and other entities. Another question is, where can facilities for recharging water be located. This is really an issue primarily of land law. However, water law becomes relevant if the proposed location of a recharge facility is a natural channel. Discharging water into a river channel raises the issue of whether that water then becomes surface water which is subject to appropriation by other water users. The Department of Water Resources has addressed this issue in one proceeding before the Department and in that case, it involves the City of Tucson and the Cortaro-Marana Irrigation District. The City of Tucson is discharging effluent from the Ina Road treatment plant into the Santa Cruz River channel. Cortaro-Marana Irrigation District filed a permit with the Department seeking to appropriate that effluent. In that case, the Department ruled that when the City of Tucson discharged their effluent into the Santa Cruz River channel and relinquished dominion and control over that effluent, that it became surface water that was subject to appropriation by other water users. There is a statute on the books right now in Arizona and it is in the surface water code which says that a natural channel may be used to carry water of another if such use can be made without diminishing the quantity of water

which naturally flows in the channel. But that particular statute has been around for a long time and has never been litigated so we are not sure what the impact of that statute would be on a city using a natural channel to transport water for their effluent or other water source for artificial recharge project. A third question that needs to be answered in this area is, is there storage space for the recharged water? Again, Arizona water law is silent on this issue. There are no guidelines for determining whether storage space is available and if so, who should have access to that space. This issue may not pose very many problems in areas where the groundwater supply is badly depleted. However, it becomes a factor where the groundwater table is closer to the surface and when recharged facilities are located in river channels.

The second phase of artificial recharge projects is the maintaining of the recharged water in the basin. Here the overriding question is, how may the entity who recharged the water protect that water from interference or withdrawals by others? Again, Arizona water law is silent on this question. In fact, this is a case where it may work against the person who has recharged the water. Groundwater in Arizona is defined to mean all water under the surface of the earth regardless of the geologic structure in which it is standing with the exception of water flowing in underground streams with ascertainable beds and banks. I know this definition gives the hydrologist nightmares but that is what the law says. In many cases, recharged water would fall within this definition. If recharged water is ground water, it may be withdrawn by any person who has the right to withdraw and use ground water. In some circumstances, recharged water might become surface water. Under Arizona case law, surface water includes subflow. Subflow was defined by the Arizona Supreme Court as those waters which slowly find their way through the sand and gravel constituting the bed of a stream or the lands immediately adjacent to the stream and are themselves a part of the stream. The court set up a test for determining when water was subflow. What the court said is that groundwater is subflow if withdrawing it diminishes appreciably and directly the flow of the surface stream. If recharged water becomes subflow, it may be diverted by a person who has the right to divert surface water.

Now while the Arizona courts have not been called upon to address the problem of encroachment by other water users, the California courts have and a couple of the cases are paramount in this area, which have been referred to earlier. The first case is Niles Sand and Gravel Company vs. Alameda County Water District. In that case, the California Court of Appeals enjoined the Gravel

Company from pumping water from its gravel pits and allowing the water to flow into San Francisco Bay. Alameda County District had for years conducted a groundwater replenishment project which was aimed primarily at preventing salt water intrusion. Water from the District's recharge facilities seeped into the Gravel Company's pit and the Gravel Company then pumped the water from the pits and let it waste into San Francisco Bay. The court said that under the Correlative Rights Doctrine, which is the doctrine applicable to groundwater in California, that land owners must refrain from discharging more than their reasonable share of groundwater. The court felt that the Company's discharges in this case were unreasonable because they were detrimental to the District's recharge program.

Another important California case that addresses this issue is Los Angeles vs. San Fernando. In this case, the City of Los Angeles sued the Cities of San Fernando, Glendale and several others to enjoin them from extracting groundwater without Los Angeles' permission. Los Angeles for many years had been bringing in water from another basin and spreading some of that water for recharge. The courts held that Los Angeles had the right to prevent others from pumping the imported groundwater that reached the groundwater basin if that pumping in combination with Los Angeles' pumping overdrafted the basin.

These are great cases for California. The problem is that they may provide some guidance to an Arizona court but they are based on a very different law governing water rights. The Correlative Rights Doctrine which was the basis for the decision of the court in the Niles case allows owners of land that overlie a common supply of groundwater to make reasonable use of the water for the benefit and enjoyment of their land. But a land owner may use only his reasonable share of the common supply. Unfortunately, in many cases, that reasonable share is not quantified. Likewise, the San Fernando case was based on a different law than what applies here in Arizona. It was based on the fact that there was something called imported groundwater that was distinguished from native groundwater. An Arizona law makes no distinction between the types of groundwater that are found in our groundwater basins. So we have a very different situation in terms of Arizona law especially in our active management areas (AMAs). Groundwater rights are quantified and Arizona law makes no distinction between imported groundwater and native groundwater. With the exception of service area rights which do not have a precise limitation on them, each person with a groundwater right may withdraw only a specific amount of groundwater that is evidenced by a permit or by a certificate. I think that it would be very difficult for a court to enjoin withdrawals of groundwater if the

person withdrawing that water had a right to make those withdrawals and he was not exceeding the amount that he was legally entitled to withdraw.

The third phase of a recharge project is the recapture of the recharged water. The critical question in this phase is, may a person who artificially recharges water recapture that water? Here again, absent some kind of further legislation we would have to look to the Arizona Surface Water Code and the Groundwater Code for the answers. So that if recharged water becomes groundwater the recharger would need a groundwater right in order to withdraw it. Likewise, if the recharge water becomes surface water, the recharger would need the right to withdraw surface water in order to recapture the water. These restrictions may pose some barriers for the recapture of water. In AMA's, as I said before, a person may withdraw groundwater only pursuant to a groundwater right. There are basically three kinds, a grandfathered right, a service area right for cities, towns, private water companies and irrigation districts, and a groundwater withdrawal permit. But there are restrictions on when the Department can issue or grant these rights and on where wells that would be used to withdraw recharge water will be located. An example would be a city which wants to recharge water in an area outside of the city's service area. The city has the right to withdraw groundwater under a service area right only from within its service area and the service area is defined by the code, as the area of land actually served by the city and additions to that area which contain an operating distribution system owned by the city. So it is conceivable that the city would not have a mechanism of withdrawing the recharge water from a well outside of its service area unless it could purchase a grandfathered right to withdraw that water. And again there may be barriers in terms of surface water because most of Arizona's surface water is already over appropriated and so it is very difficult now to obtain the right to divert surface water if you reach a situation where the recharge water has become subflow.

There are essentially two ways to answer all of these questions. One way is litigation and the other is legislation. Litigation is very time consuming, it is expensive and it is very difficult to predict within a certainty how a court will rule. Often times you will have a court ruling that does not provide very much flexibility in another situation where the facts are very different. As I said, it is very time consuming. The San Fernando case took 25 years to resolve. So I am kind of with the majority of people, I prefer legislation to address these unanswered questions and having said that, what should the legislation say? I'm sure you are not surprised to know that the Department

of Water Resources has some views on that. I am going to summarize those very briefly.

The Department thinks that the legislation should be designed to reduce the overdraft in active management areas. We also believe that the legislation should not undermine existing restrictions on water users and water providers. For example, the legislation should not undermine the effectiveness of the conservation requirements contained in the management plans nor should it allow unrestricted expansion of service areas. We think that the legislation should permit recharge of water that would not otherwise be recharged or used and that satisfies certain water quality criteria. We do not believe that the legislation should encourage the recharge of CAP water that could be directly used at a reasonable cost. We think that the legislation needs to establish some kind of permit program. The permit should specify the type of recharge project the permittee would be authorized to operate, set limits on the amount of recharged water that may be recovered and the location of the withdrawal facilities. It should impose any conditions necessary to minimize or mitigate the adverse effects of water quality on other water users and land owners. We also believe that withdrawals pursuant to a recharge recovery project should be restricted to the area of the hydrologic impact of the recharge project. And finally, this may sound strange coming from a lawyer, but we believe that the legislation must be technically sound. It must recognize that water that infiltrates at the land surface may take some time to actually reach the groundwater table. It must also recognize that one hundred percent recovery of recharge water is not feasible and that the percentage of stored water that can be recovered varies from location to location.

I know a lot of what I said doesn't sound very positive for artificial recharge projects. It wasn't meant in that light but I think it is really helpful to recognize on the front end, the legal and institutional barriers to artificial groundwater recharge and to recognize that we need to address some of these unanswered questions if we want to allow recharge projects to happen and if we don't want to be tied up in court for years and years. The Department of Water Resources is very interested in this issue and we are going to work with anyone else who is interested to develop the best legislation that we can.

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CURRENT LEGISLATIVE PROPOSALS FOR RECHARGE IN ARIZONA

Bob McCain

Currently, the Arizona State Legislature has before it two proposals concerning artificial recharge. The first proposal was developed by those cities which are members of the Arizona Municipal Water Users Association (AMWUA). The AMWUA proposal was introduced but did not receive a hearing. Instead, a Senate Subcommittee has been appointed to hold hearings this summer and fall with legislative deliberations expected next session. It is anticipated that the House will also appoint members to what will become a joint-legislative committe on recharge.

The second recharge proposal, a portion of a larger legislative package dealing with the use of effluent, was developed by the Arizona Department of Water Resources (DWR). It deals only with the recharge of effluent and thus is intended to be an interim measure, with a comprehensive approach awaiting development in the near future. Consequently, it should be noted that AMWUA will be supportive of this legislative package.

We anticipate that the two proposals will largely structure the parameters of discussion during the legislative hearings. To that end, this presentation will compare and contrast the proposals of AMWUA and DWR on the basis of the following topics:

1. Scope of legislation
2. Legal Issues Concerning Recharge
3. Management Approach
4. Role of Director of DWR
5. Externalities/Impacts
6. Service Areas
7. Incentives for Recharge

1. SCOPE OF LEGISLATION

AMWUA	DWR
Geographical	Geographical
o AMA	o AMA
Water Source	Water Source
o Effluent	o Effluent
o CAP water	
o Surface water	

AMWUA's proposal deals only with active management areas (AMA). We recognize the potential in Butler Valley but felt a policy of one-step-at-a-time would be more feasible.

AMWUA's proposal is intended to cover all types of water that may be recharged.

DWR also limits their proposal to AMA's because it is only in AMA's that recharge of effluent is likely. It will be interesting to see what role, if any, DWR will want to play in Butler Valley.

DWR's proposal deals only with effluent since the large legislative package deals only with effluent.

2. LEGAL ISSUES CONCERNING RECHARGE

AMWUA

Right to Recharge

- o Any person.

Right to Recover

- o Recharge establishes a legal right to withdraw groundwater.

Right to Store or Bank

- o Water recharged may be stored or banked for future use.

Ownership of Water Before Recharge

- o Silent.

Character of Water Once Recharged

- o Silent.

AMWUA proposes that any person may recharge and thereby establish an automatic, legal right to withdraw groundwater from a recharge savings account.

DWR

Right to Recharge

- o Treating entities (since concerned only with effluent).

Right to Recover

- o Recharge may provide a permit to withdraw water which results from recharge.

Right to Store or Bank

- o Storage neither expressly allowed nor prohibited.

Ownership of Water Before Recharge

- o Effluent under dominion and control of treating entity.

Character of Water Once Recharged

- o If effluent recharged in natural channel, it becomes surface water.
- o If effluent percolates underground, it becomes groundwater.

DWR's proposal, since its scope is restricted to effluent, permits only cities, towns and private water companies to recharge.

The AMWUA proposal, unlike DWR's, would not establish a necessary connection of identity between the water recharged and the groundwater recovered. Even so, recharging water provides banking and storage privileges.

AMWUA's proposal does not confront the issue of ownership before or after recharge. Before recharge, AMWUA attempts to finess the issue in the manner ownership was handled in the Groundwater Code, i.e., silence.

AMWUA's proposal is also silent on what the water legally becomes after recharge. However, it is treated as if it was groundwater regardless of where recharged, i.e., recharge establishes a right to withdraw groundwater.

Recovery, however, is not automatic and may only be pursuant to a permit from the Director. Unlike AMWUA's proposal, there is a definite connection of identity between the water recharged and the water recovered. Banking and storing for future use is not dealt with directly by DWR.

Unlike AMWUA, DWR deals with the question of ownership directly; effluent belongs to the treating entity but it forfeits ownership once effluent is recharged. Surface water is subject to appropriation and new groundwater withdrawals in AMAs may only be allowed pursuant to permit. DWR's proposal would also result in lawsuits.

3. MANAGEMENT APPROACH

AMWUA

- o Integrated into Groundwater Code from "market" perspective.
- o Right to recover groundwater pursuant to recharge modeled after Type 2 groundwater right.

In terms of management approach, AMWUA stresses utilization of market principles. Thus, the right to withdraw pursuant to recharge is very similar to the Type 2 groundwater right. In addition, the Type 2 right is the right over which DWR has the least authority and control.

DWR

- o Integrated into Groundwater Code from "regulatory" perspective.
- o Right to recover water resulting from recharge modeled after groundwater withdrawal permit.

In terms of management approach, DWR stresses utilization of regulatory principles. Thus, the right to recover water resulting from recharge is conceptually and procedurally similar to the groundwater withdrawal permit. In addition, groundwater withdrawal permits are subject to considerable oversightand control by DWR.

4. ROLE OF DIRECTOR

AMWUA

- o Banker: Administers Recharge Savings Account.
- o Not directly involved in approving recharge project.

DWR

- o Regulator: Monitors terms and conditions of recovery permit.
- o May be directly involved in approving recharge project.
- o Determines recoverable amount of water which results from recharge.
- o Issuance of recovery permit at discretion of Director.

Under the AMWUA proposal, the Director does not have a direct role in approving a recharge project. The approval authority rests with the Director of the Department of Health Services, though one can expect him/her to closely involve the DWR Director. AMWUA's conception of the role of the Director of DWR is more akin to a banker who administers the recharge savings account (RSA) established automatically as a result of recharge. The most significant power of the Director is to determine how much groundwater was deposited in the RSA as a consequence of recharge. Such clearly implies a recharge recovery ratio of less than 1:1. There will be system losses and if one were foolish enough to recharge in the Buckeye area, one might see little deposited in the RSA because the water recharged could easily migrate out of the AMA. Indeed, it would be theoretically possible to have one's RSA debited if recharge resulted in a net loss of water to the AMA.

It is likely that the Director will be closely involved in approving recharge projects under DWR's proposal since the entity wishing to recharge must demonstrate that unreasonable harm will not transpire.

The Director would play the classic regulatory role insofaras the recovery of water resulting from recharge is concerned. He/she would monitor the terms and conditions of the permit and determine whether the hydrological studies demonstrating recovery parameters were accurate. Clearly, principles of system losses and net gain to the AMA are contemplated.

DWR's proposal does not set forth criteria for rejection of an application for a recovery permit. One may successfully meet all tests yet have a permit denied solely at the discretion of the Director. Grounds for appeal, apparently, would be that his/her action was arbitrary and capricious.

5. EXTERNALITIES/IMPACTS

AMWUA

Recharge Operation

- o Must demonstrate recharge will meet ADHS Water Quality Standards.
- o ADHS required to develop specific rules for recharge.
- o If in compliance with standards and rules, no damages are presumed.

Recharge Withdrawals

- o Must demonstrate compliance with well spacing rules (Section 45-598).
- o If in compliance with rules, no damages are presumed.

Under the AMWUA approach, approval for the operation of a recharge project rests with ADHS because of potential water quality implications. Indeed, the AMWUA proposal specifically directs ADHS to develop rules for artificial recharge because of concerns that the existing groundwater quality protection program may not be entirely appropriate. In any event, if the proposed recharge meets the standards and rules, then it is presumed that no one will be harmed.

In terms of withdrawals, AMWUA believes the only test, insofaras the issue is damaging to others, should be whether the location of the recovery well and the amount to be withdrawn meets the well spacing rules developed by DWR. If in compliance with

DWR

Recharge Operation

- o Must receive approval from relevant governmental agencies.
- o Must demonstrate that recharge will not unreasonably harm other landowners and water users.
- o Other landowners and water user may be considerable distance from project site.

Recharge Withdrawals

- o Must demonstrate withdrawals will not unreasonably harm other landowners and water users.
- o Other landowners and water users may be considerable distance from withdrawal site.

DWR's proposal is similar to that of AMWUA's except that it is unclear who all would be involved in determining whether anyone would be unreasonably harmed. Not only will "unreasonably" have to be defined in different contexts, the question of harm is geographically unlimited. For example, if a person wants to take and recharge CAP water in the Phoenix AMA, the recharger must be able to demonstrate that use of CAP water for that purpose will not unreasonably harm other CAP users in the Pima and Tucson AMAs.

In terms of withdrawals, DWR feels that even though one must demon-

the rules, AMWUA assumes damages are non-existent.

strate that one will recover the water that results from the recharge, one must also demonstrate that no one will be unreasonably harmed from the withdrawals. This is a stricter test than what currently exists in law. Apparently, the reason DWR feels this must be the case is due to the possibility of recharging in a natural watercourse. DWR argues that recharge in a natural watercourse creates surface water. Thus, recapturing that "surface water" which results from recharge may deprive a downstream senior appropriator of his legal entitlement.

6. SERVICE AREAS

AMWUA

- All facilities for recharge and recovery, regardless of where located, are within service area.

AMWUA believes that recharge and recovery should be defined as located on service area lands. Yes, this becomes a way to expand the service area and, therefore, would allow for withdrawals from that land pursuant to a service area right. Such, however, would still be subject to well spacing rules.

DWR

- If recovery permit allows withdrawals from wells outside (within) service area, then all facilities for recharge and recovery, regardless of where located, are outside (within) service area.

Simply put, DWR does not want recharge and/or recovery to be used in a fashion to expand service areas except for the limited case where the withdrawal site is within the service area and recharge facilities are located on land that would otherwise be non-service area land.

7. INCENTIVES FOR RECHARGE

AMWUA	DWR
Recovery	Recovery
o Need not recover the water that was recharged.	o Must demonstrate that will recover the water that results from recharge of effluent.
THUS	BUT
o May recover from site hydraulically unconnected with recharge site.	o Need not recover from site of recharge if water that results from recharge has moved. Presumption of hydraulic connection.
Pump Tax Exemption	Pump Tax Exemption
o Exempt from portion.	o None.
Conveyances and Uses	Conveyances and Uses
o Groundwater withdrawn is marketable commodity. May be leased, sold, used, distributed, exchanged anywhere for any legal use.	o Water withdrawn may be used and distributed only within service area.
Transportation	Transportation
o Anywhere without payment of damages.	o Without payment of damages only within sub-basin.
Credits	Credits
o Groundwater withdrawn will not count in per capita use.	o None.
o Water recharged may be credited to farmer's operating flexibility account.	

AMWUA believes that altruism will not recharge one drop of water. Incentives are necessary. A major incentive concerns recovery flexibility. AMWUA's proposal does not require recovery of the water that results from recharge. That being the case,

Put very simply, DWR's recharge proposal provides very few incentives.

- One is required to recover the water that results from the recharge of effluent. However, one does not have to recover from the site of recharge if it can be

one may therefore recover or withdraw, pursuant to recharge, from a site hydraulically unconnected with the recharge site. In most cases, one will in fact recover in close proximity to recharge but such is not required. Probably no other proposed incentive has engendered the controversy this one has. There is a great reluctance, however illogical, to this incentive. AMWUA asks, "If nobody will be harmed by the withdrawal and if the withdrawal does not complicate the achievement of safe yield in the AMA as a whole, what is the problem?" Clearly, this is one of the instances where so-called hydrological principles should not be allowed to stand in the way of a good idea.

AMWUA also proposes that groundwater withdrawn pursuant to recharge should be exempt from those portions of the pump tax relating to augmentation and purchase and retirement of grandfathered rights. AMWUA recognizes, however, that a special pump tax or fee may be appropriate to compensate DWR for their administrative efforts.

In addition, groundwater withdrawn pursuant to recharge may be used for any legal purpose. This is somewhat more expansive than the Type 2 right because such groundwater could be sold or used, etc. for irrigation purposes. This is necessary because individual farmers or irrigation districts may want to engage in artificial recharge.

demonstrated that the water resulting from recharge has moved.

- No exemption from any portion of the pump tax.
- The water resulting from the recharge of effluent may be used only within the service area.
- Sale of water, which results from the recharge of effluent, for use outside of the service area may be illegal.
- Exchanges, however, are possible.
- Transportation and damage rules are identical to what is currently in law.
- No credit is proposed for conservation requirements.

Groundwater withdrawn pursuant to recharge may be freely transported anywhere. AMWUA recognizes that this incentive may be justifiable only if recharge and recovery are in close proximity.

Finally, AMWUA proposes the possibility of recharge credits. That is, for municipal providers groundwater withdrawn pursuant to recharge would not be considered in determining per capita use. There is room for flexibility here if one recharges water that has never been used. But if one recharges effluent, that water has been previously used. To count effluent either in terms of recharge or recapture would amount to a double or triple dip for the regulator, i.e., DWR. Farmers could have their operating flexibility account credited in the amount of water they recharged.

In conclusion, we would speculate that if history provides a model, artificial recharge legislation probably will be closer in philosophy and content to the proposal of DWR than the proposal of AMWUA. Three reasons are relevant.

1. Management of water on the basis of market principles, rather than regulatory principles, is perhaps too radical. It may be an idea which time has not yet come.
2. DWR's proposal will probably be enacted first. DWR's proposal is a small part of a larger bill on effluent management. Nevertheless, it thus will set the tone or the model for comprehensive legislation, if any, to follow.
3. There may not be any comprehensive recharge legislation. It is understood that DWR's proposal is an interim measure. However, interim measures have a history of becoming permanent. The 1948 Critical Groundwater Code, an interim measure, lasted for over 30 years.

Bob McCain holds an M.A. in Political Science from the University of Arizona and is currently Program Director of the Arizona Municipal Water Users Association (AMWUA).

THE RIO SALADO PROJECT AS AN OPPORTUNITY FOR ARTIFICAL GROUNDWATER RECHARGE

Dennis A. Davis

My purpose today is to discuss the opportunities for artificial groundwater recharge that may be offered by the Rio Salado project. One of the institutional variables associated with recharge is that of multiple use - specifically the recreational use of recharge facilities. Rio Salado, as presently conceived, may offer substantial opportunities in this area. In addition to providing a means of joining recharge together with recreation, it also will create other benefits to the urban area. Included will be the creation of attractive and desireable landscapes, the reclamation of areas that have been environmentally damaged, good urban design, and the attraction of high-quality private developments.

A brief overview of the Rio Salado project will set the stage for this discussion. The concept was born in 1966 at the College of Architecture at Arizona State University. From a student assignment came a proposal for restoring life to the Salt River, which had largely been abused for many years. The idea was to transform the riverbed into a series of water-based parks and recreation facilities, with other types of development on the adjoining land outside of the floodplain. Community-wide discussion and support of the idea resulted in the creation of the Rio Salado Development District by the Arizona Legislature in 1980. The District was given limited authority to begin the project and was specifically charged with the preparation of a Master Plan that would define a feasible project. This plan was to be the basis for a financing proposal to be made to the Legislature. That assignment has been completed. A Master Plan was prepared and a

financing mechanism is now under legislative consideration.

The Master Plan proposes the creation of almost 4,500 acres of public recreational areas and facilities - including 1,500 acres of lakes, streams and other water features. Some 4,300 acres of private development are expected to occur on the edges of these recreational areas. The bulk of the water features will exist in the channel after the completion of upstream flood control. The channel will be designed to pass the resulting smaller flood flows and to also accomodate the lakes and other recreational features. Indian Bend Wash in Scottsdale is a smaller model of the concept.

The Master Plan suggests the possibility of groundwater recharge as a part of the project. The District has supported efforts to acquire Congressional authorization and funding for the demonstration project that was proposed by the Corps of Engineers in the 1981 Phoenix Urban Study. However, no detailed technical evaluation has yet been done. Such an investigation would be needed in order to determine the feasibility of incorporating recharge into the project. This could be done, assuming the approval of Rio Salado's funding by the Legislature, as one of a series of detailed studies and plans that will build upon the Master Plan. Such a study would have to be coordinated with the efforts of other interested and responsible agencies. Obviously, the many technical, institutional, legal and economic issues that are under discussion at this conference must be resolved in order to create a successful project.

But Rio Salado, with its multi-use characteristics, may offer some special considerations - both potential problems and opportunities. It could provide a means of solving problems and testing concepts. It could generate more interest in pursuing the idea of artificial recharge.

Several points are germaine to the discussion. They are presented only as ideas for consideration, recognizing that more in-depth analysis will be needed.

Physical Parameters: Conflicts may arise in the design and operation of facilities that have both recharge and recreation purposes. For example, a recharge basin that is designed to accomodate recreational activities may be less efficient in its infiltration rate. There may be maintenance needs for recharge purposes that will disrupt the recreation activities. Numerous design factors would require consideration in order to create a compatible system. This issue is perhaps even more important for Rio Salado than for other situations. Here the concept includes a major transformation of the area. More is involved that just the individual recreational facility. The design must also consider the relationship with the overall Rio Salado concept. A careful balance among all of the various objectives would have to be designed into the system.

But herein lies a major opportunity. Some reseachers have concluded that the biggest barrier to multiuse recharge is the fact that older facilities were planned and designed for a single purpose. No thought was given to possbile multiple use. Serious problems exist in adapting these existing facilities to other uses. In our case, we have the opportunity to accomodate all of the needs from the beginning instead of trying to re-do existing systems. Thus, a major barrier to multi-use facilities is overcome at the outset.

Costs & Resources: Another institutional concern with multi-use projects is the relationship between the recreational authorities and those with recharge responsibility. This involves, among other items, the willingness of recreation officials to assume part of the cost. There are obvious limitations on fiscal resources. If the major

thrust is toward recharge, there may be no funds to cover landscaping and recreational facilities.

Here, again, Rio Salado offers a major opportunity. The project proposes to build major recreational facilities, including lakes, ponds, and water courses. The funding for these improvements is included in the Rio Salado financing program. Assuming legislative approval of the project, these resources will be available. Thus, another major barrier to joint use is breached. In fact, joining these resources with those that may become available for recharge purposes may be the key to achieving both ends where neither would be completely possible alone. Multiple benefits could be realized with smaller investments from each source. A synergistic situation would evolve.

Water Supply: Another barrier to joint use projects that has been identified by researchers is that of a seasonal variation in the water supply. Water sources in projects used solely for recharge may vary in the amounts available over time. A successful recreation project must have a reasonable stability in the amount of available water.

Again, joint consideration of this issue may generate overall benefits. In order to be successful, Rio Salado must acquire a dependable water supply - with or without artificial recharge as part of the system. The current Rio Salado water acquisition strategy specifies the use of effluent as the ultimate source. The preparation of a detailed water plan will further analyze the parameters of this source and will hopefully result in contracts for the acquisition of such water. Preliminary discussions with the City of Mesa have indicated an interest in providing effluent from the Dobson Road Treatment Plant. Other possibilities also exist.

The amounts of water that have been calculated to be needed for Rio Salado do not include groundwater recharge. They include only the water needed for irrigation and that lost to evaporation. Thus, additional water would be needed to achieve recharge. It may be possible to combine Rio Salado's acquired sources with water from the sources that are to be recharged to achieve a constant supply for the system. This recharged water would belong to and could be recaptured by some entity other than Rio Salado. Rio Salado's source would be used to maintain a constant supply. This scenario obviously has numerous technical and management issues that must be resolved, but the potential seems to deserve consideration.

Management: The system under which a recharge program would be managed adds another dimension that relates to Rio Salado. Obviously, a number of entities have interests and responsibilities that must be accomodated. Rio Salado adds one more actor to this already - complex institutional situation. In this sense, it may appear to complicate the problem even further. However, even here the project may have a positive influence.

The Rio Salado Development District has not analyzed this issue in detail and has no specific proposal to make. However, it should be recognized that Rio Salado needs to be integrated into whatever management structure is defined. The one contribution that could be made by Rio Salado is a catalytic one. The interest in and support for Rio Salado may provide a forum for the resolution of this issue.

Legislative Needs: Obviously, the legal and institutional problems will not be solved without legislation. Again, this may be difficult to accomplish. It will require support from many areas. Rio Salado's

participation may add one more influence to affect that decision. If Rio Salado is to happen the general public support that exists must be transmitted into influence on the appropriate decision-makers. That public participation could include support for the legislation that is needed to make artificial recharge possible.

This has been a rather cursory listing of some of the issues involving Rio Salado and the concept of groundwater recharge. Much more detailed analysis will be needed as Rio Salado planning proceeds. They have been presented here simply as ideas for consideration. However, it seems reasonable to conclude that efforts to implement Rio Salado and to make artificial recharge feasible can be mutually supportive. By pooling support and resources both objectives have a higher degree of probable success. The Rio Salado Development District will participate as appropriate in these efforts.

Dennis A. Davis holds a Master of Planning degree from Cornell University and is currently Deputy Director of the Rio Salado Development District, Phoenix, Az.

CURRENT AGENCY PLANNING AND PROGRAM ACTIVITIES
IN ARTIFICIAL RECHARGE:
U.S. BUREAU OF RECLAMATION

remarks by 1/
David Gudgel
Regional Planning Officer

This afternoon I would like to talk briefly about the direction of the Bureau of Reclamation's program, particularly in the arid Southwest - the Lower Colorado Region. When you think about the Bureau's program, quite often things come to mind that go clear back to the beginning of reclamation activities. Things such as Roosevelt Dam, moving forward in time - Hoover Dam, Glen Canyon Dam, and Central Arizona Project - are all relatively large water resource development projects. As has been mentioned numerous times here today, the Bureau is recognizing along with everyone else that there is not really much call for such large projects anymore. Most of the major water resources have been developed. We now recognize a need for getting into the water conservation area, water management area and other programs of this nature. As a result of that, we are redirecting our program somewhat. That is not to say that we are not going to continue to be involved hopefully in resources development activities, but we are also trying to get into the other areas that I just mentioned. As a result of that, a lot of our new planning efforts are involved in water conservation.

In this regard, we are involved in a number of conservation and management programs in the Imperial Valley in California. A reference was made in the morning session to recharge activities in the Santa Ana River Basin in California. This is an area where there are a number of different entities involved in water resource use and they don't all have the same goals and; therefore, in some cases, are causing some problems for one another. One of the studies we are going to get involved in is developing some kind of management plan for the Santa Ana River Basin. Actually, I should say that we hope to get involved in, since it's a project that we are looking at, but we don't have funds budgeted for it yet.

Another project that we are looking at is here in Arizona in the Tucson area. The Corps of Engineers has also been doing some work in that area. The City of Tucson has been and we intend to begin working with them to develop some kind of water recharge plan. We recognize that there are a lot of problems. Legal and institutional issues were reviewed earlier this afternoon. I think

1/ Edited from taped transcript

there is going to be a great deal of effort going into getting those kinds of issues resolved but if we can get money budgeted for the Tucson study we hope to get involved in that area.

One of the things I really wanted to spend more time on this afternoon was something else that will be going on in Arizona as well as in the rest of the Western reclamation states. Last September a piece of legislation was passed by Congress, Public Law 98-434, called the "High Plains Groundwater Demonstration Program Act of 1983". I'm not sure about the reference to 1983 since it was passed in 1984, but in any event that's what it is called. This legislation directs the Secretary of Interior acting through the Bureau of Reclamation to implement a series of groundwater recharge demonstration projects throughout the 17 western states. It is an interesting piece of legislation because it is quite specific in what is required. It provides that at least 12 of 21 of these demonstration projects should be in the High Plains states. There are 8 states identified as being High Plains states. This legislation also provides that there should be at least 9 demonstration projects in the remaining reclamation states. It just so happens that there are 9 other Reclamation Act states so I think the intent was probably to have at least one in each state. Although it doesn't specify that and it doesn't indicate that there can't be more than that.

As mentioned, this legislation has some fairly specific requirements and I think they are legitimate requirements, but they may cause some problems in areas like Arizona. One of these requirements is that the demonstration projects must be in areas where there is a declining groundwater table. That shouldn't be a great problem here in Arizona. Another requirement is that there has to be an identified surface water supply and another provision of the act is that the water source has to be legally available under existing interstate compacts and state water law. I don't know yet what kind of problems that might create in Arizona, that is something we will have to investigate when we reach the point of implementing this program.

The legislation provided $0.5 million to undertake phase one of the studies, which is basically a two-year effort to identify the projects that we plan to proceed with into the construction phase. There are a couple of steps in that process insofar as we are obligated within six months after funds become available for that study to submit a report to

Congress identifying the projects that will be studied. At the end of the two years, we have to submit a report to Congress indicating which of those projects will go to construction. Then we have five years to construct the projects, do whatever monitoring is necessary to determine whether or not they are effective and whether or not there are any environmental, water quality or other related problems. The program self-destructs at the end of five years, since there is no funding provided for beyond that point. What that means is that Federal involvement would come to an end and; therefore, for those projects that are developed there has to be a provision for the sponsor of the project to either reclaim the area or to continue to operate it at their own expense. Another provision includes a requirement for cost sharing of the construction phase. The legislation proposes $20 million in Federal funds for the construction phase and it requires there be a 1 to 4 cost sharing, which indicates that the states or entities involved in these projects would have to put up about $5 million total.

Next, I would like to discuss briefly how we are going to proceed with this program. As I said the legislation was passed in September of last year (1984). In October of last year, the Assistant Secretary for Water and Science and the Department of Interior sent a letter to the governors of all 17 Western states requesting that they submit a name of a coordinator to represent the governor in this program. Also transmitted to the governor was a plan for proceeding with site selection for potential sites. Our intention with the program is to have the states submit to us their recommended recharge projects. That doesn't eliminate some private entity, water district or city from submitting a plan. We would like, however, to have all those plans submitted through state channels so that we are sure it has been coordinated within the state. Since we must submit a report to Congress within six months after funding is available, we would need to have all those submitted to us within six months of the time funds become available for implementing the program. Talking about funding, I should say we have no funding for the program at this point. There was no funding specifically identified in the President's budget this year. However, there was about $2.5 million in the Bureau of Reclamation's general investigations program that was identified for new planning initiatives in fiscal year 1986 starting this October. Included in that amount was about $325,000 to initiate activities on this study. Assuming Congress appropriates those funds, we do intend to get started on that effort during the fall of 1985.

Following submittal of proposals from each state, we need to go through a period of evaluating those proposals. We are in the process of developing an interagency agreement or a memorandum of understanding with the U.S. Geological Survey (USGS) to do that evaluation. We intend to have the USGS do the hydrologic and geologic evaluations. There are also some requirements in the legislation providing that the demonstration recharge projects have some potential for economic viability so we would intend to go through some economic analysis of the projects. We would also take a technical look at the features that would be required to develop the projects.

The legislation also provides that we must coordinate this program with the Environmental Protection Agency (EPA). We are also in the process of preparing a memorandum of understanding with EPA for their involvement in the program. Their involvement is to evaluate the projects to ensure that they do not have substantial adverse quality impacts on the existing groundwater supplies. We are still in the process of negotiating these required interagency agreements. We should have that done within the next couple of months. So if the funding becomes available this fall, which we expect it might, then we will be asking for submittal of proposals at about that time. If we have some assurance that funding is going to become available before that time frame, we want to give everyone as much notice as we possibly can so they can start preparing their proposals.

I feel this is going to be a very interesting program. It is one we are really looking forward to getting involved in. I think it is going to present quite a substantial number of problems. There are specific requirements in the legislation that in some cases are going to be fairly difficult to meet and it is going to take a great deal of effort and coordination among the various Federal agencies and the states to get those things resolved successfully. I expect that we will be working with a number of you on this program to demonstrate and monitor groundwater recharge results.

David Gudgel holds a B.S. degree in Civil Engineering from the University of Wyoming and is currently Regional Planning Officer for the U.S. Bureau of Reclamation's Lower Colorado Region.

CURRENT AGENCY PLANNING AND PROGRAM ACTIVITIES

IN ARTIFICIAL RECHARGE:

ARIZONA DEPARTMENT OF HEALTH SERVICES

remarks by 1/

Susan Keith
Chief Hydrologist

Before I begin, I would like to congratulate the hosts, sponsors and organizers, in particular Floyd Marsh for putting together a real successful conference.

To begin my comments, I'm going to focus on a copper mine tailings pond located between Tucson and Nogales, Arizona, which basically constitutes an artificial recharge project for the purpose of waste disposal to ground water. To orient you, this area of interest is near Interstate 19 between Nogales and Tucson, generally west and north of Green Valley and west of the Santa Cruz River flood plain. The tailings pond of interest is in the general area near Green Valley, Arizona. Based upon contours of chemical concentrations of total dissolved solids (TDS) in ground water, we are looking at concentrations ranging from 2,500 parts per million (ppm); 2,000 ppm; 1,000 ppm and a projected 500 ppm near the tailings pond across this area of interest in contrast to ambient conditions of less than 200 ppm. Ground water flows in this direction away from the tailings pond and then turns north. This sketch (overhead transparency) and data is from a recent Pima Association of Government's report on water quality.

Ground water at this specific location is being used for the purposes of waste disposal. In fact, ground water in many parts of the State is being used for artificial recharge projects for the purposes of waste disposal. This is why we have recorded over 350 wells which are contaminated and I am sure there are a lot more contaminated wells out there. The reason that ground water has been used for the purposes of waste disposal is because of the well known scientific axiom that "in the real world waste migrates in the direction of least regulation". These are things they don't teach you in school but probably are a lot more true and valid than a lot of the science you learn. In Arizona, as in much of the United States, ground water has been the last area of regulation. In the 1950's and 1960's, air quality regulations were developed and implemented and that forced facilities that were discharging pollutants to the air to discharge to some other

1/ Edited from taped transcript

media and that went usually to surface water. But, in the 1970s we developed surface water quality regulations and standards and then that forced facilities to take the pollutants out of the surface water and the last place they had to put it was in the subsurface and into ground water. So essentially what has happened is that the earlier regulations pushed facilities into artificial recharge projects for the purposes of waste disposal to ground water. But now, the State of Arizona, as of the last 12 months has groundwater quality standards and a groundwater permit regulation system which is administered by the Arizona Department of Health Services. The purpose of this talk is to briefly review these standards and regulations to show how they will affect artificial recharge projects that are undertaken for any purpose, whether it be waste disposal or water supply and augmentation.

First, we are going to look at the standards quickly. The standards are pretty simple, quoting directly from the overhead transparency:

A. Discharges of any pollutants and disposal of any waste shall not impair the uses for which have been made, are being made or will be made of ground water for every purpose.

B. Discharges of any pollutants and disposal of any waste to ground water of the State shall not cause a public health hazard.

C. Disposal of any hazardous waste, radioactive waste, or other waste shall not cause toxic substances to be present in ground waters of this state in concentrations which are or may be hazardous to public health or which interfere with present and future uses.

D. Discharges of any pollutants and disposal of any wastes to ground water shall not directly or indirectly cause violation of surface water quality standards.

There are three important things to note about these standards. First of all they are narrative and not numeric, i.e., they don't say that ground water quality shall not exceed 10 milligrams per litre of nitrate or whatever. This has its advantages and disadvantages. It brings a tremendous amount of flexibility to the system and it gives anybody who wants to the opportunity to argue for any interpretation of what they mean. So from the positive standpoint it means that we in the Department of Health Services and other public-interest groups can take a very conservative interpretation of what the standards mean and argue for it. From the negative perspective, lawyers for a facility that does not want the extra restrictions added to its waste

disposal process can argue for a very liberal interpretation and who knows what would happen if it went to court.

The second thing to note is that the standards do recognize the relationship between surface water and ground water that exists in certain parts of the State where you have ground water that feeds surface water systems, such as in the Oak Creek area near Sedona. In this area, that allows us to take a fairly strict approach to the disposal of domestic wastes to the alluvium along the banks of Oak Creek. We are in fact applying a much stricter standard because the surface water standards are a lot stricter there than a ground water standard would be.

As a third point, a very important thing to notice is that the standards are use oriented including future uses. In one case they even mention the past uses although I don't know how that would be applied. So you can see that how uses are defined becomes a very critical part of this whole system because if a facility was discharging to an area of ground water that is protected for irrigation use, they would have to comply with far fewer restrictions and it would be much cheaper than if they were discharging to an area that were protected for drinking water use. Basically, the way we have been handling the use-designation question is to rely on use designations made by recognized planning agencies. For instance, a council of government (COG) in the Tucson area, the Pima Association of Government (PAG), has designated water quality management goals for the Tucson area. Active Management Areas (AMA's) designated by the State Department of Water Resources are also recognized planning agencies. I believe a couple of the AMA's are coming out with use designations in their next management plans. EPA is also considered a recognized planning agency. For example, they designated the Tucson basin as a sole-source aquifer and they are currently in the process of developing a ground water classification scheme to define different levels of protection for sites that are regulated by various programs including Superfund. What we are doing is when a planning agency hasn't already designated a use basically is assuming drinking water as the potential designated use, because if it isn't currently being used for drinking water there is a good probability that in the future it is going to be used for drinking water. And, we are supposed to be protecting for future uses.

That is a quick overview of the standards and now I will briefly overview our ground-water permit regulations. In a nutshell, they allow a facility

to discharge if the discharge will not cause a violation of these standards. The regulations require the submittal of data and information that would allow one to assess whether or not the standards would be violated. If it's found that the facility's discharge will not or probably will not cause a violation of standards, the facility will be permitted often times with permit conditions that require monitoring to document that standards really won't be violated.

From this previous discussion it is obvious I think how the standards and the permit regulations will affect any artificial recharge project. Remember that the standards are use oriented and that essentially, unless we are told otherwise, the Department protects for drinking water use. So the water quality constituents that we will get most concerned about at any particular site would be those with public health implications such as pathogenic microorganisms, nitrate, arsenic, barium, selenium, lead and hazardous and radioactive wastes.

This was not an unexpected outcome of the ground-water regulation and standards development process that so many of the entities and many of the representatives present here were involved with for the past 3 to 4 years. However, I think what was really unexpected -- and what threw a real wild card into the equation for all the entities that have been planning for an artificial recharge project for supply and augmentation purposes using sewage effluent or Central Arizona Project (CAP) water -- was the action taken by the Arizona Water Quality Control Council at their April 10, 1985, meeting just a few weeks ago. This is the action that Don Maughan alluded to this morning in his symposium overview paper.

I am going to review what happened at the Council meeting briefly right now and put forth an interpretation of what it possibly means in the future.

At that meeting the Department of Health Services requested the Council to find the four copper mines south of the Tucson area described earlier in violation of the Department's water-quality standard stipulating that discharges of any pollutants and disposal of any waste shall not impair the uses which are being made or will be made. We made that argument on the basis that use impairment had occurred because ground water in the area had been designated for drinking water use by the Pima Association of Governments and that the secondary standards for drinking water for TDS, which is 500 milligrams per litre, and for sulfate, which is 250 milligrams per litre, had been exceeded as a result of activities by the mines. In the "cause-effect" relationship between the mines, the TDS and sulfate concentrations were determined from

data which showed much higher concentrations of total dissolved solids and sulfate next to the mines versus the much lower concentrations of TDS and sulfate in the natural ambient ground water and also upon changes in concentrations through time. This figure (overhead transparency) shows an increase in sulfate concentration from close to zero in 1970 to over 500 milligrams per litre in 1981 and the next graph shows changes in total dissolved solids from about 200 milligrams per litre to over 1,000 milligrams per litre between 1970 and 1981.

Based upon these arguments, the Council found the mines in violation of the ground water quality standard I mentioned earlier. Again, there wasn't any question in anyone's mind that health-related water quality constituents would have to be complied with in any artificial recharge project. I don't think most people anticipated that things such as TDS and sulfate would suddenly become a part of the equation and we subsequently received a lot of expressions of concerns over the implications of that Council action on artificial recharge projects, whose purpose are supply augmentation and conjunctive use. What is the implication of this action on those types of projects? I think it is too soon to say exactly how this action will affect the projects. I think it could be used by interests who are opposed to these types of projects in the future so it could become a political weapon. I think right now, based on the facts that the standards are narrative and that they are use oriented, that when we are talking about public health-related constituents, which TDS and sulfate are not, we know there is not flexibility in the standards with respect to how we apply and interpret them. I think when it comes to constituents that are not of health concern, like TDS and sulfate, that there is going to be a lot more flexibility.

In the case of the Council action, PAG and other entities had told us and the Council basically that we are unwilling as a society to accept any further degradation of groundwater quality at these sites due to mining activities. But, that doesn't necessarily mean that the TDS and sulfate standard that was derived for this particular situation would apply to every other situation in the State. If a planning agency such as a COG or an AMA were to come to us and say we want to set aside this area for an artificial recharge project for supply augmentation, we know that TDS will increase "x" milligrams per litre as a result of these activities and that through our public participation process we have determined that this was acceptable,

given the tremendous benefits that would be realized from supply augmentation in this case. I think as a Department, it would be very probable that a different standard for total dissolved solids would be applied to that site.

To sum up, Arizona now has ground-water quality standards and regulations that will protect ground water from undesirable effects from any type of artificial recharge project. The standards and the permit regulations work together to keep water quality constituents of public health concern in ground water below levels at which they will become a problem. However, in terms of the non-health related constituents such as TDS and sulfate, there is a lot more flexibility in terms of the level to which they will be regulated.

Susan Keith holds an M.S. degree in Water Resources Administration from the University of Arizona and is currently Chief Hydrologist and Manager, Hydrology Unit for Arizona Department of Health Services.

CURRENT AGENCY PLANNING AND
PROGRAM ACTIVITIES IN ARTIFICIAL
RECHARGE: ARIZONA STATE LAND DEPARTMENT

remarks by

Robert Yount
Chief, Natural Resources Division

Introduction

You may well ask yourself why the State Land Department (SLD) is participating in this symposium. We obviously recognize the value of exchanging information in the symposium setting and we all have enough curosity to want to keep informed, but beyond this the Land Department has a vested interest in the subject and will in all likelihood be a major participant in any large recharge projects that occur. In order for you to more fully understand the need for our involvement we need to review some of the history of the Department. As we look at this history keep in mind that the State holds in trust over 9.6 million acres, a little over 13% of the land area of the State and much of this land was selected over the large alluvial valleys and in close proximity to our population centers.

Historical Perspective Circa 1915-1974

1. A.R.S. Article 7 of Title 37, relating to land settlement provided for the Department's acquisition and operation of Federal reclamation projects on state lands. Included was the authority to acquire water rights and appropriate water. This portion of the statutes was repealed in 1980. However, the Legislature retained Article 6 relating to reclamation of state lands which charged the Land Department with the responsibility of making preliminary investigations and recommendations to the Legislature for stored floodwaters and the development of groundwater reserves. Initial enactment of this statute was around 1915.
2. A.R.S. §37-105 which was enacted in 1951 provided for the inclusion of state land (trust or otherwise) in reclamation projects and §37-106 provided money to be used as a federal reclamation trust fund. This fund was established to pay for any delinquent irrigation water assessment related to said reclamation projects.
3. In 1974, the Legislature expanded our authority by adding §37-106.01 giving us the power to contract and pay for Central Arizona Project (CAP) M & I water for use on state lands. Clearly, the long-term legislative intent has been to provide for all participation of the Land Department in all types of reclamation

projects even though groundwater recharge has not been specifically mentioned.

Recent Concepts 1970's

1. During the mid-70's, as the staff of the Water Rights Division began to grow and the Agriculture Leasing Program began to evolve, it was realized that a unique opportunity existed for the utilization of Butler Valley's groundwater supply. This interest was peaked by the Bureau of Reclamation's cursory investigation of a potential alternative source of water for abatement of the salt-loading problem that existed in the Colorado River. It was determined that a desalinization plant was a more practical long-term solution to the salt-loading problem than the proposed pumping from a well field in Butler Valley. Agricultural development on state land in the Valley had been initiated and it was estimated that approximately 6,000 acre-feet per annum was being utilized for this purpose.
2. During the 75-80 time-frame applications were received by the Department to expand the farming activity in the Valley, however, the potential for using this water for M & I purposes seemed highly desirable and discussions were initiated with the Bureau of Reclamation and the Arizona Water Commission for use of the groundwater to supplement or fully provide for development of state lands in the main municipal areas of Maricopa and Pima Counties. This concept was not received very favorably. However, other entities had begun to look for supplemental supplies and Butler Valley was perceived as an excellent site for both water extraction and storage.

   At the same time the Land Department began to evaluate the potential for use of floodwaters which were to be retained behind the CAP flood protection dikes. Because of the problems related to the highly variable nature of rainfall and the need to dispose of the water retained behind the dikes in a very short period of time, as well as the problem of debris, the Bureau of Reclamation had developed a "shunt and dump" solution which did not consider the need to retain, use, or recharge this water. We now realize that that solution may no longer be viable but at the time it was the only practical or economical answer that the Bureau would consider.
3. At the same time a significant amount of energy was being exerted by the Department staff on legislative recognition of the public water responsibilities and the development of the Groundwater Code. Recharge was not considered to be one of the more important subjects during the late 70's, in the SLD, because the major emphasis was directed toward completion of stockpond registration, and filing of pre-1919 claims as well as the transfer of the Water Rights Division from the Land Department to the Arizona Water Commission.

Concepts 1980's

With the establishment of a staff of hydrologists and water resource specialists in the SLD to deal exclusively with the trusts water responsibilities we have begun to reevaluate the potential needed to husband our water resources and make the most beneficial use of the trust land holdings. We are aggressively pursuing the utilization of trust lands as recharge sites and trying to work with various cities and university personnel to develop floodwater protection and recharge projects. We are attempting to work within the flood control programs to discourage the "shunt and dump" concept and we are trying to encourage maximum conservation of our water resources where the greatest uses occur, i.e. in the area of agricultural consumption.

Summary

In other words, we are attempting to do what the Legislature directed the Land Department to do in the 1915 - make the hydrologic investigations and accompanying reports which are necessary for the reclamation of state lands. We are attempting to identify the opportunities for recharge projects on state land. We would encourage you to consider state land when you are looking at recharge projects.

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SESSION III: ECONOMIC AND FINANCING ASPECTS OF RECHARGE

MODERATOR: GARY WOODARD,
UNIVERSITY OF ARIZONA
DIVISION OF ECONOMIC AND
BUSINESS RESEARCH

An Overview of Economic Considerations in Artificial Recharge Programs

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*May, 1985

Introduction

Economics involves the study of choice-making under constraints. Economic concepts allow us to analyze and evaluate how individuals and societies allocate limited resources among competing ends. Two general economic criteria are used to evaluate policy decisions--efficiency and equity. These criteria directly address policy objectives since most polices are formulated either to increase overall well-being (efficiency) or to redistribute economic goods and opportunities (equity).

Efficiency poses the question--do the benefits from a proposed policy exceed the costs of implementing and maintaining the policy (benefits and costs estimated as accurately as possible in dollar terms), in other words are there postive net gains? If the answer is no, the policy should not be implemented unless there are some compelling equity reasons to justify incurring net losses. The efficiency concept underlies benefit cost procedures used to evaluate federal water projects. One weakness of the efficiency criterion is that benefits and costs are counted up regardless of who bears the costs and receives the benefits. Efficiency would approve a water policy which yields net economic gains even if all the costs are borne by one water-using group and all the benefits accrue to another group. Social impact analyses identify the gainers, losers, and the magnitudes of gains and losses so that policy makers will be

*Paper presented at second symposium on Artificail Recharge in Arizona, Tempe Arizona, May 2-3.

aware of the consequences of their decisions for various groups and can modify proposals accordingly. An efficiency criterion applied to artificial recharge requires that the stream of benefits attributable to a recharge project be more valuable than all the resources expended to implement and operate the project. Efficiency asks the question--when all the effects of this project are taken into account, will Arizona be "better off" with the project than without it? Equity requires that no water-using group "unfairly" gain or lose due to the project. Equity impacts could include changes in the price, quantity, quality, or reliability of water supplies available to particular groups. What constitutes "unfair" gains or losses is a subjective question and must ultimately be settled in the political arena. Efficiency and equity considerations provide the framework for economic evaluation.

Relevant Baseline Scenarios for Evaluation

What should an artificial recharge project be compared with, in an evaluation procedure? Every policy or project proposal has at least one alternative--to "do nothing", to maintain the status quo. A thorough evaluation must focus on the difference a recharge project would make in economic well-being; the "good" differences being the benefits of recharge, the "bad" differences being the costs.

A first step in evaluating recharge/recovery programs involves identifying the water management objectives that the project addresses. A second phase of evaluation determines whether the proposed artificial recharge project results in positive net benefits and acceptable distributional consequences. A final phase involves determining whether other means may be available to address the same objectives in a more efficient or more equitable manner. It is possible, even for sound policy objectives, that no available means to accomplish those

objectives will yield positive and acceptably distributed net gains. In such a case, the optimal strategy is to do nothing--to "do without" rather than undertake an uneconomical or inequitable project. Two caveats need to be mentioned here. First, one wants to be sure all relevant benefits and costs, even those that are difficult to place a dollar value on, are considered in reaching a policy decision. Second, even with net economic losses indicated, there could be compelling political or distributional reasons to go ahead with the project and incur the losses. The net costs can be viewed as the "price tag" of the political issues at stake.

A number of recent evaluations of recharge/recovery projects have used above-ground storage facilities as the basis of comparison. Underground storage has advantages in terms of less evaporative losses, land area occupied, and environmental disruption on the land surface. However, unless a decision has been made to store water irrespective of the relevant costs and benefits, a comparison to resevoir storage is not the appropriate way of evaluating recharge. This approach only asks the question--"would underground storage and recovery cost less than resevoir storage?", and does not ask whether overall effects are positive, what the distributional consequences are, and whether they are acceptable.

Recharge and recovery is sometimes compared to water supply augmentation schemes. It is important to note that recharge does not actually augment water supply. Rather, it alters the spatial and temporal distribution of existing water supplies, reducing reliance on seasonal water patterns, giving greater flexibility and control over water availablity, and allowing improved management of existing ground and surface water resources. It is this water redistribution over time and distance that makes recharge attractive, but this should not be confused with supply augmentation.

Another strategy that may address some of the objectives of recharge is reduced ground water withdrawals associated with water conservation and changing patterns of water use. If the principal goal of a recharge project is to maintain depth-to-lift at a higher level than it otherwise would have been, water conservation combined with a switch to alternative surface water supplies may accomplish similar ends, possibly at lower cost. However, if many of the benefits of recharge stem from greater control over timing of water availability rather than a higher water table per se, then these alternatives may not be attractive substitutes for a recharge project as they do not provide the degree of control that water storage does.

A final alternative that might be considered is augmentation of natural recharge through watershed management planning. Seventy to eighty percent of water yield in the West is the result of snowmelt generated from high elevation alpine and subalpine forest. Water yields can be significantly altered by timber harvest practices on these lands (Troendle, 1983). Management strategies on lower elevation range lands which alter vegetation and thus evapotranspiration can also affect groundwater recharge (Hibbert, 1983). If arrangements can be negotiated between federal and state land management agencies and the regions desiring altered watershed management, then some of the objectives of recharge/recovery programs may be acheived through augmenting natural recharge.

In summarizing points regarding an appropriate baseline scenario for evaluation; recharge/recovery programs are a means to an end and there may be other means to accomplish water policy objectives. The most appropriate baseline scenario is the "do nothing" alternative. Recharge and recovery, as well as any other water management strategy, should pass the test of positive net benefits when compared to "doing without". The with and without principle of project evaluation (Sassone and Schaffer) requires examining two scenarios over time--net benefits of water use associated with a recharge project, and net benefits

of water use without a recharge project. A decision to move ahead with recharge should be based on comparison of these two figures, along with assessment of the distributional implications and the net benefits of other possible means of accomplishing recharge project objectives. Only when set in this comprehensive framework, can decisions be made that consider the overall well-being of Arizonans.

One final note--policies can be evaluated from a national, state, or local perspective. Projects that yield net gains to Arizonans may not be efficient from a national perspective if the costs borne outside the state (by all federal taxpayers or California water users--for example) outweigh the net gains within Arizona. However, for the purposes of this Symposium an Arizona perspective seems appropriate and politically realistic, as each of the fifty states seek to maximize their own well-being, sometimes in spite of costs imposed outside their boundaries.

The Legal Framework and the Economics of Artificial Recharge

The security, exclusivity, and transferability of rights in recharged ground water are central to the success of any recharge program. The value of the recharged water depends on the assurance of being able to recover it (security), use it or sell it (transferability), and the knowledge that others are legally prevented from using the water without sharing in the costs of recharge and recovery (exclusivity). Since one of the attractions of recharge/recovery is increased water availability during seasons when demand is high and supply is low, an incentive to invest in recharge exists in the opportunity to extract an appropriate price from potential users of recharged water and to transfer water use rights to those willing to pay the price. Even if the legal environment provides well-defined water use and transfer rights to those who invest in recharge/recovery projects there are still unresolved legal issues.

Aquifer storage capacity becomes valuable when recharge programs are contemplated. Who owns excess storage capacity in an aquifer? Is such capacity held by the state, county or municipal governments? Do current and past pumpers who "created" the space own it, or do rights to aquifer storage capacity automatically accrue to anyone who invests in recharge facilities and imports water to recharge? Available storage capacity must be carefully defined--leaving room to absorb flood waters in high precipitation years, avoiding water intrusion into active mine shafts or a water table high enough to affect irrigation drainage, crop yields, and salt deposition on land surfaces. While all these problems seem farfeteched in a state with historically declining depth-to-lift, they could potentially occur with active recharge projects. High water tables are a problem for agriculture in many semi-arid regions, such as the lower San Joaquin and Imperial Valleys, although groundwater depletion has prevented these types of problems in much of Arizona--the Yuma area being a notable exception.

Several types of externalities (unintended side effects of a project in economics terminology) are relevant to recharge and recovery projects. Positive externalities ("good" side effects) would include reduced depth-to-lift and thus reduced costs for groundwater pumpers overlying the recharged aquifer. These pumpers will, in the absence of special authority to tax or charge them, enjoy these benefits without sharing proportionally in recharge costs. If a higher water table causes surface water to flow more months of the year or at higher levels this may yield benefits to surface water users, recreationists, or fish and wildlife habitat. A recharge project could be specifically designed to accommodate water-based recreation--which has very high value in the Southwest and could add substantially to the benefit side of the "project ledger". The existence of positive externalities (which should be counted as benefits of recharge even though they may be unintentional side effects from the recharging

agency's point of view) may have implications for financing recharge projects. If a substantial proportion of the benefits of recharge/recovery programs accrue to persons who cannot be effectively charged for the benefits received, there is decreased private incentive to finance a recharge project and public financing may be indicated.

There may also be negative externalities associated with recharge. These include potential for flood damage if the aquifer is filled to capacity and cannot absorb unusually heavy precipitation (a possibility that can be mitigated by careful management of recharge projects). With recharge the average depth-to-lift of an aquifer over a period of time would be higher than without recharge, but the variance in depth to lift might also be greater due to cyclical recharge/recovery patterns. This variance could pose a problem for neighboring groundwater pumpers trying to plan their water use and anticipate their pumping costs over various seasons of the year. A risk-averse groundwater pumper might prefer a larger, but predictable, depth-to-lift to a water table that fluctuates significantly up and down over time.

Externality concerns differ depending on whether the aquifer is in a unpopulated area and used only for storage (remote storage), with recovered water being conveyed over the surface to water users, or whether recharged waters are recovered and used directly on the land overlying the recharged aquifer (use-site storage). If there are no other users of the recharged aquifer then positive or negative externalities will be minimal. On the other hand, use-site storage--while subject to all the externality issues just raised, has the advantage of allowing individual pumpers to recover and use recharged water from wells located on their own property without the need of surface conveyance. A careful hydrologic, legal and economic distinction between use of native groundwater and use of recharged groundwater would be necessary in use-site

storage programs. Should the cost of using recharged water be different than the cost of pumping native water? If so, how will the distinctions be drawn and payments be calculated and collected?

The source of the water to be recharged and the alternative uses to which that water would have been put also significantly affect the economics of recharge and recovery programs. If the water would, in the absence of artificial recharge, have flowed through the state undiverted, it may have provided in-stream wildlife habitat and other environmental and recreation benefits. To the extent these are diminished by recharge, they must be counted as an opportunity cost of the project. If agricultural return flows or surface water supplies are affected by a recharge project, the economic effects on the agricultural sector need to be included as opportunity costs of recharge. Water previously unused and yielding no benefits in the absence of recharge is "free" and no costs need be attributed to its use. Artificial recharge may shift the spatial distribution of natural recharge--capturing and storing storm runoff closer to a city than it otherwise would have been, for example. In this case there will be benefits to the city but costs to those who benefited from natural recharge at the more remote site (Agthe, p.9).

A Checklist of Benefits and Costs Associated with Recharge Projects

Possible Benefits

- increased flexibility and control over timing of water availability, including reduced dependence on seasonal water patterns
- expanded management possibilities for existing ground and surface water sources
- ability to store water that otherwise goes "unused", such as storm runoff and effluent
- reduced depth-to-lift and pumping costs for pumpers overlying the recharged aquifer, energy savings
- reduced subsidence in area affected by higher water table

- recreation, aethsetic and wildlife benefits associated with higher water levels and settling ponds

- reduced saltwater instrusion (coastal areas)

- water quality effects--infiltration can remove suspended solids, bacteria, and other pollutants

- expanded flood control management possibilities

- aquifer as a substitute for surface conveyance (use-site storage)

- extended useful lifetime of aquifer

- indirect effects on production costs and output levels in water-using industries and agriculture

- value of new technical and economic information provided by recharge/recovery demonstration projects

Possible Costs

- obtaining water to recharge (legislation, litigation and conveyance costs)

- opportunity costs of water, what values would recharged water have in the absence of a recharge project?

- obtaining land for recharge facilities--purchase costs as well as opportunity costs

- modifications of activities on land overlying aquifer needed to protect groundwater quality

- water quality treatment needed before injection

- recharge and recovery structures and equipment

- energy costs associated with recharge, recovery and conveyance

- project start up costs--feasibility studies, permits, environmental impact assessment

- decreased capacity of aquifer to absorb flood waters

- seasonal variance in depth-to-left due to cyclical nature of recharge and recovery

- operation and maintenance of recharge facilities

- pest control around settling basins (no mosquitos please!)

- security and public safety measures around recharge facilities

A Checklist of Questions for Recharge Project Planners

1. Location of Recharge Site

To a large extent this will be determined by hydrogeologic considerations. However the advantages and disadvantages of use-site recharge, in which recharge beneficiaries can recover water from their own wells without the need of surface conveyance, versus remote site storage in an unpopulated area, involving minimal concern about side effects of a project, should be considered.

2. Capacity of Recharge/Recovery Facilites

Ideally capacity should be expanded to the point where marginal costs of expansion equal marginal benefits of additional capacity. However there is little data on economies of scale in recharge projects. Is it cheaper per unit of water to construct and operate facilities for 100,000 acre feet of recoverable water per year than for 20,000 AF? How much cheaper? Should several small local projects be combined into a bigger regional project? Most importantly, does regional water demand exist for the projected capacity of the project? At what price levels does sufficient demand exist? These questions should certainly be discussed by project planners even though information may not be available to formulate precise answers.

3. Timing of Recharge/Recovery Operations

Several different possibilities could be considered and can be thought of as analogous to different types of bank accounts. Water may be recharged and recovered on a regular cycle coordinated with seasonal precipitation. Water would be routinely recharged in wet months and extracted in dry months, a "checking account" arrangement for water banking. Another approach would be to recharge water with the intention of recovery only in low precipitation years with guidelines established to determine under what circumstances water will be withdrawn, a "savings account" approach. A final strategy would be to recharge water with the idea of storing it indefinitely against unexpected emergencies or

increases in demand, a "long term investment" approach.

4. Sources of Water for Recharge

Water for recharge should come from sources with low or zero opportunity costs--water which would have little value in the absence of recharge. Storm runoff, flood waters, and sewage effluent are obvious candidates if sufficient quantities are available. Undiverted surface water may appear to be a low cost source but any instream values generated by that water (fish and wildlife habitat, recreation, aethsetics) must be counted as opportunity costs of a recharge project to the extent water is diverted out of stream.

5. Selection and Prioritizing of Project Objectives

What objectives will the project be designed to accomodate? Would slight modifications of settling basin design or landscaping enhance aethsetic appearance or value (if any) for fish and wildlife? Is recreation around recharge facilities to be forbidden, tolerated to the extent it doesn't interfere with project operations, or integrated into project plans? How, if at all, will regional flood control be coordinated with recharge operations?

6. Pricing Policies

Will recovered water be priced to cover long and short term costs of the project, or will prices be set based on costs of alternative water sources in the area (CAP for example)? Will prices be raised in low water supply years to reflect a scarcity value? If so, what are the equity implications? What groups will be unable to afford project water? If prices are <u>not</u> going to be raised when demand for recharged water exceeds supply, then what non-price mechanism will be used to allocate available water among potential users?

Summary and Conclusions

Recharge projects are most likely to yield net benefits under the following conditions:

1. A significant intertemporal and spatial imbalance exists between peak water demand and supply so that potential benefits from recharge are high.
2. The costs of obtaining water to recharge, including opportunity costs reflecting the water's value in the absence of recharge, are low.
3. Adequate aquifer storage capacity has been clearly identified and is available to the recharging agency at low cost.
4. The project is planned so as to yield multiple benefits including underground water storage and conveyance, aethsetic effects, wildlife habitat, recreation, and flood control.
5. Rights to use excess aquifer storage capacity, to recover recharged water and to collect payments from water users are well defined. The legal environment provides security, transferabilty and exclusivity of rights in recharged water.

A range of water policy alternatives always exists, including "do nothing". Demonstration projects may be justified even if net project benefits are negative, if the new information they provide is expected to help make better decisions on recharge projects in the future. "Better decision" means decisions that maximize net benefits and promote acceptable distribution of income and access to water. "Better decisions" could mean acceptance or rejection of recharge projects depending on the results of site-specific evaluations.

In summary, the central questions that should be addressed in considering a recharge project are:

1. What are the water policy objectives that this project can address?
2. Is an artificial recharge project the most effective way to accomplish these objectives?
3. Are the net gains of the recharge project positive, and the distributional effects acceptable, when compared to "doing without?"

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LINKING PHYSICAL PROCESSES AND ECONOMICS OF ARTIFICIAL RECHARGE: A CONCEPTUAL FRAMEWORK

by
Thomas Maddock III

My talk is about a water management technique that links modeling of physical processes with the modeling of economics. In particular, we will be looking at artificial recharge. Artificial recharge, for the purposes of my talk, will be defined as a technique applied when water resources development has approached or exceeded available yield such that it is necessary to import surface waters or ground waters from areas of plenty to areas of scarcity and to store the water in underground reservoirs called aquifers. It is obvious that water must be available for the recharge. It may not be so obvious that the waters must be "clean", that is, as sediment free as possible and chemically and biologically compatible; and that the availability may be stochastic in nature.

Figure 1 presents a conceptual framework for the artificial recharge of a basin from a single reservoir. The following variables and subscripts are defined:

(1) $C(t)$ is the reservoir capacity at time t,

(2) $I(t)$ is the inflow to the reservoir during time t,

(3) $X(t)$ is the release from the reservoir at time t,

(4) $Q_R(j,t)$ is the amount of water recharged during time t at the jth recharge site,

(5) $Q_P(j,t)$ is the amount of water pumped during time t at the jth pumping site

(6) $D(t)$ is the demand for water during the tth time period, and

(7) t is the time duration of an activity (It may be a day, a week, a month, or even a year).

A continuity relation exists for the reservoir. The storage at time t is equal to the storage at time t-1 plus whatever inflow, $I(t)$, occurs minus whatever is released $X(t)$ to meet the demand, for the time t.

$$C(t) = C(t-1) + I(t) - X(t) \qquad (1)$$

We will assume that the demand for water, $D(t)$, for our simplified system, must be met. Hence, for time t, the quantity released from the reservoir $X(t)$ plus all the waters that are pumped from the basin minus any waters that are recharged must be greater than or equal to the demand, $D(t)$, expressed as follows:

$$X(t) + \sum_{j=1}^{N_{PW}} Q_P(j,t) - \sum_{j=1}^{N_{RS}} Q_R(j,t) \geq D(t) \qquad (2)$$

where N_{PW} is the number of pumping wells and N_{RS} is the number of recharge sites.

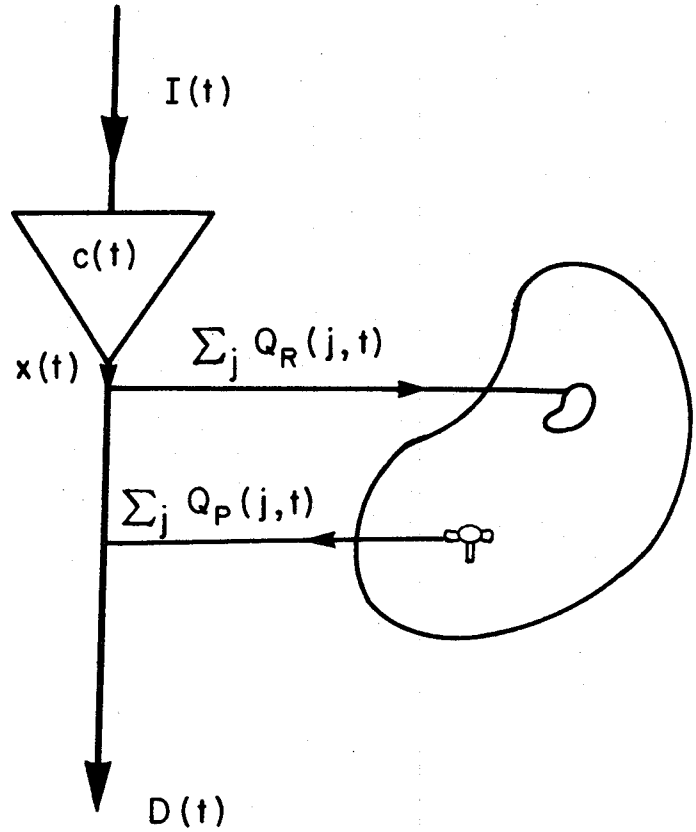


Figure 1. Conceptual Framework of Recharge to a Basin

It should be noted that it is very unlikely that artificial recharge will occur during a time period when there is pumping. Hence,

$$Q_P(k,t) \cdot Q_R(j,t) = 0 \text{ for all k's and j's.} \qquad (3)$$

There are periods of time when there is sufficient water in the reservoir to meet demands and to artificially recharge the basin, but there are also periods of time when the reservoir has insufficient water to meet the demand and the deficient quantity is provided by pumping from wells in the basin. We cannot predict into the future what a reservoir capacity will be. Therefore, the Q_P's and Q_R's are stochastic in nature. The stochastic behavior is similar to that of the I(t)'s.

Let us suppose that we are clairvoyent and can predict what the I(t)'s will be for any time period. Later, we will recast our formulation to exhibit its stochastic nature more clearly. We would like to meet the demands, D(t), over a time horizon of N_e time periods at least cost. We will ignore the questions of design such as how deep are the wells, how large are the spreading basins, and how many of each do we have.

Before we present a mathematical formulation for operating our system at least cost, we need to talk about the relations between pumping, recharge and drawdown. I believe everybody is aware that one of the purposes of the recharge is to raise the water levels in the ground-water system. Likewise, when ground-water is pumped we get a drawdown. When we recharge we usually get a mound of water forming at the site of recharge, and when we pump the drawdown forms a cone of depression (figure 2). The drawdown (s) at the $k^{\underline{th}}$ well at the end of the $t^{\underline{th}}$ time period is defined as:

$$s(k,t) = \sum_{j=1}^{N_{PS}} \sum_{i=1}^{t} B_P(k,j,t-i+1)Q_P(j,i) - \sum_{j=1}^{N_{RS}} \sum_{i=1}^{t} \alpha(j)B_R(k,j,t-i+1)Q_R(j,i) \qquad (4)$$

The B_P's and the B_R's are response functions that measure the drawdowns at an observation point k at the end of time period t, due to unit pumping or recharge, respectively, at site j during time period i. Notice in figure 2 that if there is drawdown, s(k,t) is positive and if there is a mound, s(k,t) is negative. The $\alpha(j)$ is the fraction of water recharged that reaches the aquifer from the $j^{\underline{th}}$ recharge site. Some water will be lost to evapo-transpiration and infiltration processes. Equation (4) shows that past pumping and recharge still affect the drawdown at present and future times. In otherwords, the fact that you pumped a well last month still has an effect on the well today.

As stated previously we would like to operate our system at least cost. We will consider two costs for our system; pumping cost and transportation cost.

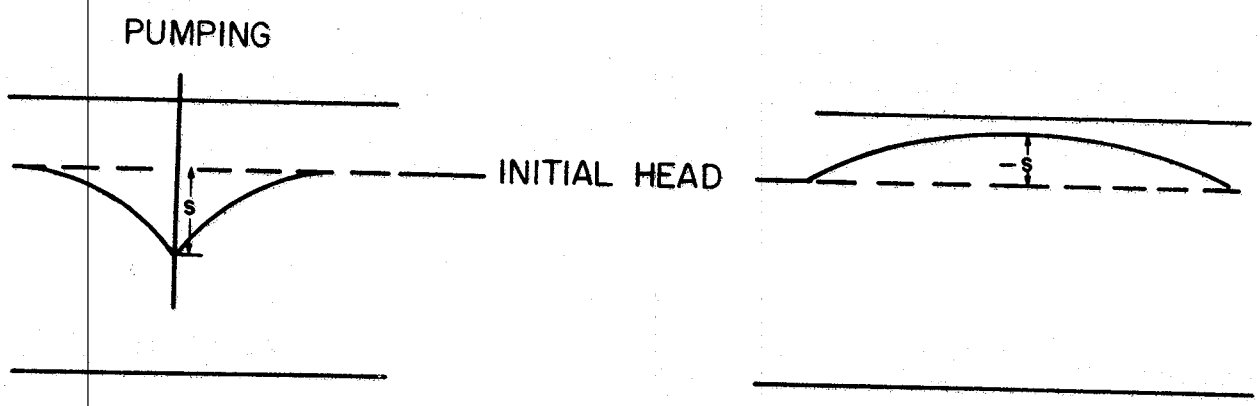


Figure 2. Relationship Between Pumping, Recharge and Drawdown.

We will not worry in our formulation about fixed costs. We will assume that we are operating an existing system at least cost. We will not consider the construction costs of the wells, spreading basins and the reservoir. Now pumping costs are a function of energy consumption; and for groundwater, the energy consumption is related to the product of the amount of water pumped and the lift. The lift is defined as the distance between the land surface and where the water enters the well in the slotted casing (figure 3). In figure 3, L_I is defined as the initial lift before pumping; thus at the $j^{\underline{th}}$ well:

$$L(j,t) = L_I(j) = s(j,t) \qquad (5)$$

The pumping cost over the design period of N_e will be

$$\sum_{k=1}^{N_{PW}} \sum_{t=1}^{N_e} \frac{C_P(k)}{(1+r)^t} Q_P(k,t)\, L(k,t) \qquad (6)$$

where $C_P(k)$ is the cost of water per acre-foot per foot of lift and r is the interest rate that reduces future costs to present values.

Transportation cost is also a function of energy consumption. For transport, energy consumption is assumed to be a function of the quantity to be recharged only. Thus, the transportation costs are:

$$\sum_{k=1}^{N_{RS}} \sum_{t=1}^{N_e} \frac{C_R(k)}{(1+r)^t} Q_R(k,t) \qquad (7)$$

where $C_R(k)$ is the cost per acre-foot of water and is a function of length or distance you have to pump to deliver it, friction factors, or lifts (if you have to move the water over a mountain).

Now we are at a point where we can combine all portions together to formulate our management model. The objective function is:

$$\min \left\{ \sum_{k=1}^{N_{PW}} \sum_{t=1}^{N_e} \frac{C_P(k)}{(1+r)^t} Q_P(k,t) L(k,t) + \sum_{k=1}^{N_{RS}} \sum_{t=1}^{N_e} \frac{C_R(k)}{(1+r)^t} Q_R(k,t) \right. \qquad (8)$$

subject to:

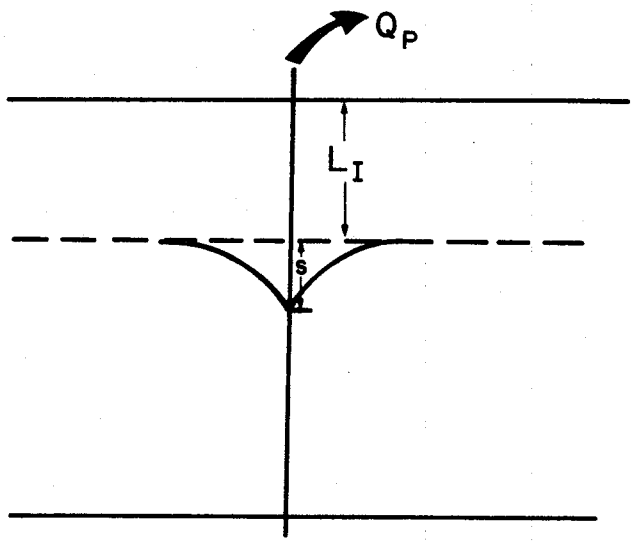
(1) drawdown constraints

$$L(k,t) = \sum_{j=1}^{N_{PW}} \sum_{i=1}^{t} B_P(k,j,n-i+1)\, Q_P(j,i) - \sum_{j=1}^{N_{RS}} \sum_{i=1}^{t} (k,j,n-i+1)\, \alpha\,(j)\, Q_e(j,i) + L_I(k) \qquad (9)$$

$$k = 1, \ldots, N_{PW}$$
$$t = 1, \ldots, N_e$$

(2) reservoir continuity constraints, and

$$C(t) = C(t-1) - X(t) + I(t) \qquad t = 1, \ldots, N_e \qquad (10)$$



$$\text{COST} \propto Q(L_I + S)$$

Figure 3. Pumping Costs.

(3) demand constraints

$$X(t) + \sum_{j=1}^{N_{PW}} Q_P(j,t) - \sum_{j=1}^{N_{RS}} Q_R(j,t) \geq D(t) \qquad (11)$$

$$t = 1, \ldots, N_e$$

The above mathematical formulation is a quadratic program. It is composed of decision variables $X(t)$'s, $Q_P(k,t)$ and $Q_R(k,t)$; state variables $C(t)$ and $L(k,t)$; and parameters $C_P(k)$, $C_R(k)$, r, B_P's, B_R's, $L_I(k)$, $I(t)$'s, $D(t)$'s, and $\alpha(j)$. Decision variables are those variables over which man can exert control. The state variable give the response of the system to the control. The parameters are "given" variables. Their values are assumed known. A solution to the quadratic program gives us the optimal values of the control variables, that is, the values of $X(t)$, $Q_P(k,t)$ and $Q_R(k,t)$ that operate our system at least cost.

The most obvious flaw in our management model formulation is that we assume the inflows, $I(t)$, are known. In reality we lack the clairvoyance that we postulated. However, the model in its present form is still useful if we are willing to generate synthetic streamflows. These synthetic streamflows exhibit the same statistical properties as some period of real record of $I(t)$'s. Suppose we have 20 years of real record of monthly flows for our stream. Using this record we calculate monthly statistics for the 20 years and then generate 1000 twenty-year records of monthly flows. We then solve our management model 1000 times and determine the statistical behavior of the solution to find the mean and variances of the costs and decision variables.

An alternative way to introduce the stochastic nature of the streamflow is to introduce an operating rule such as:

$$X(t) = C(t-1) - b_i \qquad t = 1, \ldots, N_e \qquad (12)$$

where b_i is the rule for the $i^{\underline{th}}$ season.

For example, if we are considering monthly inflows and a 20-year design period, then t goes from 1 to 240 and i goes from 1 to 12. The index i repeats itself 20 times over the 20-year design period. Substituting equation (12) into equation (10) gives:

$$C(t) = b_i + I(t) \qquad (13)$$

replacing subscript t by t-1 and i by i-1 and substituting the modified equation (13) back into equation (12) gives:

$$X(t) = b_{i-1} - b_i + I(t-1) \qquad (14)$$

We now drop the reservoir continuity constraint, equation (10), and modify the demand constraint, equation (11) to:

$$\text{Prob}\ \{\ D(t) - b_{i-1} + b_i - \sum_{j=1}^{N_{PW}} Q_P(j,t) + \sum_{j=1}^{N_{RS}} Q_R(j,t) \geq I(t-1)\} \geq 1-\alpha$$

which says that we want the probability of meeting the demand D(t) to be greater than $1-\alpha$, where α is the risk. The objective function and the drawdown constraints remain the same. We now may solve the mathematical formulation using chance constrained programming, and the stochastic properties of the I(t) are embedded in the solution for X(t), Q_R's and Q_P's.

The above mathematical expressions (models) can be modified to include fixed costs. We would like to be able to decide whether or not to build a project, how many recharge basins we want, and how many wells to put in. Fixed costs are introduced into our model using integer variables. We cannot build fractions of recharge basins or wells. Let $\delta(k,t)$ be a variable that may have the values of only zero or one. If $\delta(k,t) = 1$, then a project is initiated at the $k^{\underline{th}}$ site during the $t^{\underline{th}}$ time period. If $\delta(k,t) = 0$, then no project is constructed. Thus, we add two terms to the objective function given by equation (8); the terms we add are:

$$\sum_{k=1}^{N_{PW}} \sum_{t=1}^{N_e} \frac{C_{PF(k)}}{(1+r)^t}\, \delta_P(k,t) + \sum_{k=1}^{N_{RS}} \sum_{t=1}^{N_e} \frac{C_{RF(k)}}{(1+r)^t}\, \delta_R(k,t)$$

where $C_{PF}(k)$ and $C_{RF}(k)$ are the fixed costs of a well and recharge basin, respectively, and $\delta_P(k,t)$ and $\delta_R(k,t)$ are zero-one variables for the construction.

We must add two new constraints to our model. They are:

$$Q_{Pmax}(k)\ \delta_P(k,t) - Q_P(k,t) \geq 0 \qquad k = 1, \ldots, N_{PW} \quad t = 1, \ldots, N_e$$

and

$$Q_{Rmax}(k)\ \delta_R(k,t) - Q_R(k,t) \geq 0 \qquad k = 1, \ldots, N_{PW} \quad t = 1, \ldots, N_e$$

These constraints are logical constraints which insure that if a basin is recharged or if a well is pumped then those projects must have been constructed. These constraints also limit the pumpage to be less than or equal to $Q_{Pmax}(k)$ and the recharge to be less than or equal to $Q_{Rmax}(k)$. These are project size restrictions. The decision variables for the fixed-cost model are $\delta_R(k,t)$'s, $\delta_P(k,t)$, $Q_P(k,t)$'s and $Q_R(k,t)$'s. Thus, the solution tells when, where and

what projects are built and what their operating capacities are.

We can continue to add complexities to the model, incorporating more and more reality. However, the increased complexity only increases the confusion of the uninitiated. The point to be made is that models exist that can provide aid to the complex decision processes inherent to artificial recharge.

Dr. Thomas Maddock III received a Ph.D. in Mathematics from Harvard University and is presently Professor of Hydrology at the University of Arizona.

IDENTIFYING A GROUNDWATER RECHARGE PROJECT: THE TUCSON ACTIVE MANAGEMENT AREA EXPERIENCE

Lester A. Snow and Craig D. O'Hare [1/]

INTRODUCTION

The management goal of the Tucson Active Management Area (AMA) is safe-yield not later than January 1, 2025. Safe-yield, as defined by the 1980 Groundwater Code, means "...to achieve and thereafter maintain a long-term balance between the annual amount of groundwater withdrawn in an active management area and the annual amount of natural and artificial groundwater recharge...." in the AMA (A.R.S. § 45-561). Put simply, water demands are not to exceed available water supplies. Historic groundwater "mining" conditions are being replaced by long-term management of water as a renewable resource.

The Groundwater Code provides the Department of Water Resources (DWR) with the authority to manage both water demand and supply. While many other provisions of the Code impact groundwater withdrawal, distribution, and use, the management plans are a primary focus of the DWR's demand and supply management effort. The Code establishes five management planning periods between 1980 and 2025. For each period the AMA's must prepare a management plan which includes a continuing mandatory conservation program and starting with the second period (1990-2000), must include an augmentation program. It is through these two efforts; limiting demand (e.g. conservation) and increasing supply (e.g. augmentation) that safe-yield can be achieved.

Due to an amendment to the Code in 1984, the Tucson AMA is able to develop an augmentation program in the First Management Period (1980-1990). Because groundwater recharge was the most extensively studied augmentation method in the region, the AMA chose a demonstration artificial groundwater facility as its main element in the augmentation program. This report presents the methodology used to identify a groundwater recharge project.

1/ Department of Water Resources, Tucson Active Management Area

TUCSON AMA'S ROLE IN AUGMENTATION

The Code defines augmentation as an activity "to supplement the water supply of an active management area and may include the importation of water into the AMA, storage of water or artificial groundwater recharge." (§ 45-561) Though giving an indication of the law's intent, this definition does not necessarily preclude the DWR from pursuing other methods of augmentation. Some of these other methods include vegetation manipulation, cloud seeding, purchasing surface water rights, water harvesting, and providing incentives for recharge by individual entities.

The Code provides for the generation of revenues for an augmentation program through the levying of an augmentation fee. The augmentation fee may not exceed 50 cents per acre-foot for the first three years in the Tucson AMA and may not exceed $2.00 per acre-foot in subsequent years. Anticipated annual pumpage in the AMA is 300,000 to 400,000 acre feet per year resulting in an annual revenue generation of rougly 150 to 200 thousand dollars for the first three years. These revenues are to be used for augmentation purposes only and may not be used for other AMA costs.

A demonstration groundwater recharge facility has been selected as the type of "project" which can most expedite augmentation efforts. The intent is to construct a small-scale recharge facility and monitor its progress with respect to efficiency, acceptability, and cost-effectiveness. Information obtained during this on-going process will be used to evaluate the feasibility of implementing larger recharge facilities throughout the Tucson AMA and the state.

The DWR, as a planning and regulatory agency, will not actually operate recharge facilities. Given this and the extremely limited funding provided by the augmentation fee, efforts for the first management plan are oriented toward identifying cooperative projects. The intent is to identify projects that other entities would be willing to participate in for their own specific objectives. It

is anticipated that through cooperative efforts, costs may be minimized and mutual benefits realized. Such projects, however, allow the DWR to accomplish broader objectives applicable to the entire basin. Once a project is selected, objectives are clarified, and interagency contractural agreements are finalized, the AMA will play only a minimal role in project construction and operation. Other entities, with a history of implementing capital improvement programs, will take the lead in construction and operation. The Department has initiated discussions with the Pima County Flood Control District and Tucson Water with respect to their participation in the project and expects to enter into intergovernmental agreements with those entities. The DWR will continue to contribute augmentation revenues and monitor the progress of the facility to ensure that the original project objectives are being met.

TUCSON AMA AUGMENTATION PLANNING PROCESS

Granted the authority to implement an augmentation program during the first management period, the Tucson AMA began a process to set objectives and select a recharge site. A technical advisory committee was formed in June 1984 to identify issues, reach a consensus on objectives and provide technical review of the screening process used to narrow the number of possible sites. Members of the Augmentation Committee included representation from:

-Tucson Water

-Pima County Flood Control District

-Arizona State Land Department

-Arizona Department of Water Resources - Hydrology Division

-U.S. Army Corps of Engineers

-U.S. Geological Survey

-University of Arizona's Water Resources Research Center

The committee met monthly through March, 1985, to select the most promising

groundwater recharge sites. An iterative process was used to obtain input and feedback from the committee. The Tucson AMA staff proposed a site screening methodology to the committee. The committee then modified or added to the screening criteria. Finally, AMA staff subsequently performed the necessary data collection and assimilation. This process evolved into a series of stages each narrowing the number of potential sites and refining specific demonstration objectives. The screening stages are outlined later in this report.

Demonstration Objectives

Since the purpose of this project is to demonstrate the role and effectiveness of groundwater recharge in managing the AMA's water resources, a general list of demonstration objectives was developed to guide the process toward this conclusion. In general the demonstration objectives set the type of issues or questions which need to be answered in order to further the augmentation effort. The initial list was as follows:

- institute a transferable process for site selection and facility development. (Ideally, the methodology used to select a site can be used to identify future sites.)
- demonstrate the application of low-cost recharge technology
- evaluate cost-effectiveness of artificial groundwater recharge
- evaluate technical feasibility (water quality and quantity)
- promote compatibility with surrounding land uses
- identify and mitigate legal and institutional constraints
- demonstrate multi-agency cooperation

Site Screening Methodology

Two broad classes of demonstration projects were pursued: One utilizing multiple sources of water (e.g. effluent, surplus CAP, and flood flows), and the other integrating a recharge facility with a flood control project. Although CAP water was included as a potential source to the demonstration facility, the

issue of large scale recharge and storage of CAP water was tabled. It was felt a comprehensive look at this issue was too complex and time consuming to fit within the first management period. Since delivery of CAP water is not expected until 1991, time is available for affected entities to study the issue more thoroughly.

Site selection processes for the multi-source and flood control projects were pursued simultaneously. The screening stages for each type of project are outlined below.

Multi-Source Project

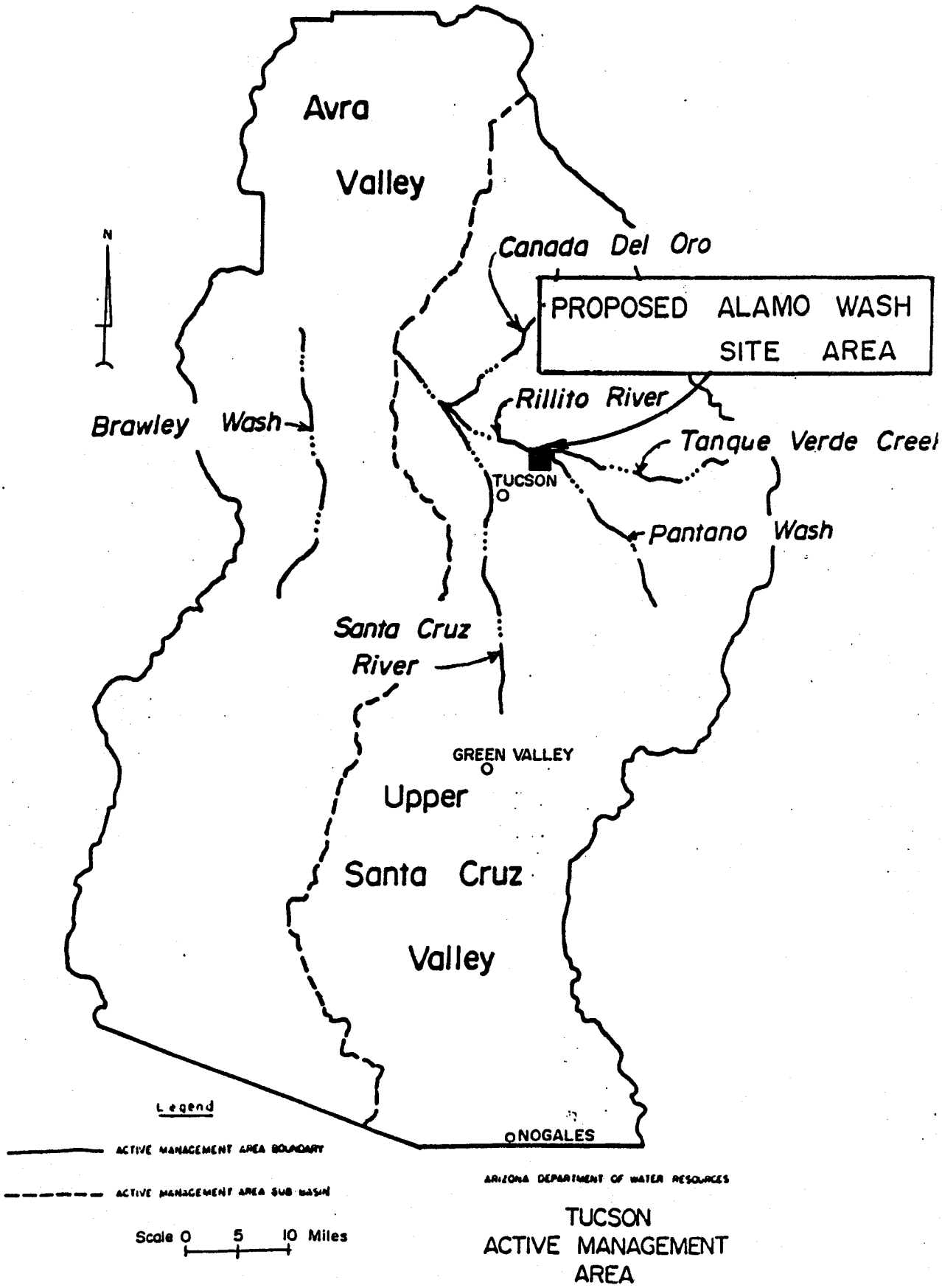
Stage 1: Generalized Screening Based on Objectives

The areas in and around the region's major stream systems (Santa Cruz and Rillito Rivers, Brawley and Pantano washes, Tanque Verde Creek, and Canada del Oro) were selected. Generally, these areas offer plenty of available storm flows and permeable coarse alluvium. Areas lacking the availability of multiple sources of water (effluent or CAP) were excluded. Areas lacking nearby recovery (production) or monitoring wells and areas with insufficient data were also excluded. Of the 4600 square miles in the Tucson AMA, 360 square miles remained as a result of this first stage. (Figure 1)

Stage 2: Identify Areas with Optimal Physical Characteristics

Data on depth to water, transmissivity, and specific yield was available in one square mile cells from a DWR two-dimensional groundwater flow model. Sites were limited to areas where depth to water was greater than 50 feet and less than 150 feet. If the depth to water is too shallow, water mounding may occur close to the surface limiting further recharge. If it is too deep, the absorption in the thick unsaturated zone and potential dispersion by horizontal flow would inhibit demonstration objectives (especially monitoring capabilities). Because data from aquifer tests was not available on a widespread basis, the model's transmissivity and specific yield information served as surrogates for

Figure 1: INITIAL STUDY AREA



vertical permeabilities and storage volumes. It was emphasized that the data from the model would not give an indication of whether confining layers existed in the subsurface. Therefore, driller's logs and well cuttings analyses were utilized as well. The 360 square miles were narrowed to 34 square miles as a result of this stage.

Stage 3: Determine Proximity to Water Source and Availability of Public Lands

Sites close to an existing or proposed effluent line or a CAP turnout were retained. The search was limited to public lands because funding constraints do not allow major land acquisition solely for the purpose of recharge. Nine parcels remained after this stage.

Stage 4: Evaluate Compatibility with Cultural and Insitutional Factors

Existing and proposed land uses in and around the remaining sites were identified. Discussions with the governing agencies owning the remaining parcels were held to determine their plans for the parcel and receptiveness towards including recharge at the site. Meetings were held with both the City and County Parks Department to explore the feasibility of integrating recharge with water-based recreation. Both agencies were receptive to the concept, however, they noted that one significant problem is that recreational objectives may compromise the ability to maximize recharge (e.g. maintaining a recreational lake water level vs. fluctuating water levels associated with recharge). These types of projects were determined to be undesirable for this initial demonstration project but may be pursued in subsequent recharge efforts.

Flood Control/Recharge Project

Stage 1: Identify All Current and Proposed Flood Control Activities

The City and County flood control districts provided the Tucson AMA with maps noting the locations of all moderately large detention basins and overbank

storage sites. Public lands immediately upstream and downstream of these sites were identified for their retrofit potential.

Stage 2: Screen for Proper Physical Characteristics

Same as multi-source Stage 2.

Stage 3: Evaluate Remaining Sites Based on Operational Objectives

Need for flood control in watersheds of remaining sites was assessed. Sites with a potentially high cost of retrofitting facility for recharge were discarded.

Process Results

Three sites remained as a result of the selection processes for both types of recharge projects: one multi-source and two flood control. All three sites, however, are capable of utilizing multiple sources of water (effluent and storm runoff) and operating as a complement to flood control facilities or objectives. It was determined that the project should demonstrate the integration of a recharge facility into a flood control program, recharge of urban runoff. For the purpose of implementing a project within the first management period, the screened sites were ranked as follows:

1. Alamo Wash at Rillito River
2. Columbus Blvd. at Rillito River
3. Julian Wash at the Santa Cruz River

The Columbus Blvd. site would involve the diversion of the main flow of the Rillito River. This was not desirable for this initial demonstration project. The Julian Wash site is located in close proximity to a number of landfills. The Augmentation Committee felt that this problem could be mitigated but that the site was not preferred to the Alamo site. The favorable site characteristics of the Alamo site are discussed below.

DESCRIPTION OF DEMONSTRATION PROJECT

The Tucson AMA has selected as the augmentation project for the FMP a multi-

objective demonstration groundwater recharge project at a site near the confluence of Alamo Wash and the Rillito River. (Figure 2) The project will consist of spreading basins or recharge pits designed with storage (or desilting) features for the initial recharge of storm runoff and subsequent consideration of effluent recharge.

Project Features

The primary goal of this initial demonstration project is to obtain information on recharge which can be used to evaluate future recharge projects. The selected project offers a number of key demonstration features:

Demonstration Objective	Project Feature
Interagency Cooperation	Project will require formal committment and cooperation between Pima County Flood Control District, City of Tucson, and DWR
Integration of Recharge and Flood Control	Located in area with active flood control planning efforts
Recharge of Multiple Water Sources	Project will have access to urban runoff and subsequently effluent
Feasibility of Urban Runoff Recharge	Tributary Wash drains an urbanizing watershed. Gaging and sampling will help determine impact of urbanization on runoff quantity and quality and on natural recharge conditions
Evaluate Recharge Efficiency	Project will include detailed gaging and monitoring
Determine Flood Control Benefits	Project will evaluate recharge impact on hydrograph
Assess Water Quality Impacts	Project will sample surface water and groundwater quality
Promote Compatability with Surrounding Land Use	Project will use landscaping to help achieve desirable open space and habitat requirements
Evaluate Cost-Effectiveness	Determine costs per acre-foot recharged and assess benefits

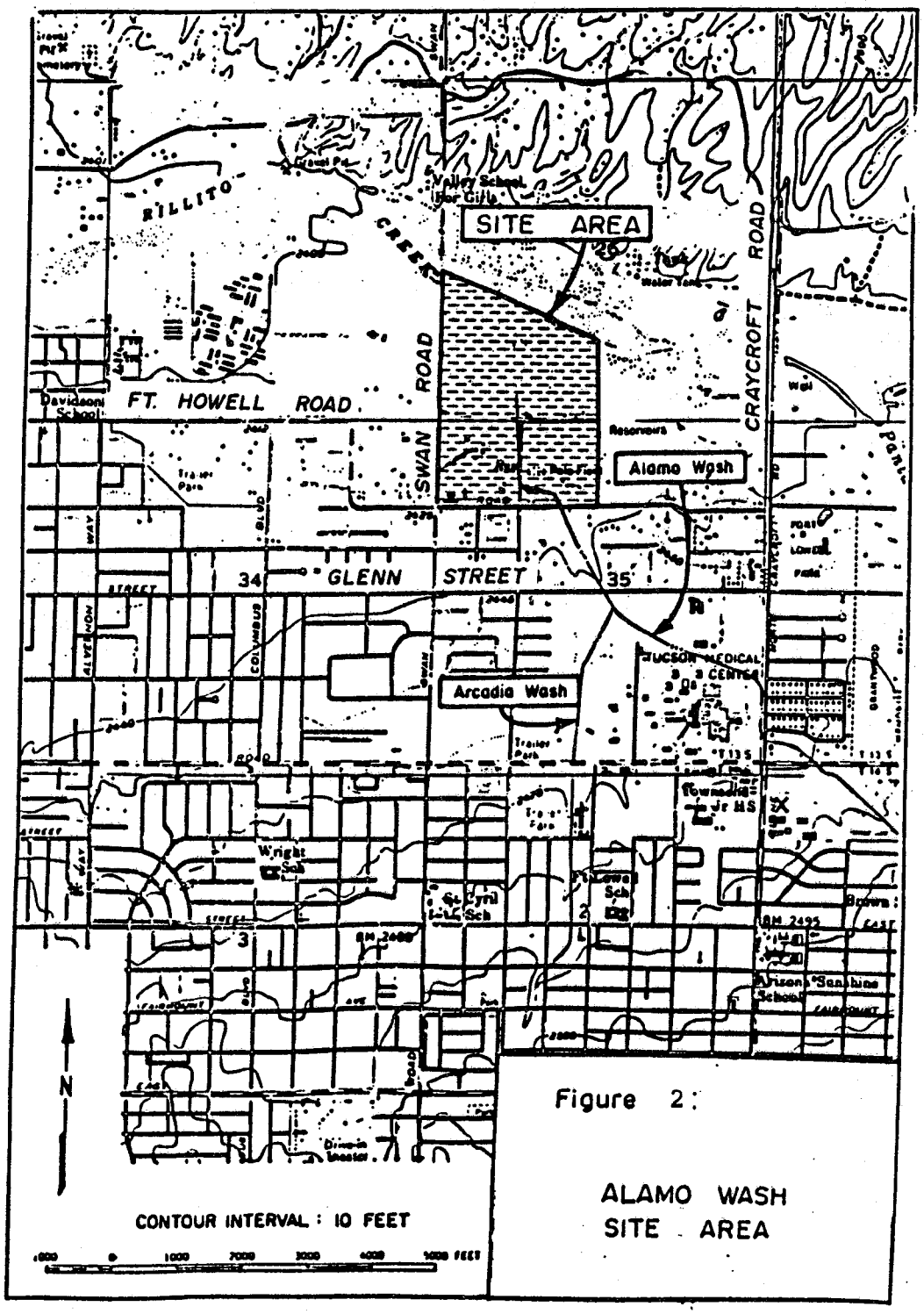


Figure 2:

ALAMO WASH
SITE AREA

Site Characteristics

The Alamo Wash parcel typifies the site characteristics necessary to meet the demonstration objectives stated above. A suitable alternative site or sites, with similar site characteristics, may be considered in the final feasibility analysis. These characteristics are:

- site is located in proximity to major tributary next to main channel
- drains moderate size urbanizing watershed
- possesses favorable physical characteristics for recharge (coarse permeable materials, depth to water between 50 and 150 feet deep)
- additional flood control needed in area
- effluent distribution line is proposed nearby
- land is presently vacant and undeveloped

The specific statistics of the Alamo Wash site are:

Location:	Township 13 South, Range 14 East, Section 26 Just south of Rillito River, and east of Swan Road.
Drainage Area:	9.5 square miles
Site Area:	To Be Determined
Ownership:	Part Pima County Flood Control District, part private land
Land Use:	Flood plain and vacant
Zoning Status:	Residential - Up to 20 units per acre
# of Wells Within One Mile:	70 (approx.)
Average Annual Flow in Alamo Wash:	900 acre-feet
Hydrology	
- Depth to water:	100'
- Transmissivity	49,000 gallons/day/foot
- Specific Yield	9%
- Q10 Discharge:	3640 cfs.
- Q100 Discharge:	8580 cfs.

General Project Costs

Total project costs will be shared among the final cooperators based on formal agreements. The revenues from the DWR augmentation fee will be utilized to finance the costs of developing the transferable or "demonstration" data. As such, DWR fees will generally be used for the project design and monitoring portion of the project. While exact costs will not be developed until the final engineering feasibility and site design aare completed, it is anticipated that the DWR cost will range between $100,000 and $175,000 per year for a period of 5 years. Continued financial support will be considered subsequent to a formal project evaluation.

IMPLEMENTATION PROCESS

Once adopted as an augmentation project there are four key steps to implementation:

1. Interagency Agreements

   Formal interagency agreements will be prepared among the cooperators. Such agreements will specify responsibility throughout the project including cost-sharing levels and construction, operation, and monitoring responsibilities.

2. Engineering Feasibility and Site Design

   A site analysis will be conducted, including soil borings to depth, to determine physical structure and chemical make-up of subsurface. A final engineering feasibility will be prepared which will lead to preparation of actual site plans and operational manuals. A project description will also be prepared.

3. Construction and Operation

   As per the interagency agreements, the appropriate entity(s) will construct and operate the facility.

4. Monitoring and Reporting

The DWR will collect and analyze data on an on-going basis. An annual progress report will evaluate the degree to which the project objectives are being met. A formal demonstration report will be prepared after five years of project operation. Assuming a successful demonstration, other projects will be pursued in other areas of the AMA with other cooperators.

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FINANCING RECHARGE: THE CALIFORNIA EXPERIENCE

Richard A. Rhone

About 40 percent of the area of California is underlain by ground water basins with a total storage capacity of some 1.3 billion acre-feet and a usable storage of over 143 million acre-feet. With the advent of the efficient deep well pump in the early 1900's extraction of ground water accelerated, supporting major economic development particularly in the more arid south central and southern California areas. Today over 40 percent of the water used in California is derived from ground water.

Over pumping in excess of long term recharge in many of these basins has required major import projects to resolve the resulting supply deficiency, excessive pumping lifts, subsidence, water quality and sea water intrusion. Significantly, the import projects also provide a source of supply for ground water basin management to restore and maintain the viability and benefits of the ground water basins storage capacity, conveyance and distribution capability as well as the water yield lost if the basin became unusable. This lost yield may be in excess of the natural yield of the basin. Of the 16 million acre-feet of ground water pumped in California nearly 8 million acre-feet is recharged from deep percolation of applied water, from canals, and other sources which would not have occurred naturally in the absence of water development.

In California, we have found that each basin has unique, physical, political, institutional, legal, cultural and economical characteristics. The ground water basin management and financial arrangements must encompass these unique characteristics. The addition of imported water supplies for surface and ground water management requires equity of rights and costs. While recharge of local supplies occupies a significant role it is much more easily handled than imported supplies largely due to the much higher costs of imported supplies.

Table 1 lists some ground water basins in California in which imported or other water which would not otherwise serve a beneficial purpose is used for direct or indirect recharge.

Presented by Richard A. Rhone, Supervisory Engineer, Bookman-Edmonston Engineering, Inc., Glendale California before the Second Symposium on Artificial Recharge in Arizona; Tempe Arizona May 3, 1985.

TABLE 1

GROUND WATER BASINS IN WHICH OVERDRAFT CORRECTION DEPENDS ON IMPORTED WATER (a)

County	Basin	Operating Agency	Import System	Initial Import
Alameda	Alameda Bayside	East Bay MUD, City of Hayward	Mokelumne Aq. Hetch Hetchy Aq.	1930 1950
Alameda	Niles Cone	Alameda Co. WD	South Bay Aqueduct (State Water Project)	1962
Alameda	Livermore Valley (Central Area)	Alameda Co. FC & WCD, Zone 7	South Bay Aqueduct (State Water Project)	1962
Alameda and Contra Costa	Livermore Valley (Pleasanton Area)	City of San Francisco	Hetch Hetchy Aq. (Substitution)	1934
Contra Costa	Walnut Creek Concord Area	Contra Costa Co. WD	Contra Costa Canal	1941
Fresno, Kern, Kings, Madera, Tulare	Southern San Joaquin	Many water agencies	California Aqueduct Delta-Mendota Canal Cross Valley Canal Mid-Valley Canal Other	1968 1951 1975 ? ?
Los Angeles	Raymond	City of Pasadena, et al	Colorado River Aq. California Aqueduct	1944 1972
Los Angeles	West Coast	Central and West Basin WRD	Los Angeles Aq. Colorado River Aq. California Aqueduct	1935 1948 1972
Los Angeles	Central	Central and West Basin WRD	Los Angeles Aq. Colorado River Aq. California Aqueduct	1935 1954 1972
Los Angeles	Main San Gabriel	Upper San Gabriel Valley MWD	Colorado River Aq. California Aqueduct	1964 1974
Los Angeles	San Fernando	City of Los Angeles	Los Angeles Aq. Colorado River Aq. California Aqueduct	1915 1941 1972
Orange	Costal Plain- Orange County	Orange Co. WD	Colorado River Aq. California Aqueduct	1949 1973
San Bernardino	Bunker Hill	San Bernardino Valley MWD	California Aqueduct	1972
San Bernardino and Riverside	Chino-Riverside Area	Chino Basin MWD and Western MWD	Colorado River Aq. California Aqueduct	1951 1973
San Joaquin	Central San Joaquin	Stockton-East WD No. San Joaquin WCD	Folsom South Canal	?
Santa Clara	Santa Clara Valley	Santa Clara Valley WD	South Bay Aqueduct (State Water Project) San Felipe Project	1965 1986
Solano	Solano	Solano Co. FC & WCD	Putah South Canal	1959
Ventura	Oxnard Plain	Calleguas MWD Ventura Co. FCD	Colorado River Aq. California Aqueduct California Aqueduct	1968 1972 ?
Yolo	Davis-Woodland Area	Yolo Co. FC & WCD	Tehama-Colusa Canal plus extension	1980 ?

Abbreviations:

FCD — Flood Control District
MUD — Municipal Utility District
MWD — Metropolitan Water District
WCD — Water Conservation District
WD — Water District
WRD — Water Replenishment District

(a) Source: Water Resources Management in Southern San Joaquin Valley California by Bookman-Edmonston Engineering, Inc., 1979.

Financing Formulas

Table 2 shows the major elements of ground water management programs in eight basins in Southern California. Ground water management principles employed include:

- Adjudication of individual rights to pump water,
- A limit on the amount of pumping,
- Taxes or assessments on pumping,
- Direct recharge by a management entity,
- Equivalent recharge by surface delivery in lieu of pumping.

Only two of the eight basins utilize common methods and these two are contiguous. Unique and individual solutions have been developed for each of the basins. The solutions have generally been arrived through rigorous efforts of all parties involving comprehensive legal, engineering and economic analysis. The solutions have mostly been negotiated settlement implemented by legislation and judicial actions.

The fundamental elements of a recharge project include:

1. A physical solution.

2. Equity among basin pumpers. (This is most difficult among multiple pumpers with a wide divergence in water values such as between municipal and agricultural uses).

3. Benefits received must exceed costs.

4. Long range recharge for storage recovery financed by future beneficiaries.

To illustrate financing of recharge in California, I will describe two management areas in Southern California.

San Gabriel River System

The San Gabriel River System in south eastern Los Angeles County has a population of over 4 million people. Water demands are met by a combination of ground water pumping of local and imported water and by imported surface supplies. The northerly quarter of the area consists of the San Gabriel Mountains which reach elevations of over 9,000 feet and form a very important watershed. This area is drained by the San Gabriel River, and several minor streams which empty into the San Gabriel Valley. The San Gabriel Valley covers an area of approximately 200 square miles and is a large sand and gravel filled bowl, susceptible to recharge at almost any location. The lower

TABLE 2

ELEMENTS OF GROUND WATER MANAGEMENT PROGRAMS IN SELECTED BASINS OF SOUTHERN CALIFORNIA(a)

Basin	Individual Rights to Pump Adjudicated	Amount of Pumpage Limited	Tax or Assessment on Pumping	Direct Recharge By Management Entity	Equivalent Recharge By Surface Delivery In Lieu of Pumping
Raymond	Yes	Yes	No	No	Yes
San Fernando	Yes (a)	Yes (a)	No	Yes	Yes
Central	Yes	Yes	Yes	Yes	Yes
West Coast	Yes	Yes	Yes	Yes	Yes
Main San Gabriel	Yes (b)	No	Yes	Yes	Yes
Orange County	No	No	Yes	Yes	Yes
Bunker Hill	No (c)	No	No	Yes	Yes
Chino	No (d)	No	Yes	Yes	Yes

(a) Adjudicated rights granted to the City of Los Angeles for local safe yield and all pumpers, including the City, allowed to recapture imported water reaching the ground water supplies.

(b) Adjudication of individual rights as a percentage of the operating safe yield.

(c) No adjudication of individual pumping rights for overlying uses, but exporter rights are individually adjudicated.

(d) No adjudication of individual agricultural pumping rights but industries and cities' rights are individually fixed as a percentage of the operating safe yield.

(a) Source: Water Resources Management in Southern San Joaquin Valley California by Bookman-Edmonston Engineering, Inc., 1979.

portion of the San Gabriel Valley is bounded by two sets of low hills which divide it from the coastal area. The River cuts through these hills at an area known as the Whittier Narrows and thence across the coastal plain. Ground and surface water from the San Gabriel area pass through the Whittier Narrows to the coastal plain.

The coastal plain has two ground water basins, the Central and West Coast Basins which cover an area of 420 square miles. The Central and West Coast ground water basins, which are in hydraulic contact, consist of interbedded sands and clays overlain by confining clays except in the Montebello Forebay area of Whittier Narrows. Surface recharge activities are thus limited to the Montebello Forebay area. The Central and West Coast Basins also border the Pacific Ocean with some aquifers in direct contact with the ocean. Historical ground water pumping in the Central and West Basin far in excess of safe yield drew water levels below sea level creating a landward gradient resulting in the intrusion of seawater into the aquifers. This intrusion has been halted by the construction of hydraulic barriers consisting of a line of wells injecting imported water, and creating a fresh water mound.

In 1959 a suit was filed by the Central Basin interests because of a dimunition in flow from the San Gabriel Valley caused by lowering of ground water levels therein. In 1965, the San Gabriel Valley and the Central Basin interests reached agreement over the amount of usable water which passed from the San Gabriel Valley to the Central Basin. The agreement defined the rights of each area to the available water supply and allowed each to develop its own ground water basin management plan. Since 1965 any decrease in agreed flows is compensated by the San Gabriel Valley by delivery of imported or reclaimed water through the Whittier Narrows.

San Gabriel Valley

The San Gabriel Valley's management plan, which became effective in 1973, works in the following manner. The individual rights to pump ground water were determined for all ground water pumpers based on their historic ground water use. This right, in terms of acre-feet, was converted to a percentage of the basin safe yield. Each year a nine member Watermaster Committee sets the annual operating safe yield based on existing and anticipated ground water conditions. When ground water elevations are high due to wet years, this operating safe yield is set at a higher amount and is reduced in years when ground water levels are lower.

The Watermaster then determines three separate assessments which it can apply to ground water pumpage to pay the costs of management. These are:

1. An administrative assessment levied on all safe yield pumping to pay administrative costs. This is currently $2.50 per acre-foot.

2. A make-up water charge applied to all safe yield pumping to generate funds for purchase of water to satisfy the agreement between the San Gabriel Valley and the Central Basin. This charge is currently $5.00 per acre-foot.

3. The third charge, termed a replacement water charge, is currently $153.00 per acre-foot. This charge is applied to all ground water pumping by any producer which is in excess of allocated safe yield pumping. This charge represents the cost of importing water and replacing it in the ground water basin. In essence it is the cost to a ground water user for water obtained directly from imported souces.

In addition to the above programs managed by the local agencies, there is also a cyclic storage program. Under agreement with San Gabriel interests the Metropolitan Water District of Southern California, which is the overlying importer of water into Southern California, may recharge and store water for its own account in the San Gabriel Valley. This water, termed cyclic storage water is limited to a maximum of 150,000 acre-feet. This water is later sold to the nine member Watermaster Committee as replacement water in lieu of direct import when needed.

The management plans in the San Gabriel Valley permit the individual ground water producer to operate in the manner he sees fit and charges the user for the cost of importing water which needed to replace pumped water in excess of that producer's adjudicated rights in the basin.

Central and West Basins

The Central and West Coast Basins located on the coastal plain of Los Angeles County share a common boundary at the Newport-Inglewood uplift which restricts ground water movement along a part of the common boundary. Ground water management is provided to both areas through the Central and West Basin Water Replenishment District, a special California district formed in 1959 to manage the ground water in the combined basins. At that time total ground water overdraft was estimated to be 950,000 acre-feet. There are several hundred wells and about 70 separate water companies operating in the basins. Artificial recharge by injection for seawater intrusion control was started in 1952 and artificial recharge by spreading in the Montebello Forebay began in 1953, both by the Los Angeles County Flood Control District (now the Department of Public Works).

Initially, the financing of recharge within the Replenishment District area was by dues levied by an informal Association and later by ad valorem taxes. These methods were phased out and currently the financing of all recharge water is provided through a pump tax assessed by the Central and West Basin Water Replenishment District. The total amount of recharge water which has been purchased is now nearly 4 million acre-feet. A large amount of the recharge paid for by ad valorem taxes reduced the accumulated overdraft to its current level of about 600,000 acre-feet. The amounts of recharge are shown in Table 3.

Unlike the San Gabriel Valley, an unlimited amount of pumping in a year cannot be offset by increased ground water recharge. The amount of effective recharge to the comfined aquifers and thus, sustained ground water pumping, is limited by the transmissivity of the aquifers from the Forebay. A substantial gradient from the Forebay to the pumping area is required to transmit the recharge. Increased pumping in the West Coast Basin causes a substantial decrease in ground water elevation and increases injection for seawater intrusion control. The main pumping areas of both basins are maintained below sea level to maximize water transmission. Thus, it was necessary to limit the amount of ground water extractions. The pumping limit was achieved by an adjudication of ground water pumping which became effective in 1962.

Because ground water extractions by an individual pumper are limited, the physical solution required a surface distribution system for imported water. The distribution grid was provided by the Metropolitan Water District of Southern California. Most larger ground water pumpers also have direct access to imported water. For those pumpers who have no access to imported water an exchange pool was created whereby unconnected parties are given additional pumping rights. These rights are annually provided by connected purveyors with reimbursement based on the difference in cost between ground water which is pumped and the cost of imported water. Thus, equity is maintained.

The Replenishment Assessment is determined each year by estimating the cost of imported water for injection in the barriers and recharge in the Montebello Forebay plus other costs and applying it equally to the total annual ground water production of about 280,000 acre-feet. The assessment rate is currently $40 per acre-foot for purchase of water plus $1 per acre-foot for administrative cost and will increase to $60 per acre-foot on July 1, 1985.

The recharge facilities consist of spreading grounds and the San Gabriel River channel in the Montebello Forebay and injection wells along the coast. These facilities are owned and operated by the Los Angeles County Department of Public Works, a full partner in the basin management plan.

TABLE 3

SUMMARY OF WATER PURCHASED FOR REPLENISHMENT
IN THE CENTRAL AND WEST BASIN WATER
REPLENISHMENT DISTRICT(a)
(In Acre-feet)

Water Year	Water Purchased for Spreading: Imported Water	Reclaimed Water	Subtotal	Water Purchased for Injection	Replacement by In-lieu Replenishment	Total
1952-53				1,100		1,100
-54	30,000		30,000	3,300		33,300
1954-55	24,800		24,800	2,700		27,500
1955-56	54,500		54,500	2,800		57,300
-57	50,000		50,000	3,600		53,600
-58	105,100		105,100	4,300		109,400
-59	54,400		54,400	3,700		58,100
1959-60	80,900		80,900	3,800		84,700
1960-61	147,200		147,200	4,500		151,700
-62	208,100	1,200	209,300	4,500		213,800
-63	80,600	12,400	93,000	4,200		97,200
-64	104,900	13,300	118,200	10,500		128,700
1964-65	160,100	14,500	174,600	35,800		210,400
1965-66	128,200	15,100	143,300	47,800	700	191,800
-67	84,300	16,200	100,500	46,500	900	147,900
-68	95,400	18,300	113,700	43,800	800	158,300
-69	17,800	13,900	31,700	40,700	800	73,200
1969-70	68,900	17,100	86,000	33,200	900	120,100
1970-71	72,100	19,500	91,600	35,400	900	127,900
-72	34,400	17,500	51,900	40,100	800	92,800
-73	91,900	21,900	113,800	40,900	900	155,600
-74	92,100	20,400	112,500	41,500	900	154,900
1974-75	71,900	21,200	93,100	36,000	400	129,500
1975-76	50,800	21,500	72,300	44,300	400	117,000
-77	30,700	22,900	53,600	48,400	400	102,400
-78	39,900	19,100	59,000	39,400	16,600	115,000
-79	65,300	22,500	87,800	33,600	17,800	139,200
1979-80	21,100	24,400	45,500	36,700	14,700	96,900
1980-81	63,500	26,100	89,600	33,800	23,800	147,200
1981-82	35,500	29,400	64,900	33,900	18,900	117,700
1982-83	10,900	17,000	27,900	43,200	19,800	90,900
1983-84	22,300	27,800	50,100	38,100	41,800	130,000
1984-85(b)	36,000	29,000	65,000	46,000	27,000	138,000
Total	2,233,600	426,200	2,695,800	888,100	189,200	3,773,100

(a) Values rounded to 100 acre-feet.
(b) Estimated amounts.

Source: Bookman-Edmonston Engineering, Inc., "Annual Survey Report on Ground Water Replenishment", February 1985.

The spreading program consists of purchase by the Replenishment District of supplemental imported and reclaimed water supplies in addition to the local runoff including storm flows, rising ground water and local runoff stored in the upper area for later release.

There are several current ground water recharge programs within the Replenishment District. Currently, about 40,000 acre-feet of treated imported water is obtained from the Metropolitan Water District for injection. Up to about 70,000 acre-feet annually of imported raw water from the Colorado River and State Water Project is purchased for spreading at the Montebello Forebay from the Metropolitan Water District of Southern California. This water is delivered on an "interruptable" basis and is priced at $153 which is $44 per acre-foot less than "noninterruptable water". Metropolitan's "interruptable" pricing policy is instrumental in the ground water basin management program.

Preference is given to spreading local waters including storm waters and water captured in the San Gabriel Mountains. The Replenishment District also purchases about 30,000 acre-feet of reclaimed waste water for spreading in the Montebello Forebay. An intensive health effects study demonstrated no measureable adverse effects on the area's ground water or the health of the population ingesting this water. Based on these findings, the Replenishment District is planning to raise the annual amount spread from this source to 50,000 acre-feet per year. Reclaimed waste water currently cost the Replenishment District $7 per acre-foot.

In recent years ground water replenishment has been accomplished through an in-lieu replenishment program. Under this program a ground water producer takes additional water from its surface connection in-lieu of ground water. The producer foregoes the right to extract that amount of water from the ground water basin and is paid by the Replenishment District an amount which equals the difference in cost between ground water pumping and imported water. A cost savings results from no pumping cost incurred for extracting the water. A benefit results because water is in effect replenished at the point of pumping and does not have to be physically recharged and transmitted through the basin to the point of use. This in-lieu replenishment has developed into an extremely important part of the basin management plan.

Summary

Because of the importance of maintaining ground water basin capabilities and yield, and coupled with the high cost of imported water for ground water recharge, comprehensive basin management plans are needed to effectively implement recharge programs. Each basin is unique, and depending upon circum-

stances, numerous procedures may be established. It should be emphasized that there is no single procedure which will serve all areas. It is necessary and extremely important to develop equity among the ground water basin users. In a water short area such as the southwest our water future lies in the ground water basins. These basins should be fully managed as early as possible; all of which is dependent upon developing a workable, equitable and reasonable financial program for purchasing imported water for replenishment.

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The net result of the "Privatization" concept to state and municipal governments is savings on design-construction, financing and operation.

The growing interest in the new concept of privatization for the construction, acquisition, extension or improvement of water supply, storage and distribution systems carries with it questions regarding both the structure of this new type of transaction as well as the financing of projects themselves. With this in mind, we want to briefly address five of the questions we are most frequently asked about project economics and financing.

1. How do the financing economics of privatization compare with those of conventional water supply, storage and contribution system financing?

Facility financing under privatization is considerably less expensive than under conventional financing, even though both use the same basic financing vehicle: tax-exempt revenue bonds.

Using a $15 million system as an example, under conventional financing, the entire construction cost would be financed by a revenue bond issue. Construction costs, plus financing and issuance costs, would result in a $20,800,000 bond issue. Assuming a 10% bond interest rate, annual debt service would be $2,237,500.

Under privatization the private owner would invest equity in the project usually up to 25% of project costs. This would result in the need to finance only 75% of project costs, producing a bond issue of $14,270,000 (the equity would be $4,230,967). With a 10% interest rate, annual debt service would be $1,574,000.

Since debt service would be the largest portion of the total annual service costs of the system, the savings on this cost element would have a significant effect. In this example, the nearly $700,000 in annual savings would, over the 20 year term of the debt, generate savings to a state a municipality of $14 million.

2. How would a state or municipality benefit under privatization?

The principal benefits are economic. Under privatization, a system could be built on a fast track turn-key basis, which would mitigate the effects of inflation on construction costs. In the opinion of some engineers, facilities could be built on a turn-key basis for guaranteed not-to-exceed prices which actually could be less than traditional public works-bid based construction.

Under a long-term service agreement, the private operator of the facility would charge the state or municipality a service charge based on debt service and O & M costs. Because the investment of equity would reduce borrowing needs, the debt service portion of that charge (which would be the same each year) would be significantly lower than that under conventional financing. The agreement would set the first year operating cost portion of the service charge, and set forth the conditions underwhich, and only underwhich, that portion could be adjusted (i.e., inflation, change of law requirements, Force Majeure). Since the debt service portion would be level over the term of the financing, the only changeable component of the service charge would be O & M costs, which could only be changed for specified reasons established in the agreement. Therefore, the service charge would be controllable and predictable over the long term.

If O & M costs exceeded the stipulated levels due to management inefficiency, the operator would have to absorb those costs; it could not charge them to the state or municipality. In effect, the municipality would be shielded from the economic consequences of bad management.

The efficiency of private operation could also be reflected in lower first year costs being established in the agreement and serving as an even lower basis for downstream adjustments.

There are other less tangible, but equally important, benefits. In addition to establishing and controlling cost aspects, the service agreement between the state or municipality and the operator would include performance standards that the operator would have to meet for the facility, for example, these could include the acceptance of certain volumes of water, the treatment, if necessary, and distribution of that volume. Under privatization, the state or municipality would be assured of the long-term guaranteed operation and performance of the facility.

3. What financing security aspects would be required under privatization?

The security requirements for both privatization and conventional financing are essentially the same. Both would require:

1) a rate covenant by the state or municipality to set user charges at levels that would achieve specified debt service coverage ratios, and to adjust the charges whenever necessary to maintain those rations under all circumstances;

2) the establishment from bond proceeds, and the continuous maintenance, of a debt service reserve fund equal to one year's principal and interest;

3) the maintenance of a specified debt service coverage ratio (for example, that net revenues -- total revenues less O & M costs -- would be at least 110% to 125% of debt service), achieved by adjusting charges under the rate covenant; and

4) the collection of these service charges from ultimate users of the commodity.

4. Since privatization is a new concept, won't there be resistance in the usually conservative bond market to privatization financings?

Although privatization is a new idea, we expect that market acceptance will be high. Unlike other earlier new fields such as waste-to-energy or cogeneration, which involve new technologies and were initially viewed as risky, there would be no particular technology risk associated with the contemplated recharge program. The use of traditionally accepted security and credit mechanisms would underscore this. Although some segments of the market might be concerned with an apparent dilution of public control over a project, it could be readily demonstrated that state and/or municipal control under leases and service agreements was strong.

Today, privatization in other fields such as solid waste and cogeneration is well accepted. In fact, the presence of cost and performance guarantees (as in solid waste projects) might enhance the attractiveness of the proposed projects.

5. The state or municipality has a responsibility to safeguard the obvious public interest in a project such as water supply. Given the private ownership and operation of a system, how can a state or municipality assure its constituents that their interests are being protected?

Although a state or municipality will be relieved of day-to-day construction and operation responsibilities, it will not relinquish control or its capability to protect the public interest. This would be exercized through the strict enforcement of key agreements, which might include:

a. the ground lease between the owner and the state or municipality, which would set site occupancy and facility construction requirements; establish provisions related to completion and start-up; and provide the mechanism for the eventual state or municipal acquisition of the facility;

b. the financing agreement between the financing agency (such as state, local and IDA) and the owner, which would include provisions related to debt retirement: financial covenants; defaults and remedies; and, for foreclosure and removal of the owner under certain default circumstances;

c. the service agreement between the operator and the state or municipality, which would include provisions specifying the operator's cost and performance requirements and guarantees, such as to accept specified volumes, to meet certain specified distribution standards, to adhere to certain cost control measures, to absorb certain losses or to pay certain damages for non-performance.

A Financial Checklist

In addition to the above, in the development of a privatization transaction, the investment banker must consider myriad interrelated issues and concerns, a kind of shopping list of requirements and questions. Briefly, these include:

1. The Project

The project must be truly needed.

A financial feasibility study must document that the project is economically viable without resorting to extreme financial machinations.

The current and projected economic health of the service area must be adequate to support the project.

The assurances of related parties (for example, to supply bulk water and purchase bulk water) must be strong and enforceable.

2. Financial Structure (Equity)

The state or municipality must decide early on whether it will require equity investment.

If equity is required, the choice usually will be between leveraged lease development or limited partnership development (a leveraged lease requires a lower internal rate of return (IRR) but more cash return; a limited partnership requires shorter term and higher IRR but lower cash payout).

If equity is infused during construction or at start up, rather than in full upfront, it must be fully committed and irrevocably secured by the time of bond closing.

The structure must meet IRS "at risk" provisions, but must effectively shelter the equity owner(s) from actual construction/O & M burdens.

3. Financial Structure (Debt)

The issuer must be a state or local IDA or other agency which can issue bonds on behalf of private parties.

Generally, the issue should be conventionally structured: capitalized interest; fund trusteed under an indenture; unqualified approving opinion of bond counsel.

The term of the financing should be 20-30 years, to realize affordable annual debt service coverage.

Generally, the bond issue should be designed for public distribution, unless institutional market-oriented devises such as "low floaters" are used.

There should be "additional bonds" provisions to accommodate expansion.

4. Principal Contractors

Construction. The builder(s) must have the demonstrated technical capability to build the project on time and within budget, and the financial resources (including insurance) to pay potentially substantial damages for partial or complete non-performance.

O & M. The operator must have the demonstrated capability to operate the project according to set standards and the financial resources to pay damages and/or state-imposed fines for partial or complete non-performance.

Ideally, the operator should be sufficiently substantial to covenant to remain in business for the duration of its service agreement.

If the operating company is a subsidiary of a larger firm, its performance should be guaranteed by that parent.

5. Contractual Basis

The procurement of construction and/or operating services must strictly adhere to state law to protect the financing from legal challenges.

The supply of "raw material" (water) must be guaranteed for the life of the bonds.

There should be provisions for the builder to pay damages or "buy down" bonds for non-delivery of the project or if guaranteed design (processing) capacity cannot be attained.

There must be adequate provisions for adjusting service prices to reflect inflation, Force Majeure events, expansion, etc.

The establishment of competing systems should be precluded.

The operator should be subject to damages and/or fines for substandard performance, as well as subject to requirements to correct self-created problems at its own cost. The removal of the operator for default should be enabled.

6. Financing Security

The financing must be adequately secured, using mechanisms such as:

- debt service reserve fund
- other reserves (such as repair and replacement)
- governmental rate covenant
- guarantee of collections from individual system users
- enforceable contractor guarantees
- municipal bond insurance or letter of credit, if available.

7. Regulatory Basis

If the project is subject to rate regulation by a state utilities commission, the effect of this on the marketability of both the debt and equity will need to be assessed.

Because of the essential public health and welfare nature of water supply and distribution it is unlikely that a PUC would allow a project to financially default by not enabling rate increases. Therefore, rate regulation should not fatally affect bond marketability.

Regulation will affect the tax credits and benefits available to equity investors, which in turn will affect the amount of equity invested. This will have an impact on the amount of debt required, and, thus, annual debt service levels.

Conclusion

The economic advantages of lower initial capital costs and controllable long-term costs under privatization are apparent, as are non-economic advantages such as assured system performance. Both quantitatively and qualitatively, states and municipalities can benefit from privatization.

Although privatization is a new concept, the actual security and credit support structure of a privatization financing is virtually identical to that of a conventional transaction. Given that, and the market acceptance of similar solid waste and co-generation financings, the market acceptance of privatization will be high. Privatization project bonds can be sold.

The involvement of private parties in development and operation will not dilute ultimate public control over projects. Adequate safeguards and control mechanisms can be incorporated in financing and service agreements to assure the proper protection of the public interest in the long-term operation of a project.

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SESSION IV: CASE STUDIES OF ARTIFICIAL RECHARGE STUDIES

MODERATOR: JACQUELINE RICH,
RICH AND ASSOCIATES

UTILITY OF BUTLER VALLEY, ARIZONA, AS A RECHARGE - RECOVERY BASIN: AN OVERVIEW

by

Floyd L. Marsh

INTRODUCTION

The demand for water in central and southern Arizona has created the need for strategic regulatory storage of imported surface water. Southwest desert alluvial basins, frequently underlain by deep aquifers, seemingly offer significant potential for efficient subsurface storage of artificially-recharged water and conjunctive management of limited water resources. By storing surface water underground during times of surplus, future demands can be met during periods of subnormal runoff by ground-water withdrawal. Such a conjunctive management scheme has been referred to as ground-water "banking".

Butler Valley, a deep alluvial-filled basin in west-central Arizona, has been proposed as a potential location for investigating and demonstrating the technical, institutional and economic feasibility of conjunctive water management using ground-water recharge, storage and recovery facilities. The unique physical, geographic and institutional setting of this ground-water basin provides an excellent opportunity to conduct a case study of recharge, storage and recovery of Central Arizona Project (CAP) water supplies and additional water sources. The University of Arizona Water Resources Research Center is presently engaged in reconnaissance-level applied research to determine the technical, economic and institutional feasibility of using the Butler Valley ground-water basin as a phased demonstration to full-scale operational recharge project.

Principal study objectives of this interdisciplinary research project, which is being conducted with support of and under provisions of the federal Water Resources Research Institute Program, include:

(1) Technical - to characterize hydrogeology relative to storage <u>in</u> and recovery <u>from</u> ground-water basin

(2) Institutional - to analyze legal and institutional impediments and alternatives for project implementation, and

(3) Economic - to conduct a quantatative benefit - cost analysis of project alternatives for recharge and recovery.

This paper presents both a descriptive overview and an interpretative overview of the Butler Valley project area relative to these study objectives.

DESCRIPTIVE OVERVIEW

Butler Valley has a unique hydrogeologic and institutional setting among other Basin and Range valleys in Arizona. Such uniqueness contributes to its utility as a case study of the feasibility for a recharge and recovery project investigation. Elements of the following descriptive overview include geographic location, hydrogeologic setting, geology and aquifer stratigraphy, ground-water quality and ground-water withdrawal and land use patterns.

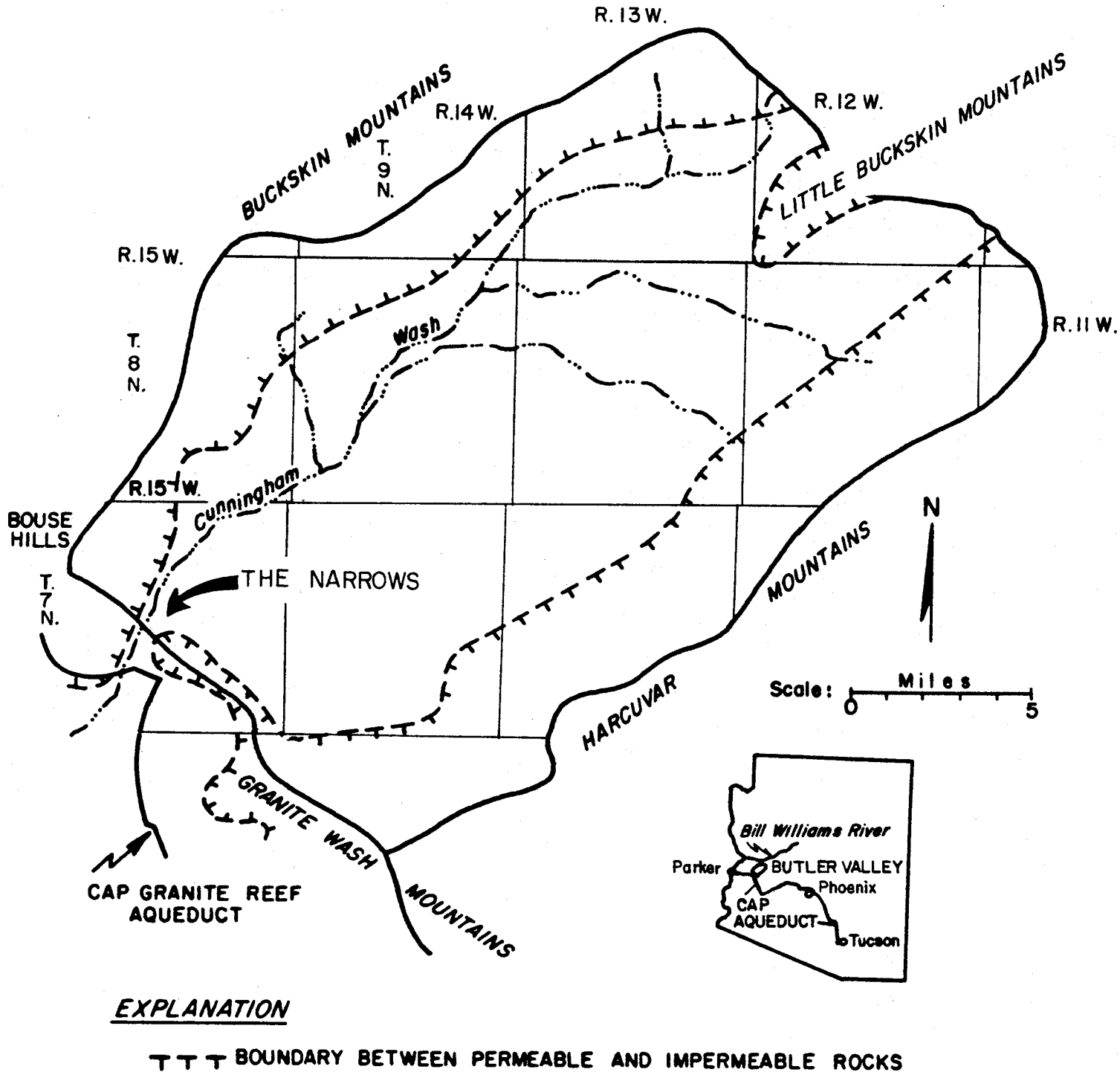
Geographic Location

Butler Valley is a flat, rectangular alluvial basin in northeastern La Paz County, Arizona. This basin lies midway between the Bill Williams River and the Central Arizona Project (CAP) Granite Reef Aqueduct, approximately 40 miles east-southeast of Parker and about 120 miles west-northwest of Phoenix, Arizona. Butler Valley is drained by Cunningham Wash, an ephemeral watercourse bisecting the Valley flowing southwesterly into the Ranegras Plain and Bouse Wash. The upper end of this valley is about nine miles south of the Alamo Dam and Reservoir on the Bill Williams River, while the lower end of the Valley is less than one mile upgradient from the existing CAP aqueduct. General location and physical boundaries of the basin are noted in Figure 1.

The Valley comprises a remote desert plain, which is underlain by a 160 square mile alluvial-filled basin, draining a 210 square mile watershed. Butler Valley is a northeast-southwest trending fault-bounded (graben) valley almost completely enclosed by mountains except for a mile-wide narrows, which provides an outlet for Cunningham Wash. Such a bedrock enclosure, which forms an effective ground-water barrier, consists of the Harcuvar, Buckskin, Little Buckskin and Granite Wash Mountains and the Bouse Hills. On a historic note of interest, General Patton used portions of the Valley for armor training purposes during World War II field exercises.

Hydrogeologic Setting and Aquifer Stratigraphy

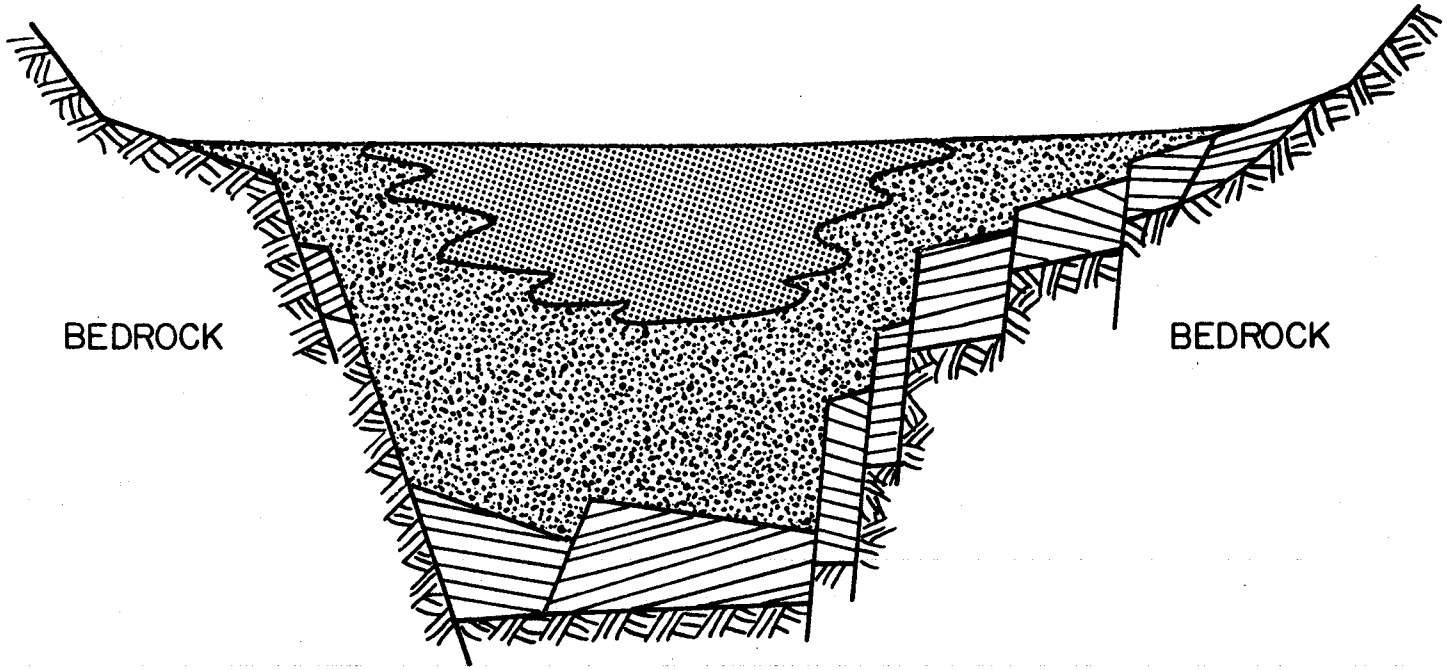
Butler Valley is a deep alluvial-filled basin consisting primarily of silt, sand, clay and gravel deposits, ranging in depth from about 1,000 to 2,000 feet. Aquifer stratigraphy and subsurface geology of Butler Valley is typical of the West Basins characterized by Pool (1984). General stratigraphy of these basins consists of rugged, steep fault-blocked mountain ranges surrounding highly faulted and tilted bedrock overlain by deep, layered alluvial fill, as represented in Figure 2. In these basins, alluvial fill is separated into lower and upper units which together are about 2,000 feet thick. The lower



EXPLANATION

BOUNDARY BETWEEN PERMEABLE AND IMPERMEABLE ROCKS

Figure 1. General location and physical boundaries of Butler Valley, Arizona.



EXPLANATION

- PRE-BASIN AND RANGE DEPOSITS
- FINE-GRAINED FACIES OF BASIN FILL
- RELATIVELY COARSE-GRAINED SEDIMENTS

Figure 2. Typical structure and generalized aquifer stratigraphy of West Basins (after Pool, 1984).

basin fill comprises the main aquifer and typically is limited to the central-basin area, although some saturated basin fill may overlie shallow bedrock at basin margins.

Surrounded by mountains of igneous and granitic rock, Butler Valley is virtually an isolated hydrologic unit comprising a semi-closed ground-water basin. The only potential subsurface outflow is in the vicinity of the narrows, where ground-water outflow may possibly occur. This geological setting attests to the overall hydrogeologic competency or physical integrity of the basin to store and contain additional water in addition to native ground water stored in the aquifer system.

Since Butler Valley is relatively undeveloped, the ground-water flow system is essentially in equilibrium and ground-water occurrence is relatively uniform throughout the basin. Ground water typically occurs under unconfined conditions, although confined conditions may exist in localized areas, particularly in the lower-central basin. Available well logs in the lower portion of the basin generally suggest dry alluvium to a depth of 200 feet, an unconfined aquifer in unconsolidated alluvium from 200 to 600 feet deep and a semiconfined aquifer in semiconsolidated alluvium below 600 feet (U.S. Bureau of Reclamation, 1979). Natural recharge (inflow) to Butler Valley is small and consists of minor mountain-front recharge and infiltrated streamflow beneath Cunningham Wash, the ephemeral watercourse that drains Butler Valley through the narrows. Natural discharge (outflow) consists of evapotranspiration losses at the downstream end and minimal, but unquantified, underflow into the adjacent Ranegras Plain.

Limited hydrogeologic data including driller and geophysical logs are available for the Butler Valley area. Water levels range from 95 feet in the lower (southwestern) end to more than 500 feet in the upper end (Wilkins and Webb, 1976). The piezometric surface of the water table is virtually flat with an elevation of about 1,275 feet above mean sea level. The depth to water becomes progressively greater toward the upper northeastern end of the Valley with increase in topographic elevation. Typical piezometric surface elevations throughout the Valley are presented in Figure 3.

Limited field investigations have been conducted to characterize the layered alluvium, impermeable boundaries and hydraulic properties of the aquifer sediments. Aquifer tests, consisting of a step-drawdown test and a constant-discharge performance test, were performed on a 1,200 foot production test well by the U.S. Bureau of Reclamation (1979) in the west-central portion of the basin. Results of these tests indicate an average transmissivity (T) of about 50,000 gallons per day per foot, ranging from 47,000 to 58,000 gallons

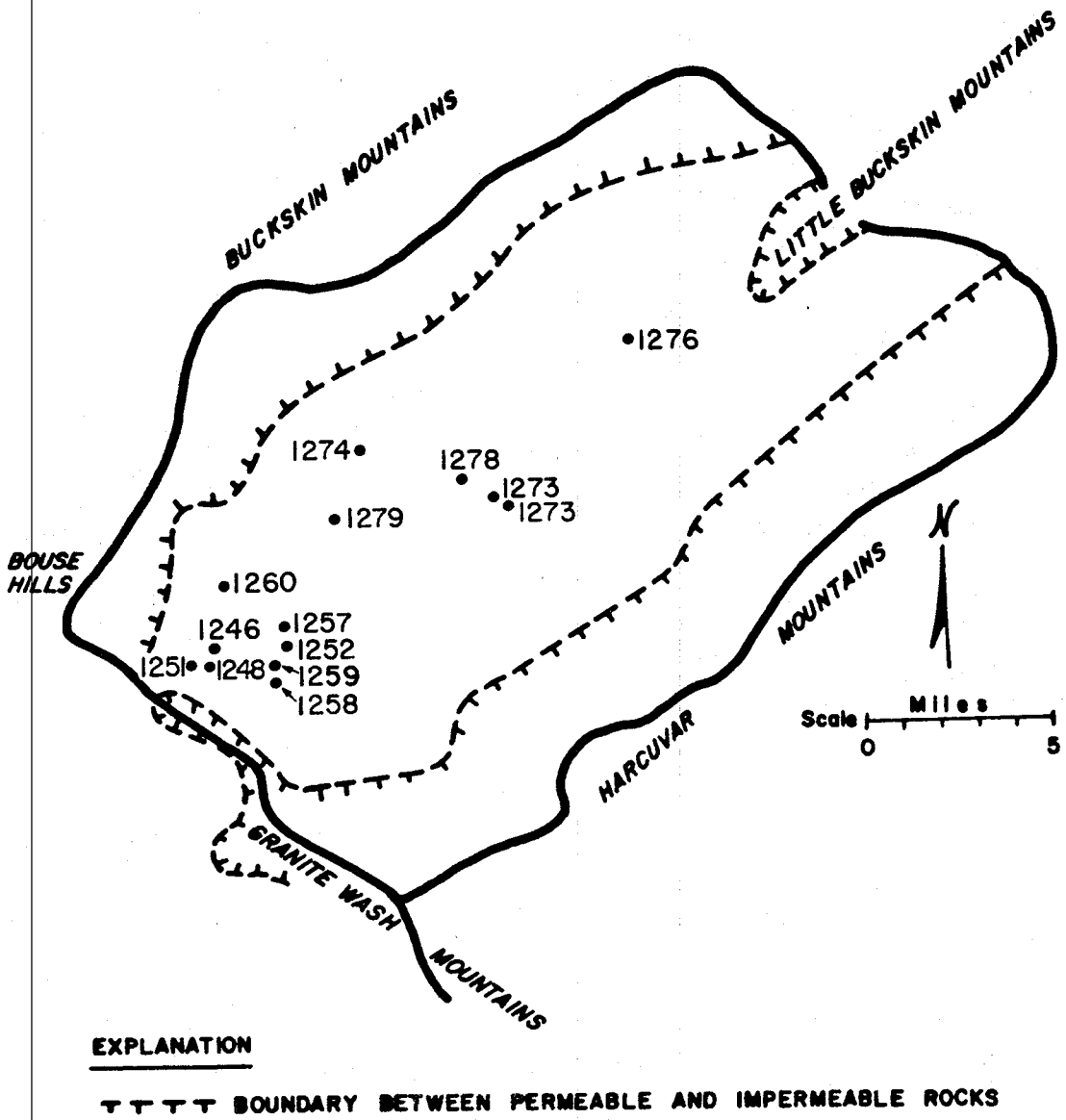


Figure 3. Piezometric water surface elevations above sea level (in feet).

per day per foot (U.S. Bureau of Reclamation 1979). Inasmuch as an observation well was not used in conjunction with the aquifer tests, a specific yield value (storage coefficient) ranging from 10 to 20 percent was estimated, based upon interpretation of available geologic and geophysical logs.

Surficial soils in Butler Valley are greater than 60 inches in depth, consisting of moderately coarse-textured sandy loam which has formed in old alluvium. Subtratum of these soils are typically calcareous, averaging more than 15 percent calcium carbonate. Permeability of these soils is moderately rapid, ranging from two to six inches per hour.

Ground-water Quality

Although water quality data are sparse, water quality in Butler Valley appears to be unusually good at about 400 ppm total dissolved solids (TDS). Dissolved fluoride levels as high as 7.5 mg/l have been detected in a well in the center of the basin, while a well in the upper end of the basin indicated 0.2 mg/l dissolved fluoride (Wilkins and Webb, 1976). Saturated extracts of soil samples collected in the central basin from virgin desert areas indicate a high nitrate content from natural sources.

Ground-water Withdrawal and Land Use Patterns

Butler Valley is sparsely populated and relatively undeveloped with ground-water pumpage estimated at 4,000 acre-feet in 1974 (Wilkins and Webb, 1976) and approximately 2,000 areas of agricultural lands existing in 1979. Ground-water withdrawal is currently limited to irrigation of less than 1,000 cropped acres. As noted, additional acreages have been in production in the past, but have since been abandoned, largely for economic reasons. Ninety-five percent of the land in the Valley is controlled and managed as public lands by the U.S. Bureau of Land Management (BLM) and the Arizona State Land Department (ASLD). After pending land exchanges between BLM and ASLD are consummated, virtually all the public lands will be under control of the state land agency. The remaining five percent consists of privately-owned mining claims in the surrounding mountains.

INTERPRETATIVE OVERVIEW

The overall purpose of this research project is to analyze and interpret the feasibility of a recharge-recovery program in Butler Valley, accounting for technical, economic and institutional elements of such a dual-purpose program.

Technical Analysis

Technical analysis of Butler Valley involved examining the ground-water and surface water characteristics of the project area. This analysis included examination of all available hydrogeologic data, performance of additional field investigations, simulation modeling of the ground-water flow system and conceptual development of the project area as a recharge-conjunctive management facility. Available data gathered for this analysis included water levels, borehole logs, structural geologic maps, precipitation data, pumping data and geophysical data. These data were compiled and analyzed to build a numerical ground-water flow model of the basin. Previous investigations performed prior to the current effort comprise three exploratory boreholes, limited geophysical work including gravity and electrical resistivity surveys and one single-well aquifer-pump test.

As part of the current investigations, University of Arizona personnel completed surface geophysical studies including gravity and seismic refraction surveys concentrated at the lower end of the Valley (Williams et. al, 1985). The immediate study area and field layout of geophysical studies is presented in Figure 4. The purpose of these surveys was to estimate the depth to and configuration of a shallow bedrock saddle beneath the narrows and to tie these data in with existing depth-to-bedrock data in the remainder of the Valley. By delineating the aquifer boundaries, estimates of aquifer storage capacity and potential ground-water outflow at the basin outlet were possible. Based on interpretation and correlation of geophysical data, Figure 5 notes a depth to bedrock at the basin outlet ranging from about 55 feet to 90 feet along a cross-sectional profile between bedrock outcrops, a distance less than three-fourths of a mile. These geophysical data indicate that ground-water outflow during recharge operations would be minimal due to the existing shallow bedrock saddle forming an aquiclude at the basin narrows.

The amount of ground water currently in storage depends primarily upon the estimation of aquifer boundaries. The U.S. Bureau of Reclamation (1979) reports a current storage volume of 20 million acre-feet based on a saturated thickness of 1,000 feet over an area of 160 square miles assuming a specific yield of 20 percent. Based upon the recent depth-to-bedrock and stratigraphic data, a more conservative estimate of 12 million acre-feet of existing ground water in storage was determined using a saturated thickness of 700 feet averaged over 130 square miles assuming an effective porosity of 20 percent.

In addition to the single-well test performed by the U.S. Bureau of

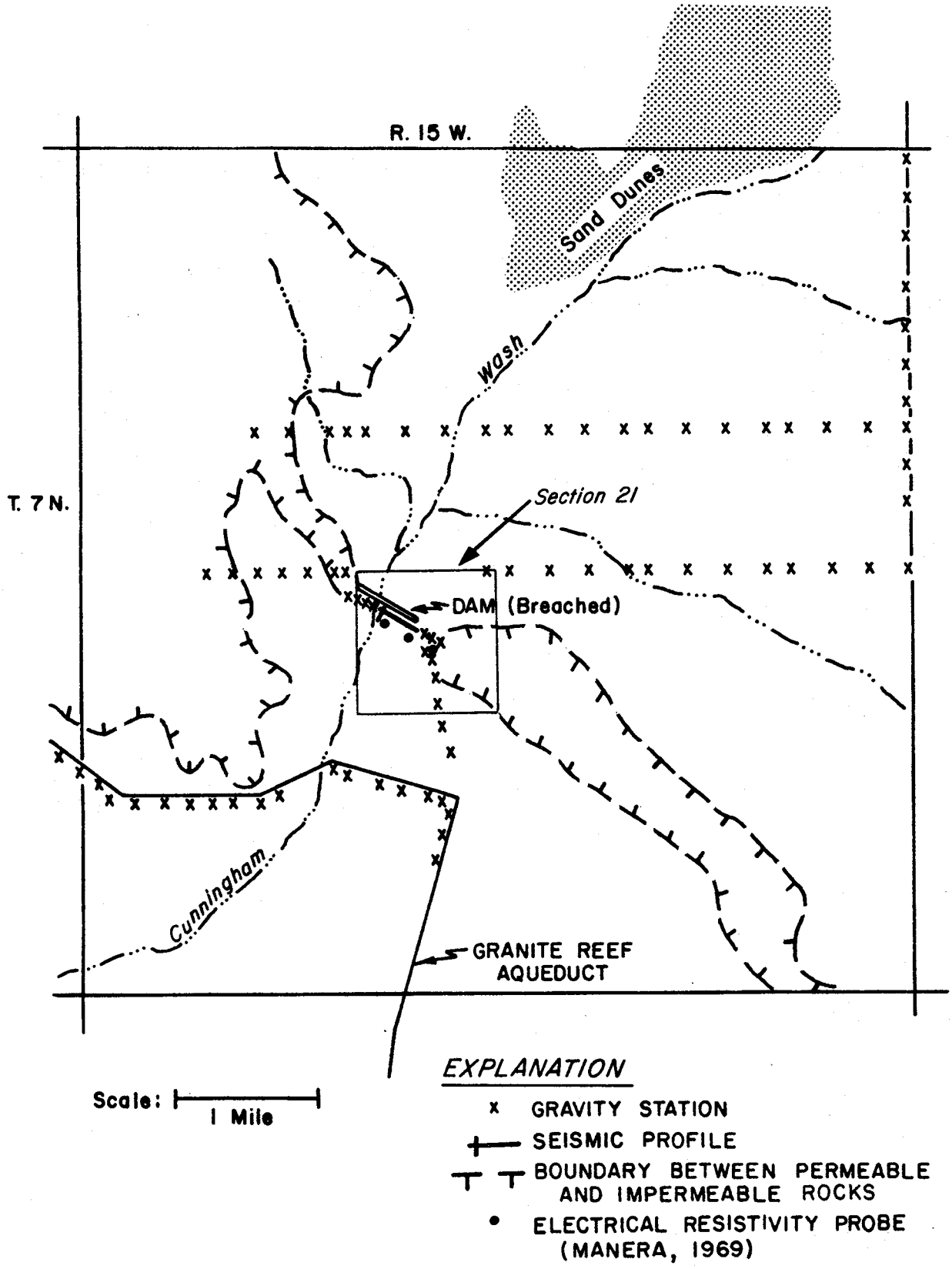


Figure 4. Study area and field layout of geophysical surveys in vicinity of Butler Valley narrows.

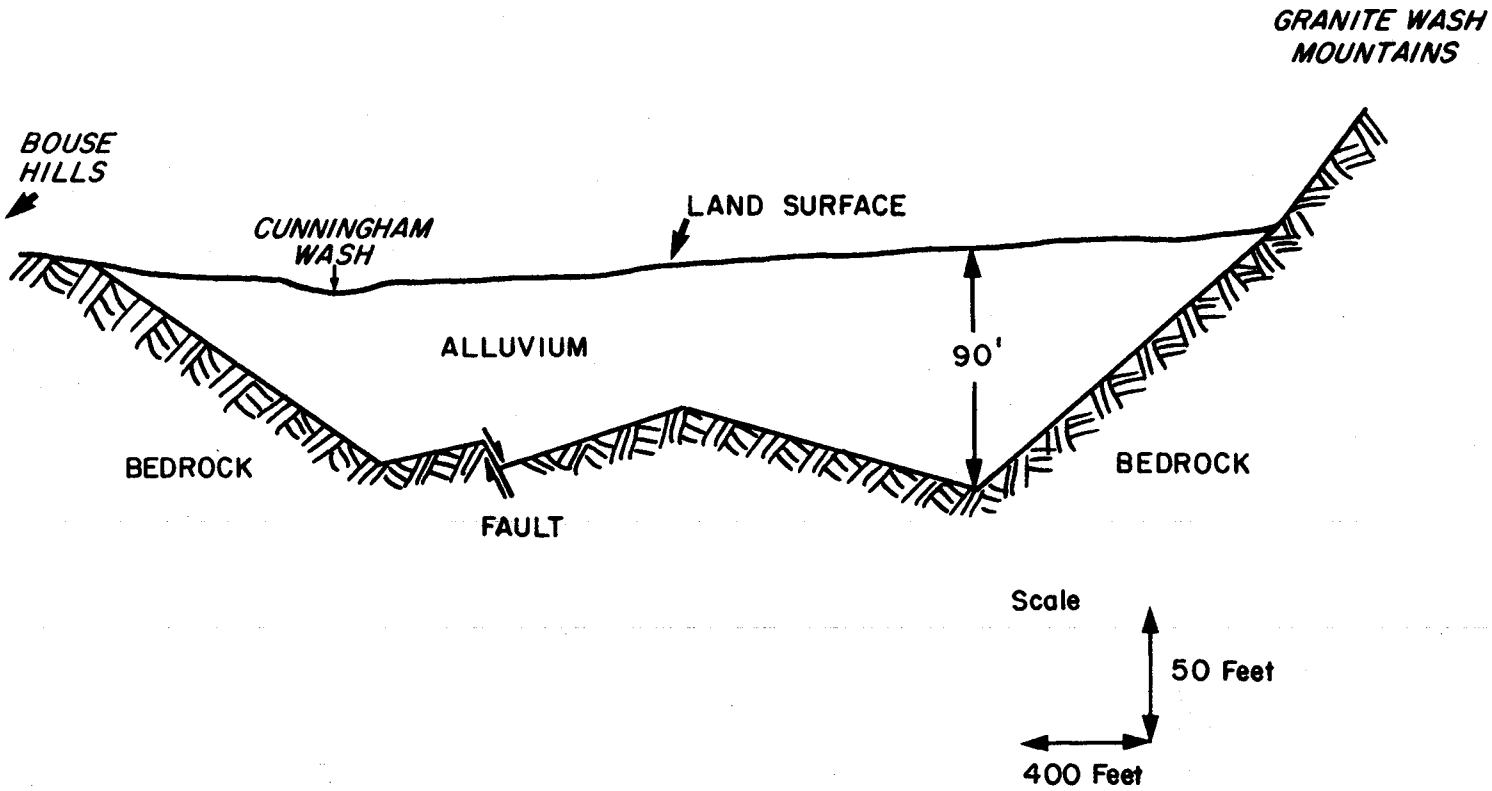


Figure 5. Cross-sectional profile of Butler Valley narrows.

Reclamation (1979), a recent aquifer-pump test with two observation wells was conducted in the lower portion of the basin to determine the hydraulic properties of the aquifer (Herndon, 1985). Results of this test suggest that a considerable portion of the aquifer system may be confined, thereby constraining the use of surface spreading as a recharge method. In this test, transmissivities (T) ranged from 40,000 to 58,000 gallons per day per foot, which correspond closely to values determined at the U.S. Bureau of Reclamation production test well located five miles to the northeast. Storativity values (S) obtained from the test were between 5×10^{-4} and 8×10^{-4}, corresponding to those of a confined aquifer. This finding is supported by the fact that the water level in the borehole of the two observation wells rose nearly 50 feet when the bottom of the confining layer was penetrated during drilling. Other supporting evidence of a confined system is that the drawdown in the observation wells occurred almost instantaneously when pumping began.

Hydraulic conductivity values (K) calculated from the two aquifer-test sites range from 3,200 to 6,400 feet per year. Based upon general soil survey work by the U.S. Soil Conservation Service, infiltration rates (saturated hydraulic conductivity) of the basin's surface soils range from 2.0 to 6.0 inches per hour, which indicates a moderately rapid permeability rate. Due to silt clogging of these soils, long-term infiltration rates may in reality be closer to 1 foot per day.

Subsurface stratigraphy of the basin-fill sediments is known only from driller's logs of about 15 wells plus the three exploratory holes mentioned previously. Most of the geologic borehole logs contain references to clay and silt layers throughout the central and lower portions of the Valley. The areal extent and continuity of this fine-grained confining layer, however, is unknown due to inadequate geologic data closer to the mountain fronts and in the upper basin as well as the need for more detailed information in the central and lower basin.

The piezometric surface in Butler Valley is virtually flat with an elevation of about 1275 feet above sea level, as noted previously in Figure 3. Ground-water withdrawals for irrigation in the lower portion of the Valley have created an artificial trough with water table levels as low as 1246 feet. Before the existence of this trough, a very slight regional gradient sloped upward northeasterly thereby moving ground water in the opposite direction toward the narrows, although the potential outflow was likely less than 1,000 acre-feet per year due to the small cross-sectional area of the narrows. The current pumping

depression reversed the gradient allowing ground water to flow away from the narrows toward the center of the basin. Although it is believed that much of the aquifer is overlain by an aquitard or aquiclude only in the lower portion of the basin is the aquifer actually under hydraulic pressure. This pressure occurs when the piezometric surface intersects the gradually sloping aquitard which hinders upward movement of the water thereby creating a confined system (Herndon, 1985a). The schematic cross section of a longitudinal profile of Butler Valley in Figure 6 illustrates this point. Under current conditions with a reversed gradient due to the pumping trough, ground-water outflow is assumed to be negligible.

Surface water hydrology of Butler Valley is being investigated to determine the possibility of harvesting in-basin runoff as a water source to supplement imported water. The purpose of this investigation is to predict the amount of annual runoff and to determine which areas of the basin are best suited for location of supplemental recharge facilities in conjunction with the basic recharge project. A stochastical rainfall-runoff model has been developed for major sub-watersheds in the Valley for predicting annual runoff volumes. This model predicts that runoff volumes along the mountain fronts range from 12,000 acre-feet per mile of mountain front for a 100-year recurrence interval to 2,000 acre-feet per mile for a one-year recurrence interval, without consideration of potential evaporation losses.

Available hydrogeological data were compiled and analyzed to construct a numerical ground-water flow model of Butler Valley for simulating an array of recharge and recovery distributions as they may affect the basin's ground-water flow system. The model, a contemporary U.S. Geological Survey three-dimensional finite-difference model (McDonald and Harbaugh, 1983), is being developed and used as a planning-management tool to identify and simulate ground-water level responses under the stresses of various recharge and recovery schemes at alternative locations in the Valley. Figures 7 and 8, respectively, represent a plan view of the model's gridwork of cells and longitudinal cross-section of grid layout superimposed on the basin aquifer system. As noted in Figure 8, the modeling configuration assumes a confined system in the lower and central basin and an unconfined system in the upper basin.

Four recharge schemes, including various combinations of spreading and recharge well fields, and two combination recharge-recovery schemes were simulated with time durations lasting from one to twelve years. To compare the various schemes, recharge and recovery rates were assigned a value of 100,000 acre-feet per year for all but one simulation, which as it turns out may likely constitute the maximum volume that can be feasibly rechargedannually. By way of comparison,

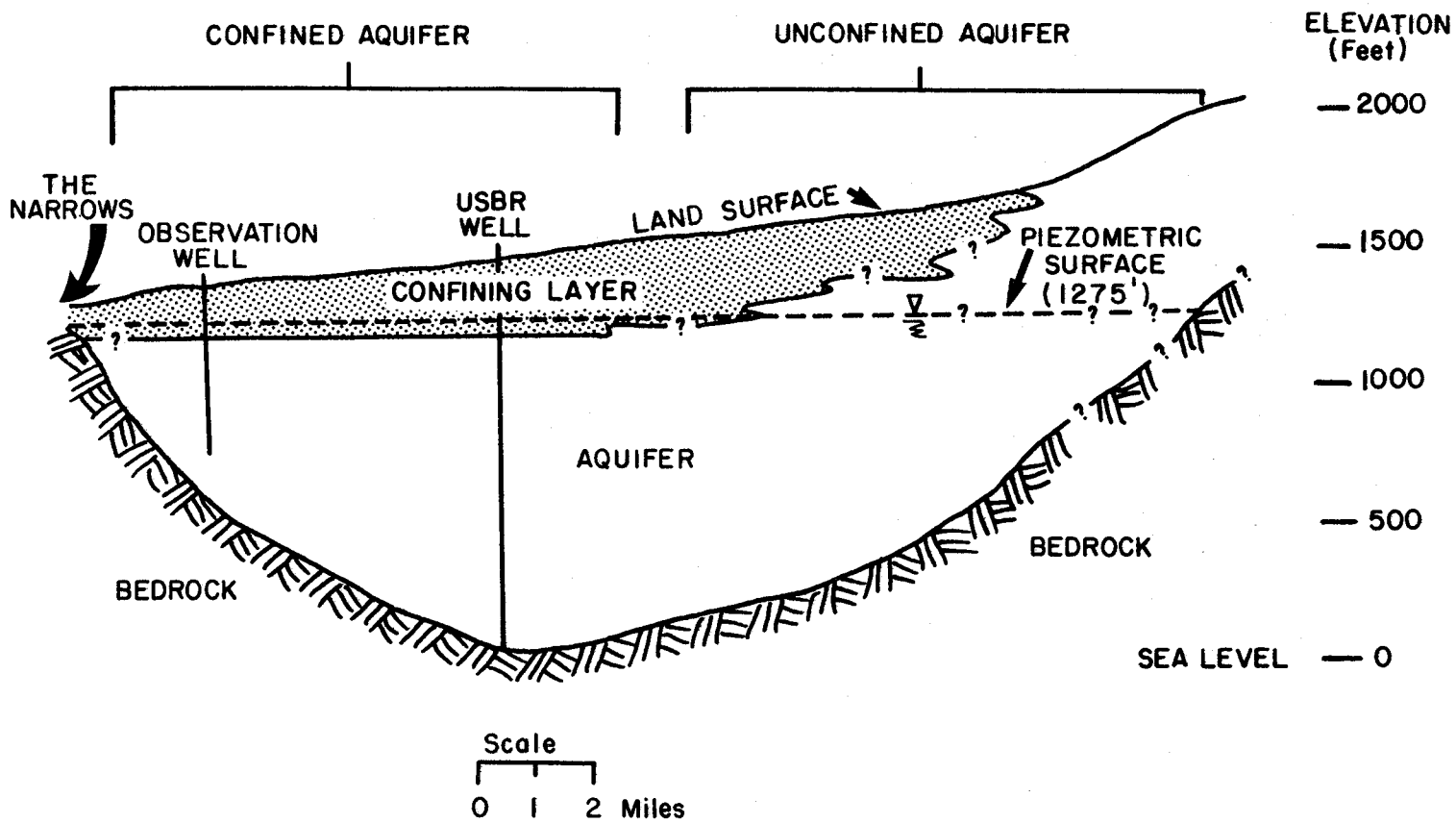


Figure 6. Longitudinal profile of Butler Valley basin.

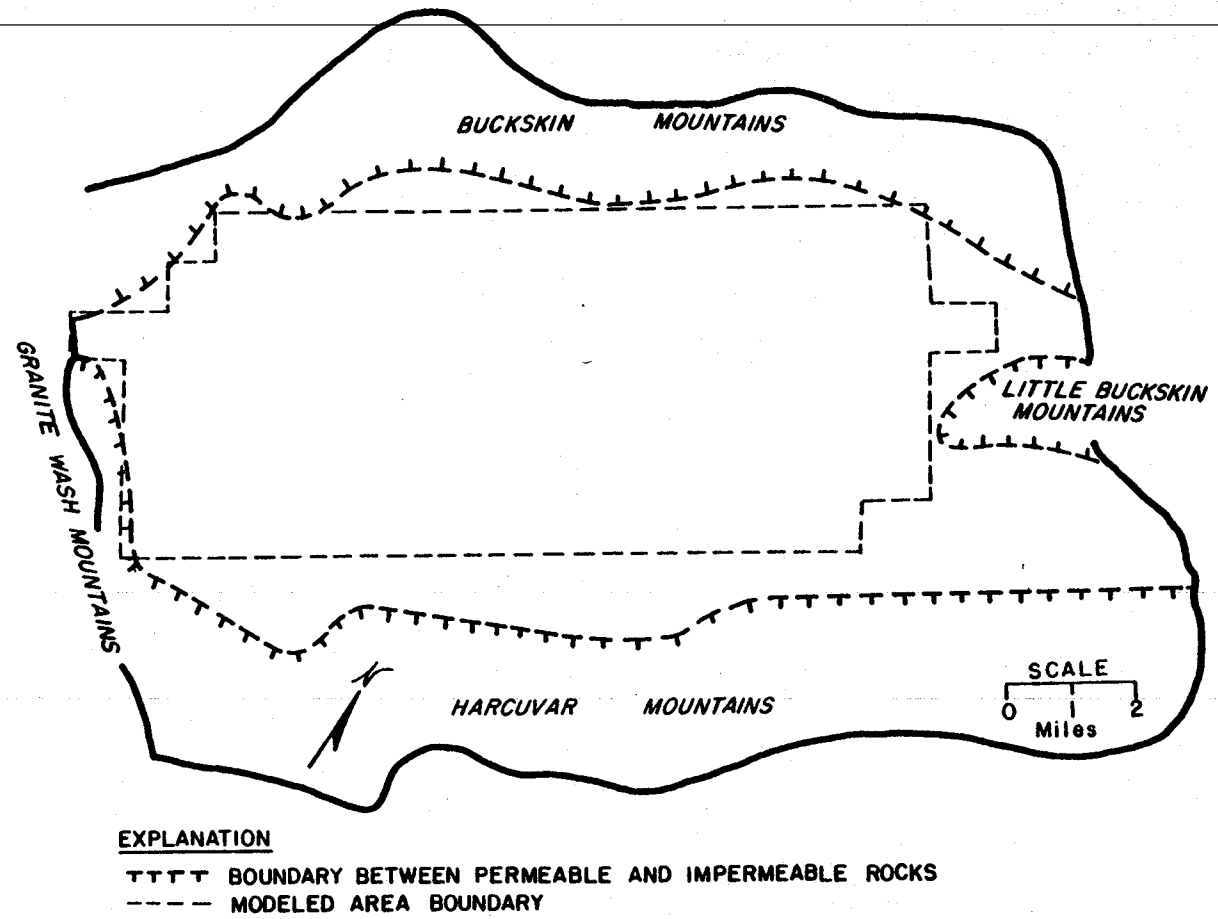


Figure 7. Plan view of active computer grid boundary superimposed on Butler Valley basin.

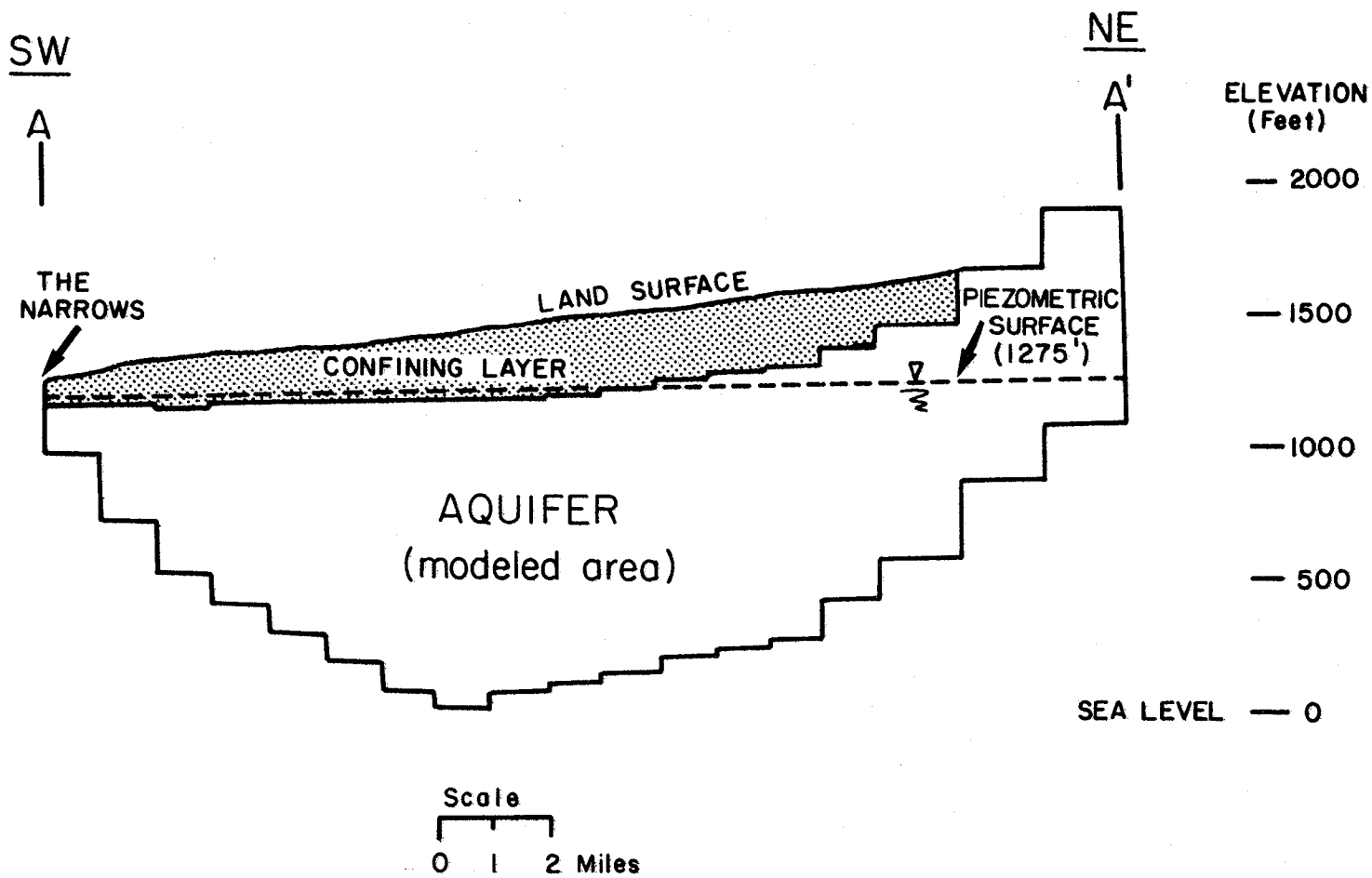


Figure 8. Longitudinal cross section of computer grid layout for Butler Valley basin.

a simulation involving recharge only in the central and lower portions of the Valley resulted in up to 200,000 acre-feet of total storage at a recharge rate of 100,000 acre-feet per year; whereas, a recharge-recovery combination simulated in the central and upper parts of Butler Valley indicated that 600,000 to 700,000 acre-feet could potentially be stored at the annual rate of 100,000 acre-feet. The basic tradeoff is storage versus lift costs. The value of greater storage in the upper basin may be offset by significantly higher lift costs to deliver the water for recharge. Whereas, the lower-central basin has lesser storage but also reduced lift costs.

The results of the computer simulations indicate that aquifer storage capacity increases in the upper portion of Butler Valley due to a confined system in the lower portion. Hence, it is concluded that artificial recharging should be performed in the central and upper portions of the Valley where depth to water (available aquifer storage capacity) is greater than elsewhere. Concomitantly, recovery wells could be located at the lower end of the basin where lift costs would be minimized. Further, preliminary results indicate that Cunningham Wash and its major tributaries and the basin margins along the mountain fronts appear to be the most favorable locations for surficial spreading due to potentially high infiltration rates in these areas.

The preliminary findings of this reconnaissance-level research project indicate that an artificial recharge and ground-water storage project operation in Butler Valley is likely feasible from a hydrogeological standpoint. Additional information on the aquifer stratigraphy and hydraulic properties of the basin-fill deposits is needed, however, before more definitive conclusions can be drawn. An exploratory drilling program would be most useful in determining the areal extent of the confining layer in the lower portion of the basin.

Conceptual Development and Operation 1/

A proposal on conceptual development and operation of the Butler Valley project area as a ground-water conjunctive-management bank (referred to as Clean Water Bank) has been advanced.

1/ Following section is edited from brief remarks by Alan Haws and the Butler Valley feasibility study work plan. Alan Haws holds an M.S. degree in Civil Engineering from the University of Oklahoma and is currently Vice President of Engineering Enterprises, Inc., Norman, Oklahoma.

Engineering Enterprises, Inc. and Signal Environmental System, Inc., a joint-venture consortium, have been collecting data and evaluating Butler Valley and the Arizona Clean Water Bank privatization concept since 1983. The University of Arizona and Engineering Enterprises, Inc. have collected and reviewed most of the available technical information.

Throughout this period the State Land Department which controls a majority of the public land in Butler Valley and the Central Arizona Water Conservation District (CAWCD) have assisted with and been supportive of the project proposal. Because of the mutual interests the proposal has evolved from either a public project or a private venture to a potential cooperative effort between the public and private sectors.

In November 1984, CAWCD requested proposals of technical and financial capabilities of interested investigators, developers and operators of a Butler Valley water banking operation as follows:

> "The Central Arizona Water Conservation District (CAWCD) is seeking a multi-dimensional engineering and financial entity to develop a program for the utilization of a particular Arizona groundwater basin as a storage reservoir for Central Arizona Project water under a water bank concept. Modified privatization is being considered. The selected entity must be prepared to participate in a staged process which could ultimately involve the entity as the developer and/or operator of a water recharge project under appropriate long-term arrangements with CAWCD. The extent of the entity's involvement will be decided by CAWCD after evaluating information produced in three or more developmental stages."

At an April 4, 1985, Board meeting following competitive interviews, CAWCD selected Engineering Enterprises, Inc./Signal Environmental Systems, Inc. as the entity to pursue Butler Valley in a public-private partnership of privatization. By letter of June 7, 1985, CAWCD directed the entity to develop a plan; subject to their approval, for conducting a $300,000 feasibility study at Engineering Enterprises, Inc./Signal Environmental System, Inc.'s expense, in accordance with the Engineering Enterprises, Inc./Signal Environmental Systems, Inc. proposal.

The objective of this study is to determine the feasibility (costs/benefits) of recharging and storing surplus or unused CAP water in Butler Valley and subsequently recapturing it as needed. Engineering Enterprises, Inc./Signal Environmental Systems, Inc. proposed to conduct the study at their cost and in March, 1985 expressed confidence to CAWCD that sufficient information could be obtained to develop accurate cost estimates for about $300,000. If after the study, they and CAWCD felt the project was economically and politically feasible, they would also design, finance, construct

and operate the project in a public-private partnership with CAWCD. Project phasing would involve three phases: Phase I, a multi-faceted feasibility study; Phase II, preliminary design; and Phase III, project implementation (design, construction, financing and operation).

Currently, details of the work plan which includes a pilot demonstration program and exploratory test drilling in the initial phase are being finalized and land-lease arrangements are being negotiated among the parties of interest.

Institutional Analysis

Since a preceding paper addresses the institutional considerations of recharge in detail, this section will summarize the institutional analysis for the Butler Valley project. Specific objectives of this effort includes assessment of the institutional, legal, political and administrative constraints on the ability to recharge water in and recover water from Butler Valley.

The institutional analysis involved itemizing the alternative entities or combination of interests who could finance, administer, operate and use the Butler Valley project; determining the feasibility of the project under current Arizona law; determining the process for integrating the project into the operational framework of the Central Arizona Project; and estimating the political and environmental ramifications. The effort on this phase of the project involved an extensive literature search, including examining pertinent federal and state statutes, court opinions, and analysis of administrative decisions, and agency directives. For additional information, contact was made with key members of the legislature, various agencies, districts, and interests involved in possible privatization schemes.

From an institutional and legal viewpoint the research to date concludes that a recharge-recovery project in Butler Valley is possible provided that the following problems are resolved: (1) the current lack of state legislation defining the rights to recharge and recapture water in a basin such as Butler Valley, (2) the current lack of legislation to protect ground-water quality during a recharge operation, (3) the lack of specific legislative authority for the Central Arizona Water Conservation District to operate a recharge project in Butler Valley, and (4) the Plan 6 controversy including both configuration of physical components and cost-share financing. It was also concluded that a privatization scheme is feasible provided that questions of water rights, land-leasing arrangements, state regulation of operations, cost of electricity and formulation of contracts are resolved.

In summary of these issues, the institutional setting is both dynamic and complex. Overall, the legal-institutional framework is constantly

changing, primarily due to political considerations. The impediments can be overcome, but any Butler Valley project alternative must be analyzed within the overall framework of state water policy. Current investigations establish a foundation for more detailed site-and issue-specific analysis as the institutional picture comes together. The institutional research is ongoing through provisions of a continuing grant proposal with more definitive conclusions forthcoming.

Economic Analysis

An overview of economic considerations of artificial recharge is presented in a previous paper, therefore, this section summarizes the ongoing economic analysis of the Butler Valley project. The principal study objective of the economic component is to conduct a quantitative cost-benefit analysis of project alternatives for recharge and recovery facilities in various combinations. Given available technical and institutional information, a set of recharge-recovery schemes were selected for economic appraisal.

Based on technical studies to date, current economic research involves selection of recharge-recovery schemes and estimating engineering costs. Three hydrogeologic factors affected the selection of recharge schemes, namely, (1) depth to water, (2) presence of confining beds and (3) confined vs. unconfined conditions. Several simplifying assumptions made in the recharge-recovery system design include:

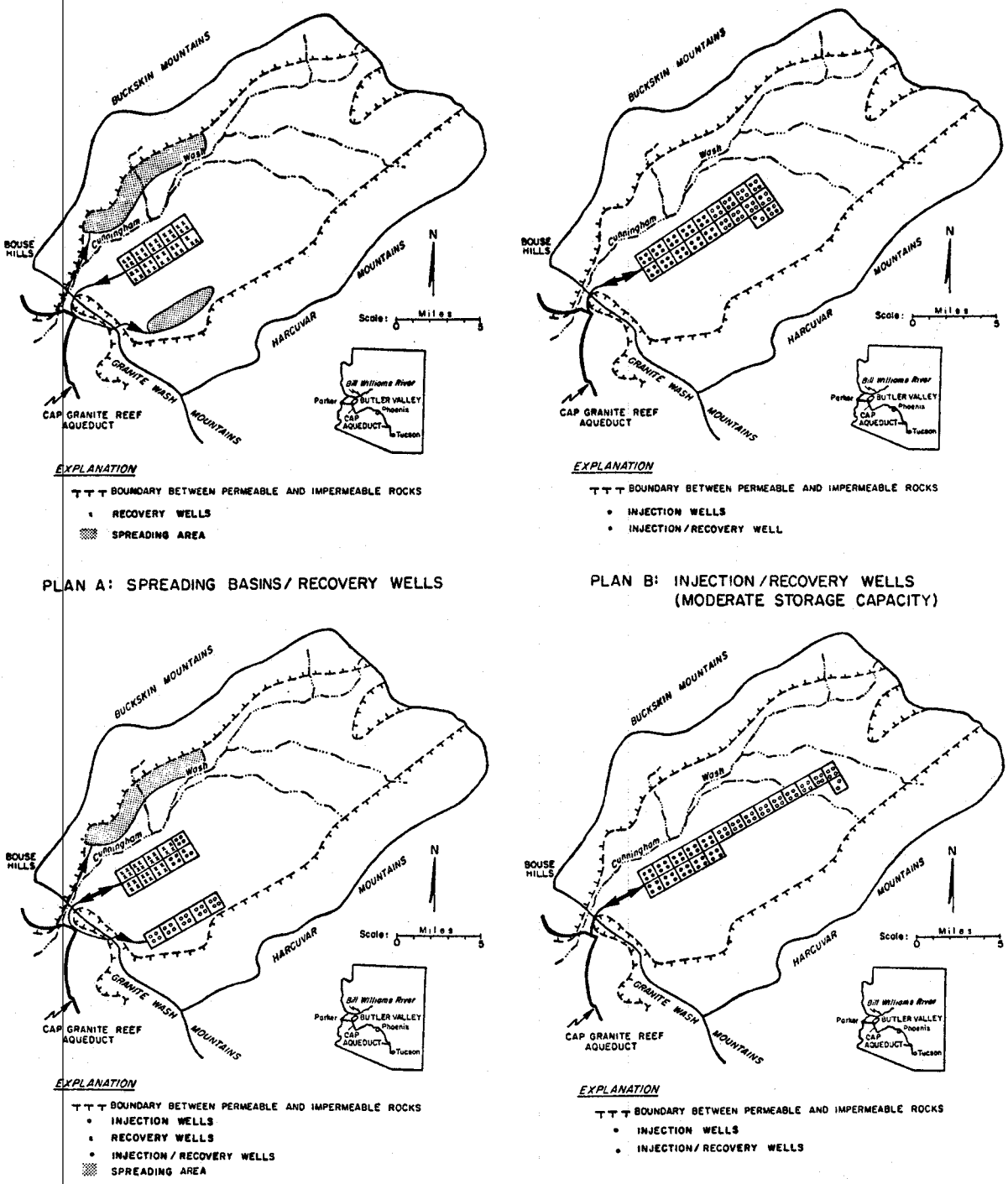
- annual artificial recharge equals 100,000 acre-feet,
- all injection wells are identically designed each with a capacity of 1,000 gpm,
- all recovery wells are identically designed each with a capacity of 2,000 gpm,
- well spacing of four wells per square mile,
- recharge capacity via spreading is directly proportional to spreading area,
- surface spreading operations are 70% efficient and wells are 96% efficient, and
- distribution system costs are estimated using reasonable engineering design.

Five representative alternatives of recharge and recovery were selected for the cost-benefit analysis.

These project alternatives include:

Plan A: spreading basins/recovery wells
Plan B: injection/recovery wells (moderate storage capacity)
Plan C: spreading basins and injection wells/recovery wells
Plan D: injection/recovery wells (high storage capacity), and
Plan E: baseline - no recharge project.

General field configurations of these alternatives are presented in Figure 9.



PLAN A: SPREADING BASINS/ RECOVERY WELLS

PLAN B: INJECTION /RECOVERY WELLS (MODERATE STORAGE CAPACITY)

PLAN C: SPREADING BASINS AND INJECTION WELLS/ RECOVERY WELLS

PLAN D: INJECTION / RECOVERY WELLS (HIGH STORAGE CAPACITY)

Figure 9. Configurations of Plans A-D.

Preliminary cost estimates of the selected recharge-recovery alternatives were obtained from various literature sources and from discussions with consultants. Capital engineering costs for each plan were converted to equivalent uniform annual costs, assuming a discount rate of 8% and a design period of 25 years. The sum of these annual costs and annual operation, maintenance and energy costs (O,M, and E) provides an estimate of the total annual cost of each scheme. Dividing total annual cost by the net amount of water reaching the aquifer yielded a cost per acre-foot of water diverted for recharge. Preliminary costs ranged from $115 per acre-foot for a system of spreading basins and in-channel recharge, coupled with recovery wells, to $138 per acre-foot for a combination system of recharge and recovery wells. Additional refinement of the preliminary cost per acre-feet figures is required for further comparison of selected schemes with each other and against other water uses in Arizona. The next phase of the economic analysis will attempt to assess benefits and opportunity costs of using Butler Valley as a ground-water recharge-recovery bank.

Summarizing the economic analysis phase, the physical and institutional setting of the Butler Valley project area provides an excellent opportunity to evaluate economic feasibility of alternative recharge-recovery designs, as well as examine effects of exogenous institutional and socioeconomic aspects. Like the institutional analysis, the economic investigation is ongoing through provisions of a continuing grant proposal.

SUMMARY AND GENERAL CONCLUSIONS

General hydrogeology of Butler Valley, Arizona, appears favorable for recharge, storage and recovery of imported water, although some technical parameters require further field evaluation. Likewise, economic considerations and institutional constraints remain but appear to be surmountable, while requiring additional investigation of site-specific issues.

With its unique physical and institutional setting, Butler Valley serves as a prototype project to investigate and demonstrate the technical, institutional and economic feasibility of using alluvial basins in the desert Southwest as ground-water management banks through the physical processes of recharge, interim subsurface storage and recovery of imported water sources. This project also provides an opportunity to explore the financing and management concepts of privatization (that is, a joint public-private partnership) to design, construct and operate large-scale water supply projects involving conjunctive water management. Overall, we are encouraged by the promise

which this innovative approach to water supply management appears to offer, particularly using preliminary results in the Butler Valley project area for development of a phased research-demonstration to full-scale operational recharge/conjunctive management program.

Acknowledgement is made of efforts of the Butler Valley project co-principal investigators, Drs. Mike Bradley and Gray Wilson, along with assistance of the project staff of six graduate research assistants.

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RECHARGE IN THE PHOENIX METROPOLITAN AREA

remarks by 1/
Bill Chase

Before I begin, I would like to take the opportunity if I might to introduce a gentleman in the audience. David Iwanski is an assistant to Congressman Eldon Rudd (Dist. 3, Arizona) and the reason I wanted to introduce him today is that I want to take a little time out of my program to give you a good announcement at least as far as I am concerned. A group of people called together by the Congressman in the Phoenix metropolitan area have formed, referring to themselves as SAFE, Supporting Arizona's Future Economy. The purpose of this group which has been meeting for over a year now is to talk about what can we do here in the Salt River Valley to help ensure water supplies beyond the Central Arizona Project (CAP). In other words, what is the next step we should be looking at? This group, as I have mentioned, has been meeting with many of you involved with this effort. We have people represented from a good cross-section of the community.

We have been getting together and talking about what are we going to do next assuming that we get the CAP issues sorted out and actually done; what can we do next knowing that water projects take a lot of time? After talking about this, looking at it, working on it, we have come to the conclusion, as a group, that what the group should do for the next year is dedicate their efforts solely to the question of groundwater recharge. We intend to take a look at the technical and institutional issues associated with the recent legislative initiatives on recharge including the draft bill advanced by the Arizona Municipal Water Users Association, a bill that they are expecting to work on next legislative session. Our objective is to get this group in a position to be very supportive of these efforts, which I think represents a major step forward in that we now have a group of people who typically have not been involved in this issue who are getting together with other people that have technical backgrounds. I think the Congressman has done a good service for our community in getting this group together.

1/ Edited and summarized from taped transcript of presentation which was structured around a series of slides.

The group is not exactly like the Southern Arizona Water Resources Association (SAWARA) in Tucson but it does have some of the same kinds of goals and same kinds of people involved.

My message today is fairly simple. The message really has to do with the City of Phoenix and why the City of Phoenix as an organization is interested in groundwater recharge. Why are we really promoting it? The reasons are obvious to those of you who have been involved, one of them is money. We see it as a mechanism to accomplish a lot of our water management programs in the most efficient and the cheapest way possible. In some cases it is the only way we can do the very important job of water management. What I have is a series of slides that will show you what the future holds for the City of Phoenix, at least as far as its long-range water planning is concerned. I want to show how this water planning relates to groundwater recharge.

For those of you who are not familiar with the water service area of the City of Phoenix, we serve more than just our citizens. We serve a portion of the City of Scottsdale, Town of Paradise Valley and we have ambition to go far beyond that into outlying areas in the Valley. We break our area into two kinds of general service areas: (1) is "on project" within the Salt River Project and (2) is off project. The total is 340,000 acres, the "on project" area is an area of about 130,000 acres. It happens to have most of our resident now. Some 600,000 individuals in the City of Phoenix are served in "on project" areas and only 300,000 off project. But in the future we are going to have a reversal of that because of the area and land development trends.

Looking at the population data for the "on project" service area, we are going to grow. We expect to be serving something less than 1,000,000 people by the end of our planning period. Since I had the trepidation or the urban planners did to try to find out what will happen "on project", we also tried to figure out what would happen to us off-project. And, the roughly 300,000 people that we're serving now is expected to grow to somewhat over 1,000,000 people by the end of our planning horizon. So we are going to have little reversal in terms of total numbers.

There is a significant difference in the City of Phoenix relative not only to where our population grows, but also relative to where our future water supplies are going to be. We use a mechanism of gallons per person per day to translate our future people into our long-range water needs. It really doesn't have to do with what each of us uses in our household. Since

we take all the water that is served to all our customers -- residential, commercial, industry and everything else -- lump it into one number divided by all the people and we come up with a gallon per capita per day figure. So the values fluctuate a great deal. Part of that is because we have data problems and part of it is that we have annual fluctuations since people respond to weather. We have selected sort of an averaging trend for both of those and you will note that the "on project" area has a history of, at least in terms of City of Phoenix deliveries, using slightly more water than the off project water does. In addition to that, the "on project" has an additional amount of water that is delivered by the Salt River Project that we are not counting, such as deliveries for flood irrigation. We translate our population demand into water demand in the future. You can see that our water demand is actually a little bit different in this relationship, but you can still see a lot of growth. We still have a slightly larger water demand "on project" even though we have a slightly smaller population "on project" in the future because of this discrepancy in the projected per capita use. In any event, we are talking about a great deal of water.

What about "on project" supplies? This graph basically says that our supply and our demand are not that far apart. There is a little bit of differential in there but we are basically in pretty good shape with "on project" supplies, assuming a lot of complicated things about what is going to happen to the Salt and Verde supplies over time.

The next graphic shows where we are getting our water currently to serve our off project area which is the more difficult area to serve. Basically, we are currently using ground water and "gate" water. "Gate" water is a limited amount of surface water supply we acquire in return for improving and building gates on one of the six dams that the Salt River Project owns and operates. The big red block is the Central Arizona Project (CAP) water which we anticipate importing up to the extent of our treatment plant capacity.

Relative to supply sources, there is a tapering off of groundwater supplies in response to the Groundwater Code which says we are going to reach something called safe yield by the year 2025. The gate water supply will continue indefinitely. The CAP supply will also continue indefinitely. When you take the supply line on this graphic and you compare it to what our demand projections would be, comparing the population, you have a large gap.

The real question is, how do we fill the gap? What do we do as a planning agency to deal with that? One of the things we had to do was to try and understand where our water is going and how is it being used. Basically, when you

look at the pie chart, you see the bulk of the water is being used for either indoor or outdoor residential type uses. Not that much of our water is going into commercial or industrial uses. Since we are basically a mature community we are probably not going to see tremendous changes in that unless we, as a municipal water institution, influence that or began influencing the homeowners to stop using that tremendous block of water for outdoor water use. That in fact is what we intend to do! In part because we are public spirited and part because the Department of Water Resources explained it to us in a way that we understand real well. The Department, as you know, has set a conservation goal of 6% reduction in municipal usage. Based upon projections, we are saying we can probably achieve something like 20% and that's 20% based on the water we deliver. That number is a little deceptive in the case of the City of Phoenix because there is a significant block of water that we are not currently delivering which is delivered as untreated channel water for flooding of residential lawns, parks, commercial areas, cemeteries and that sort of thing. That is not expected to continue in the future. What is there now will probably continue but it will not continue to grow at the same rate that it has in the past. That means all of that new growth that comes in will have to be served out of our treated water and so a 20% reduction in fact is really more like a 30% reduction when you consider the fact that we are going to have to make up that difference in treated water. Whether we can do that or not I don't know but we have planned for it.

What does it do to the supply-demand relationship we looked at? It shaves the top off, coming out of demand reduction. It is a pretty significant supply or reduction in a need for supply. Unfortunately, it still leaves a lot of area between that which we can clearly project that we have and that which we need.

What are some of the possibilities for gaining a supply? In some of the City's service area, we have made application for additional CAP water and if we get some additional CAP water obviously that will help fill the gap. That's beginning to relate again long-range planning to the issue of recharge. Let me say that the marvelous facility which we call the Central Arizona Project does something for the cities and for others in this area that we have obviously never had before. It connects us with the Colorado River which in turn connects us to a number of other states and locations. We now have a whole field of things out there to look at. As a water planner, I previously had to go out and figure out how to reuse waste water, conserve

water, maybe wrestle a little away from Scottsdale. Now I have this whole new horizon. We can buy farms on the Colorado River. We have people coming in from Utah and Colorado that want to sell us water for interstate import. Once you make the Colorado River connection, you begin really in essence as a water planner for a specific area to connect yourself to lots of future potential supplies.

Unfortunately one of the problems with those future potential supplies is you have to bring it in through a system that is dedicated primarily to another use. That is, bringing in supplies for farmers and cities who have a dedicated right to use that system. They are going to get first right of use or first right of refusal of use. So one of the things that happens when you begin to look at a field for future potential supplies -- as we all are looking for groundwater supplies to buy in the state or supplies to buy off the Colorado River -- is that we can transport it in that system but only on a space available basis. What does that mean? It means that the purchase of the land is probably fairly inexpensive and there is lots of water out there. It also means that the plan of the Bureau of Reclamation relative to the operation of the aqueduct, if they build New Waddell Dam, is that in the summer time they are going to operate pretty low coming out of the Colorado River. They are going to try to minimize the pumping in the summer so they can have surplus power to sell and they are going to make that supply up out of storages that have been put in there during the summer months. In the winter months they are going to put water into the reservoir behind New Waddell Dam and then they are going to take it out in the summer. There is space available in the aqueduct to move water to that location. The City of Phoenix is near the confluence where all that comes together, so we could probably move summer time water. We could probably get space in excess to the system to move it.

What happens to us in the winter? In the winter, the Bureau or the Central Arizona Water Conservation District (CAWCD) plans to operate the system the other way around. They plan to do all their pumping in the winter, take the water that is surplus to the needs or deliveries to their customers and put it into the New Waddell Reservoir. What is the effect of that? The effect is there is no space for the City of Phoenix to move water off the Colorado River. So, if one of our solutions is to find water, we have to figure out a way to bring the water in when the space is available, maybe only half the year and have it available for twelve months out of the year. The only way we know of doing it is to provide some very large storage.

Surface storage is out of the question in terms of the City of Phoenix building reservoirs, so where do we turn--to groundwater storage! So part of what we have to do if we are going to promote some of these schemes for moving water is have the ability on a seasonal basis to bring the water in when the space is there and put it underground and take it back out later. This concept is part of what we are looking at.

What is one of the other effects of having the aqueduct arrive in Phoenix? Of course, it is going to come into our treatment plant, the Union Hills Treatment Plant, which is under construction to take the water. It has a large raw water storage reservoir, which stores about two days of flow in terms of the use of the treatment plant and allows for dampening there. It will be treated and go into another reservoir and store about one-half day's worth of normal daily flow. One of the things that happens relative to our system, like it does to farmers and other water users, is we have a tremendous variation between our summer demands and our winter demands. In fact, there is a ratio of 3 to 1. Our summer peak is about 3 times higher than our winter low. In the summer it is one-half times greater than the average for the year. What does that mean to us? It means that this facility is going to be sitting around idle part of the time. During winter when we don't have demand to take water out, we don't have any place to store a couple of days raw water or one-half day of finished water. Hence, we are going to have a facility we bought and paid for that is there but it can't be used because there aren't people to take water immediately. What can we do with that? You heard such a discussion during yesterday's luncheon from our consultant, Cella Barr Associates, who are looking at how we might do that. The City of Phoenix has a huge investment in wells and in distribution systems, including 4,700 miles of pipelines. This represents a lot of opportunity to use this system that we bought and paid for with taxpayers money to treat CAP water, which otherwise would be idle, and introduce it into our distribution system. One of the things about a city distribution system -- and it is a standard design practice for a distribution system like ours -- is that it is all hooked together so that we can serve water from various locations. From an operation perspective it also has floating reservoirs built into it. We have some sense of how demand changes throughout the day but we build one day's total storage in reservoirs strategically located in our system. Then we can run our surface water treatment plants and our wells at a somewhat more constant rate. When people's demands are real high, the reservoirs help supply it. When people's demands are

lower, then the surplus water backs up in the reservoirs and the system kind of floats on the reservoirs and it operates in a self-actuating mode.

These same reservoirs can function to help us use this system as a means of recharge. In the summer what we have to do is operate this plant at full capacity. We have to supplement it with wells in order to keep those reservoirs from dropping too fast. Our system operators watch the reservoir levels and if they are coming down too fast they turn on a few more wells. That is how we run the system. In the winter we can do the same thing except in reverse. If we see the reservoir levels rising too fast, that means our production is greater than demand. We simply open a few recharge wells and let the water go back underground. That's really the concept between using your production system and your distribution system in a recharge-storage mode. Again, it is a seasonal storage principle, but it is very important to economizing and operating our system effectively.

We also have in our future planning, the Cliff Dam, a component of Plan 6. The City of Phoenix is very interested in seeing this dam promoted for flood control as well as for the water that will be conserved. The Horseshoe Dam is upstream from there about seven miles. Horseshoe Dam is where our gates and our surface water supply that I have talked about called gate water comes from. When Cliff Dam is built, it will back the Verde River up completely over Horseshoe Dam. So we are going to have some kind of ownership in this structure, whether or not we buy the extra space.

Finally, for those of you who like the idea of taking the water and cleaning it up like they are talking about doing in Denver, running it through high technology equipment and putting it right back into your distribution system rather than storing it underground for two years like El Paso is doing, you don't have to worry about groundwater recharge. You just get a lot of bells and whistles and you can go straight from one end of the pipe to the other. The El Paso system ranges from a big pond where they have been piling the water up and letting it do what a big pond can do out in a nice desert climate, which is a pretty good job of treating waste water, to a $37 million investment for about 10,000 acre-foot per year facility. This facility is a high class, very expensive operation for wastewater treatment. It is an activated-sludge plant but they are also going to add powdered-activated carbon to absorb all those bad things. Then they intend to put it into huge furnaces and burn all the good things off which will go into the atmosphere where it becomes someone else's problem and the water is going

to be clean. If that is not clean enough, they are going to run it through a standard water treatment plant and then they intend to recharge it underground where it has a residence time of at least two years. Then they are going to pump it and drink it and be happy. That is an option and in fact, it is the bottom option on our costs.

What does that bring you to? The City of Phoenix is quite supportive of groundwater recharge as an operational element of effective water management. This interest and support is due to extreme fluctuations of summer and winter demands and as a means of long-term water storage. That is basically the message that I want to leave you with.

Bill Chase holds an M.S. degree in Water Resources Engineering from the University of California at Los Angeles and is currently Water Advisor to the Phoenix City Manager, Mayor and Council.

Presented To The
Second Symposium on Artificial Recharge in Arizona
by
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ARTIFICIALLY RECHARGED WATER--IS IT GROUNDWATER, SUB-FLOW SURFACE WATER, OR ____? 1/

INTRODUCTION

Many opinions have been expressed in Arizona as to how water, which has been artificially recharged, should be regulated by the Department of Water Resources. The type of regulation depending on the kind of water it becomes after it has been recharged i.e. groundwater or sub-flow surface water. This paper reviews recharge and storage in general, and presents another view of the use of the state's underground aquifers.

RECHARGE

Water is naturally and artificially recharged to the underground. **Recharge** is the method by which water is transferred from the surface of the ground to the aquifers beneath the ground.

Natural recharge occurs when rainwater or snowmelt percolates below the surface of the ground essentially where it falls. In addition, rain or snow melt can percolate into the ground through the sands and gravels in the bottoms of streams, ponds and lakes.

Artificial recharge is recharge performed by man. There are many recharge techniques available which include the use of natural river beds, ponds and lakes. In addition, pits and wells may be used.

Why does man want to artificially recharge water to the underground? Although there may be more, the two major reasons that come to mind are:

1. For the purpose of using the earth to **naturally** treat and clean up water.

2. To **store** the water for use at a future date.

STORAGE

Natural storage occurs when rainwater or snowmelt is impounded in ponds and lakes on the surface of the ground or when it is recharged to the underground aquifers.

Over the hundreds and thousands of years since the formation of our underground basins, water has percolated into these aquifers and been stored there until man developed pumps capable of lifting water from deep within the ground.

1/ Paper was preceded by a slide series titled "Water Is Our Future", providing an overview of the City of Scottsdale, Arizona, Master Plan and importance of recharge to this plan.

Man has learned how to store water in surface reservoirs by constructing dams and placing the water he wishes to store behind the dams. He then releases the water from the reservoir as needed. Sketch A is an example of this type of storage.

Man also stores water below the ground surface in concrete-lined reservoirs. Again, as we see in Sketch B, the water is placed in the reservoirs and then pumped out as needed.

In many instances, it is desirable to cover these concrete-lined reservoirs and actually bury them below the surface of the ground (see Sketch C). Usually this is done for aesthetic reasons but it also protects the water from wind-blown dust and, at the same time, reduces the amount of water lost due to evaporation. As in the previous example, the water supply is placed into the underground reservoir and then pumped out as required.

In Sketch D, the only thing that has been done differently from Sketch C is that the concrete walls of our buried underground reservoir have been removed and the water placed into the spaces between the soil particles instead of in a large open space between concrete walls.

In these four sketches the **KIND OF WATER** that is in our reservoirs is **STORED WATER.**

LABELING

In Sketch A, B and C the water is not changed to a **NEW TYPE OF WATER** depending on the type of reservoir it is stored in. It is still water stored for irrigation, municipal and industrial, or some other type of use. The container it is stored in does not make it into some new type of water such as **groundwater** or **sub-flow surface water. In view of this neither should the storage of water in our aquifers require that a new label be placed on the water that is stored there.**

VALUABLE ASSET

The majority of this state has been blessed with an extremely valuable asset. It lies beneath our feet. It is not the water which has been naturally placed in our aquifers and mined by man. **It is the underground reservoirs.** Its value results from man's ability to store large quantities of water over long periods of time...10-20-40 years... without the evaporative loss and resulting increase in the saline content of the water.

GROUNDWATER MANAGEMENT ACT AND STORAGE

In the event that we chose to construct one of the reservoirs as shown in Sketches A, B and C and then storing water therein, the water would belong to the individual(s) who placed it there and would not be subject to the Groundwater Management Act. The goal of the Groundwater Management Act is **not** the control of **all** of the water in the state but **only** the control of groundwater from the standpoint of **mining**, not from the standpoint of

storage. In view of this, why should any water, which an individual(s) places into the underground for storage purposes, be regulated by the Department of Water Resources any more than had the individual(s) stored it in one of the man-made reservoirs described above.

STATE'S INTEREST

In view of the importance of water management in Arizona it appears that it is in the State's best interest to clearly establish the right of an agency or an individual to store and treat water in underground reservoirs, retaining the right to withdraw those waters exclusive of the rights of anybody else to withdraw and use, and not subject to the management plans and conservation goals of the Groundwater Management Act.

CONCLUSION

It is reasonable and proper that water, which has been naturally recharged to the underground, needs to be used in accordance with State law. However, it is equally reasonable and proper that the underground reservoirs of this State, not the waters naturally occurring therein, belongs to the land which overlies it and, therefore, agencies or individuals which overlie it should be able to use it to store, treat and recover water therefrom exempt from the Groundwater Management Act.

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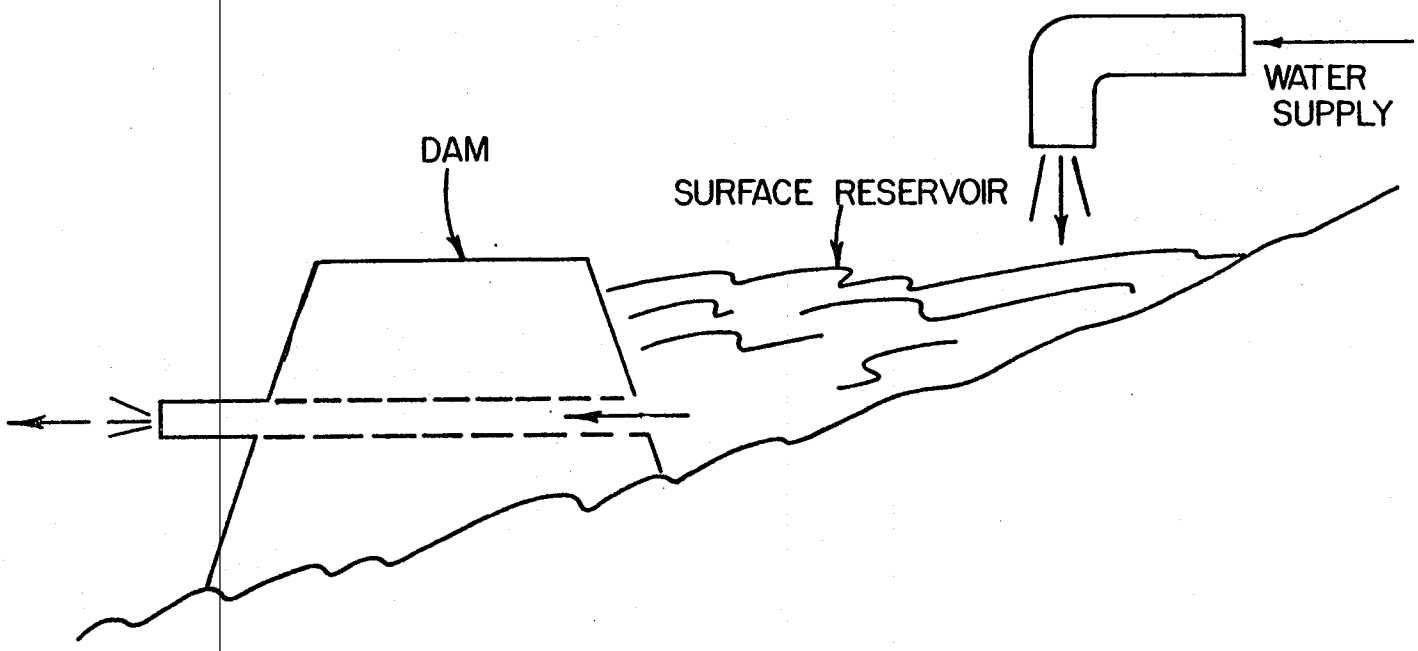
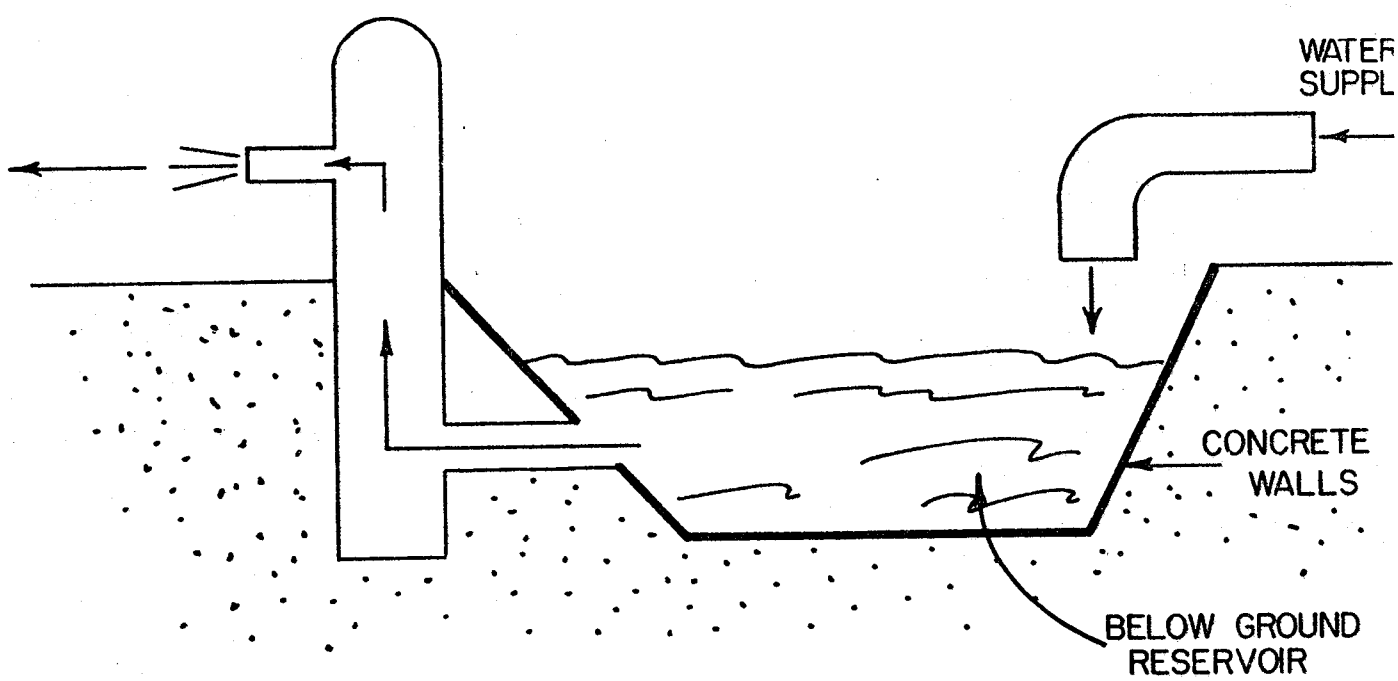


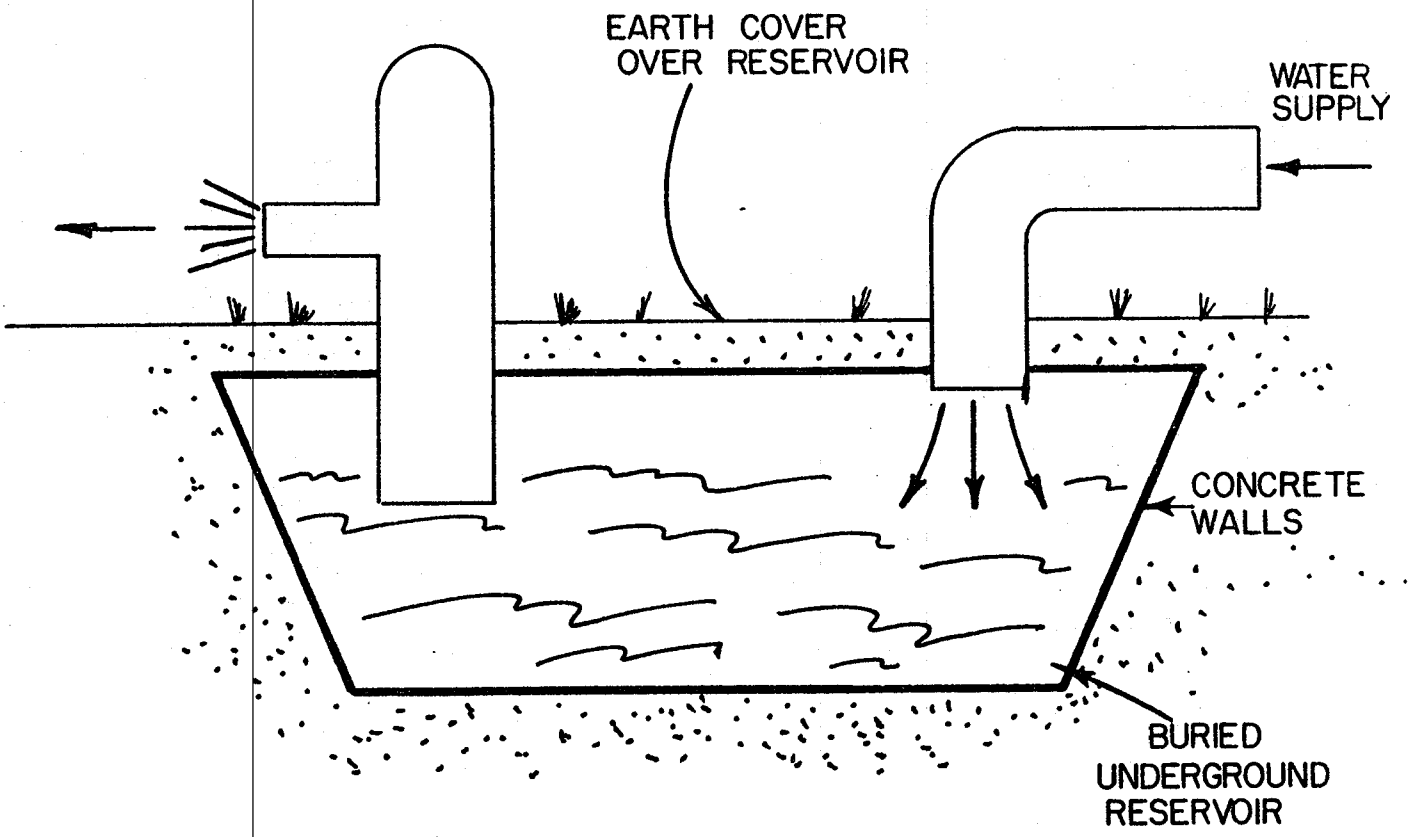
WHAT KIND OF WATER?

SKETCH A



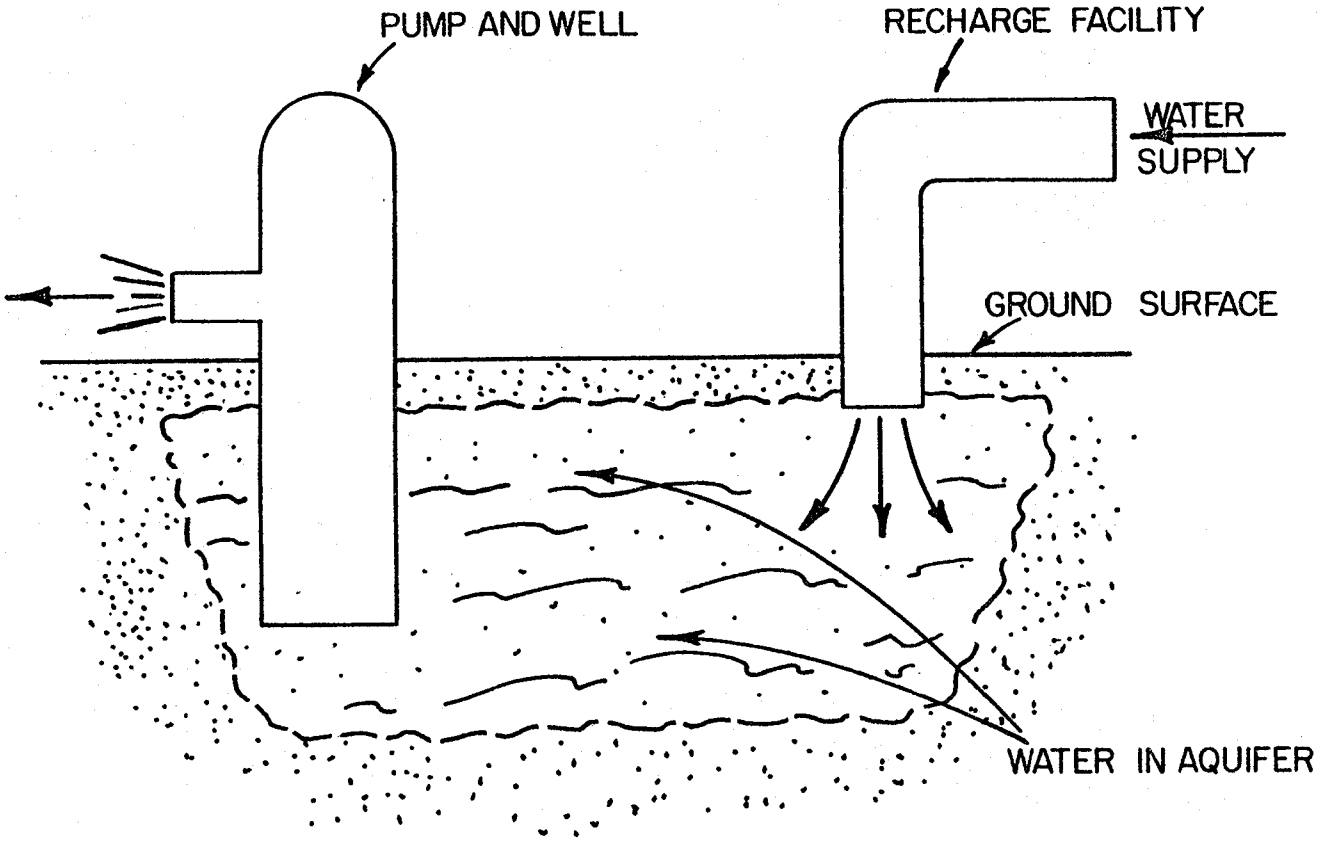
WHAT KIND OF WATER?

SKETCH B



WHAT KIND OF WATER?

SKETCH C



WHAT KIND OF WATER?

STORED

SKETCH D

A DEMONSTRATION RECHARGE PROJECT IN TUCSON, ARIZONA

Richard A. Randall
R. Bruce Johnson

INTRODUCTION

The water supply problems for the Tucson area have been much discussed and highly publicized during the past 10 years. Our local problems have paralleled statewide interests in water conservation, water supply development and resource management which culminated with the adoption of the 1980 Groundwater Management Act by the Arizona State Legislature.

This new law created a strong agency called the Arizona Department of Water Resources (ADWR) to deal with the growing problems of water management within the state. In addition, Active Management Areas (AMA's) were created to solve the problems of local groundwater overdraft. These are the Phoenix, Tucson, Pinal and Prescott active management areas.

The primary management goal of the ADWR in managing the Tucson AMA is to realize a safe-yield condition (long-term balance between withdrawals and total recharge) by 2025. The basic tools which are available to the ADWR to achieve this goal are water conservation, supply augmentation and wastewater reuse programs.

The staff of ADWR has completed an updated baseline estimate together with projections of existing and anticipated water uses and supplies for 1980, 1990 and 2025. These data are contained in the Tucson Active management Area Proposed Management Plan, 1980-1990 dated April, 1984. The Management Plan document depicts the extent of the existing groundwater overdraft condition in the Tucson AMA and the vital role which effluent will play in bringing the region to the desired safe-yield condition by 2025. The Proposed Management Plan calls for effluent use amounting to 66,000 acre-feet in 1990 and increases to an estimated use of 146,000 acre-feet by 2025.

TUCSON METROPOLITAN REUSE ASSESSMENT

The current interest in effluent utilization gives the casual observer the impression that this concept is new. In actuality, effluent has been used to augment water supplies to agricultural interests as early as 1900 (Davis, 1983).

Recognizing that reuse of wastewater would become a significant factor in basin water management, the City of Tucson adopted generalized effluent reuse policies in September 1982. These policies encouraged reuse of wastewater and established priorities for reuse to maximize benefits to the community.

In November 1982, the City retained CH2M HILL/Rubel and Hager, Joint Venture, to prepare the Tucson Metropolitan Wastewater Reuse Assessment, herein referred to as the reuse assessment. The assessment was undertaken to evaluate the technical and economic feasibility of alternative wastewater reuse projects within the metropolitan area.

Alternative wastewater reuse projects that would apply up to 18,800 acre-feet per year of reclaimed water to 2,000 acres of golf courses and 1,300 acres of parks, school grounds and cemeteries were identified and evaluated. The potential sites represent approximately 80 percent of the existing landscaped areas of this type within the metropolitan area as well as approximately 500 acres of proposed golf courses, park expansions and new school grounds.

Estimated unit costs for more favorable projects varied from $230 to $385 per acre-foot delivered, including capital amortization and annual operating expenses.

Major issues considered in the reuse assessment included a comparison of supplying reclaimed wastewater from regional plants versus upstream wastewater reclamation facilities, identification of constraints and benefits of groundwater recharge, discussion of impacts due to future use of Central Arizona Project (Colorado River) water, analysis of the effect of the Papago Indian water rights settlement, identification of institutional considerations, evaluation of public health aspects, and discussion of public acceptability. Identified potential uses of reclaimed wastewater in the metropolitan area included landscape irrigation, industrial use, and groundwater recharge. This paper will concentrate on the issues relating to the use of groundwater recharge.

GROUNDWATER RECHARGE

Concepts of groundwater recharge with effluent can be conveniently classified into two groups, uncontrolled and controlled.

Uncontrolled recharge means that the recharged water is allowed to mix freely with the native groundwater; no attempt is made to directly recover only recharged water. The potential contamination of groundwater with nitrates and volatile organics and to a lesser degree with viruses and other constituents, places severe restrictions on groundwater recharge with reclaimed wastewater. There are indications, however, that significant improvement in water quality can occur by passage of effluent through the unsaturated zone.

Controlled recharge with reclaimed wastewater requires nearby recovery wells to extract the recharged water. The recovery wells would prevent the reclaimed wastewater from uncontrolled mixing with the native groundwater and thus prevent groundwater contamination by pollutants that may be present.

The reuse assessment determined that reclaimed wastewater recharge is feasible in and adjacent to the major washes that traverse the city. Because of the risk of contamination of the drinking water supply, it was recommended that the recharged reclaimed wastewater not be permitted to freely mix with the native groundwater. A controlled recharge program that includes withdrawal of effluent with recovery wells was, therefore, recommended.

A serious drawback in using reclaimed wastewater for irrigation purposes is that the supply of effluent is available at a relatively steady rate year round while the irrigation demand has a monthly variation of up to 300 percent. In order to effectively use the available supply on an annual basis a means of seasonal storage for vast quantities of reclaimed wastewater is required.

A relatively new concept in providing storage capacity for water distribution systems is aquifer storage and recovery. Aquifer storage and recovery is a form of controlled recharge with the added concept of storing the water underground for an extended period of time prior to withdrawal. Aquifer

storage and recovery can, therefore, provide the seasonal storage needed for the City's reclaimed wastewater delivery system.

Aquifer storage and recovery can prove to be a key factor in optimizing Tucson's wastewater reuse program. Reclaimed wastewater could be allowed to percolate into the ground at selected locations during the fall and winter and pumped during the spring and summer to meet peak irrigation demands. An added benefit is the additional treatment achieved as the reclaimed wastewater passes through the soil which enhances its quality. The extent of additional treatment achieved will be dependent on operational procedures. For example, the system can be operated to provide nitrogen removal if desired.

Underground storage of reclaimed wastewater would significantly reduce the size and costs of conventional treatment facilities and reservoirs. Aquifer storage would enable these facilities to be sized and operated to meet average irrigation demands instead of peak demands. Further, locating recharge sites on the periphery of the community and near large reclaimed wastewater users would reduce the size of the required transmission pipelines.

DEMONSTRATION RECHARGE PROJECT

To assess the feasibility of reclaimed wastewater recharge, a relatively small scale (0.5 to 1.0 mgd) demonstration recharge project was proposed. A project this size can store and recover about 1,000 acre-feet of reclaimed wastewater annually.

After a review of alternative sites, it was decided that the demonstration recharge project would be located on a parcel of City-owned land on the west bank of the Santa Cruz River channel less than one-half mile from the City's new Reclaimed Wastewater Treatment facility. Objectives of the demonstration recharge project are to:

- Evaluate the feasibility of temporarily storing large quantities of reclaimed wastewater underground on a seasonal basis.
- Evaluate the feasibility controlling the movement of the recharged water so it does not mix with groundwater beyond a limited area.
- Evaluate the effectiveness of the recharge facility in removing potential pollutants such as nitrogen, trace organic compounds, viruses, and other constituents.
- Gain experience in operating a recharge facility in the Tucson area to develop operating criteria for flooding and drying cycles.
- Develop criteria that can be used in evaluating similar recharge sites within the groundwater basin.
- Determine the cost-effectiveness of this method of recharge and treatment relative to conventional treatment and storage facilities.

In the long run, the City hopes to develop sufficient data to allow large-scale recharge to the aquifer. Filtered, disinfected secondary effluent would be used initially, and later, if feasible, secondary effluent would be used.

Specific phases involved in implementing the recharge project include the following:

- Preliminary Investigations
- Detailed Hydrologic Investigations
- Project Design
- Construction
- Freshwater Testing
- Operation with Reclaimed Wastewater
- Operation with Secondary Effluent (if feasible)

A technical advisory committee has been formed to review and comment on the project at various stages of implementation. The committee includes members of regulatory agencies and recognized experts in the fields of groundwater hydrology, virus removal, and soil/aquifer treatment of wastewater effluent.

Preliminary Investigations

The preliminary investigations for the 22 acre site included the gathering of data on hydrology and water quality, detailed surface soils mapping and soils infiltration testing.

Hydrogeologic Data. Drillers logs and water quality data for 33 wells within two miles of the site were examined. Only two wells nearby had reported pumping tests. The data indicated that the depth to groundwater is about 100 feet and that the aquifer permeability and transmissivity are adequate for a recharge project. Based on major anions and cations as indicators, the water quality is not good and is remarkably similar to the secondary effluent. This similarity means that an artificial tracer such as bromide will be required to monitor the travel of recharged water.

Surface Soils Mapping. A soil scientist performed the detail soils mapping using five test holes dug with a soil auger and thirteen test pits dug with a tractor backhoe for data collection. The principal product of the investigation was a delineation of those areas underlain by soils of high infiltration capacity which comprise about 60 percent of the site. Generally the soils suitable for recharge are described as deep, well-drained soils consisting of stratified sandy loam, loam, silt loam, and silty-clay loam textures. The soil is underlain by gravelly, loamy coarse sand at depths greater than 10 feet.

Infiltration Testing. To verify the infiltration capacity of the soils three infiltration basins 20 feet square and 2 feet deep were constructed on the site. The basins were filled with potable water to a depth of 12 inches and a constant water level was maintained through the use of float operated valves. Inflow into each of the basins was measured by water meters. The test was conducted for a period of seven days.

The results of this test indicated that the rates of infiltration vary significantly across the site and range from 0.7 feet per day to 2.5 feet per day (Randall, etal 1984). The average rate of infiltration was determined to be 1.6 feet per day.

Detailed Hydrologic Investigations

Wells will be used at the demonstration recharge facility to extract recharged water for reuse and to monitor the effect of operations on local aquifer groundwater quality. To accomplish this requires one extraction well capable of pumping 1,500 gallons per minute (gpm). Additionally, ten monitoring wells have been drilled. The locations for these wells are shown on Figure 1. Design criteria are listed below:

Monitoring Wells

- 150 feet deep
- 12-inch borehole
- 6-inch steel casing (75 feet slotted)
- gravel packed
- 75-foot surface seal
- developed until clear
- geophysical logging
- permanent submersible pump installed

Extraction Well

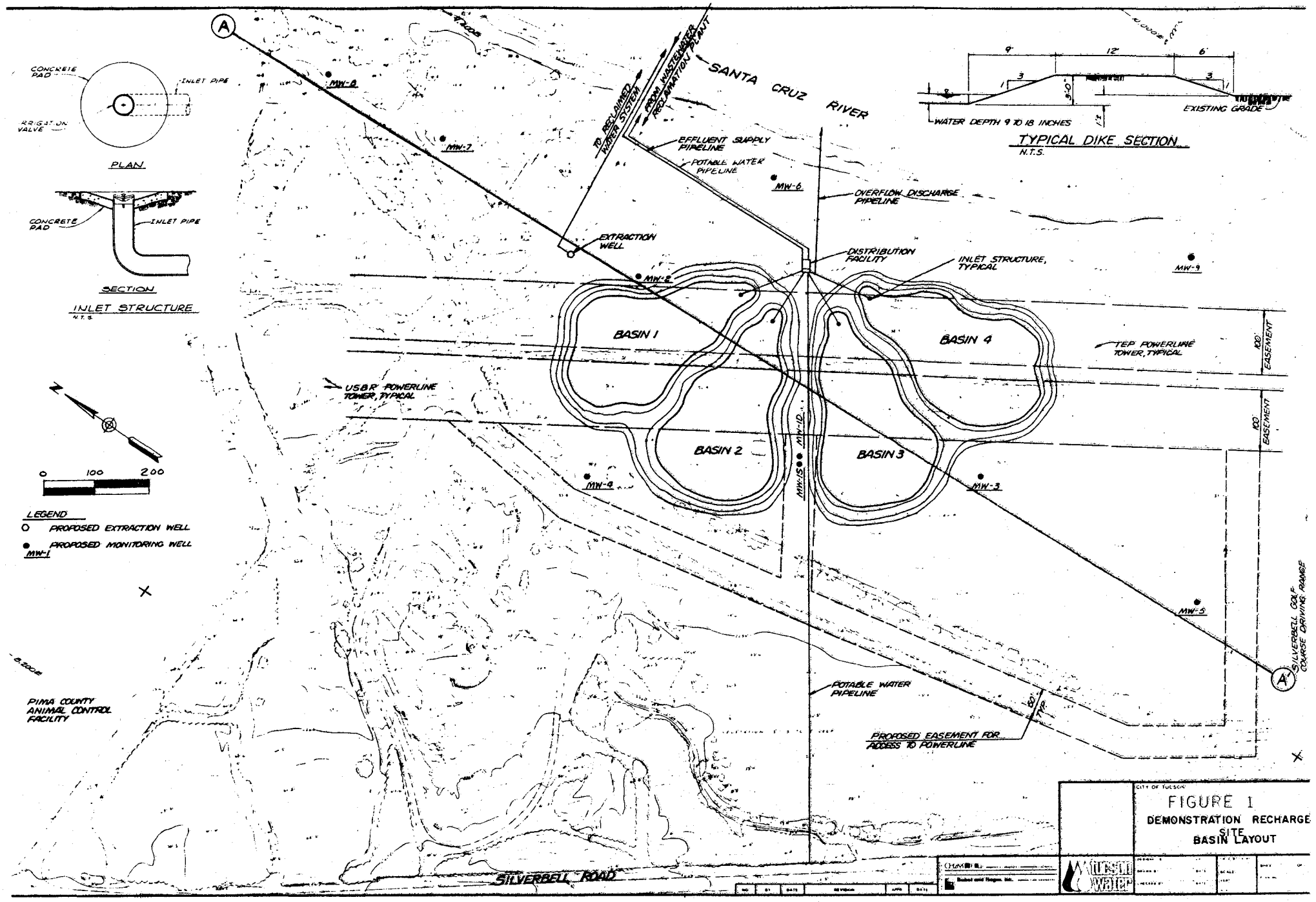
- 300 feet deep
- 26-inch borehole
- 16-inch steel casing (200 feet perforated)
- gravel packed
- 100-foot surface seal
- develop until clear, with step drawdown test
- geophysical logging
- 150 HP vertical turbine pump installed

Subsurface geology throughout the project site has been defined based upon the first phase of well drilling activities. During the Phase 1 drilling the extraction well and monitor wells MW-1S, MW-1D, MW-2, MW-3, MW-6 and MW-7 were constructed. These wells were drilled using the reverse-circulation drilling method during which well cuttings were collected and analyzed on five foot depth intervals. Additionally, geophysical logs were obtained in each of the monitor well bore holes prior to casing installation.

An added element of this particular phase was that four of the bore holes were initially drilled dry to the water table using the casing hammer technique. Cuttings were recovered during this work also and used to define the subsurface geology of the recharge site.

Figure 1 depicts the location of Section A-A' which transects the recharge site in a north-south direction. Figure 2 presents the generalized geologic nature of the subsurface beneath the facility.

In general, the upper soils between the surface and a depth of about 10 feet appear to consist of a fine, silty loam grading to a loose, coarse, granite


CONCRETE PAD
INLET PIPE
IRRIGATION VALVE
PLAN
CONCRETE PAD
INLET PIPE
SECTION
INLET STRUCTURE
N.T.S.
9'
12'
6'
3
1
3
1
3'-0"
1'
WATER DEPTH 9 TO 18 INCHES
EXISTING GRADE
TYPICAL DIKE SECTION
N.T.S.
SANTA CRUZ RIVER
TO RECLAIMED WATER SYSTEM
FROM WASTEWATER RECLAMATION PLANT
EFFLUENT SUPPLY PIPELINE
POTABLE WATER PIPELINE
OVERFLOW DISCHARGE PIPELINE
EXTRACTION WELL
DISTRIBUTION FACILITY
INLET STRUCTURE, TYPICAL
BASIN 1
BASIN 2
BASIN 3
BASIN 4
TEP POWERLINE TOWER, TYPICAL
100' EASEMENT
USBR POWERLINE TOWER, TYPICAL
MW-1
MW-2
MW-3
MW-4
MW-5
MW-6
MW-7
MW-8
MW-9
MW-10
MW-15
A
A'
0
100
200
LEGEND
PROPOSED EXTRACTION WELL
PROPOSED MONITORING WELL
MW-1
PIMA COUNTY ANIMAL CONTROL FACILITY
POTABLE WATER PIPELINE
PROPOSED EASEMENT FOR ACCESS TO POWERLINE
60' TYP.
SILVERBELL GOLF COURSE DRIVING RANGE
SILVERBELL ROAD
CITY OF TUCSON
FIGURE 1
DEMONSTRATION RECHARGE SITE
BASIN LAYOUT
TUCSON WATER

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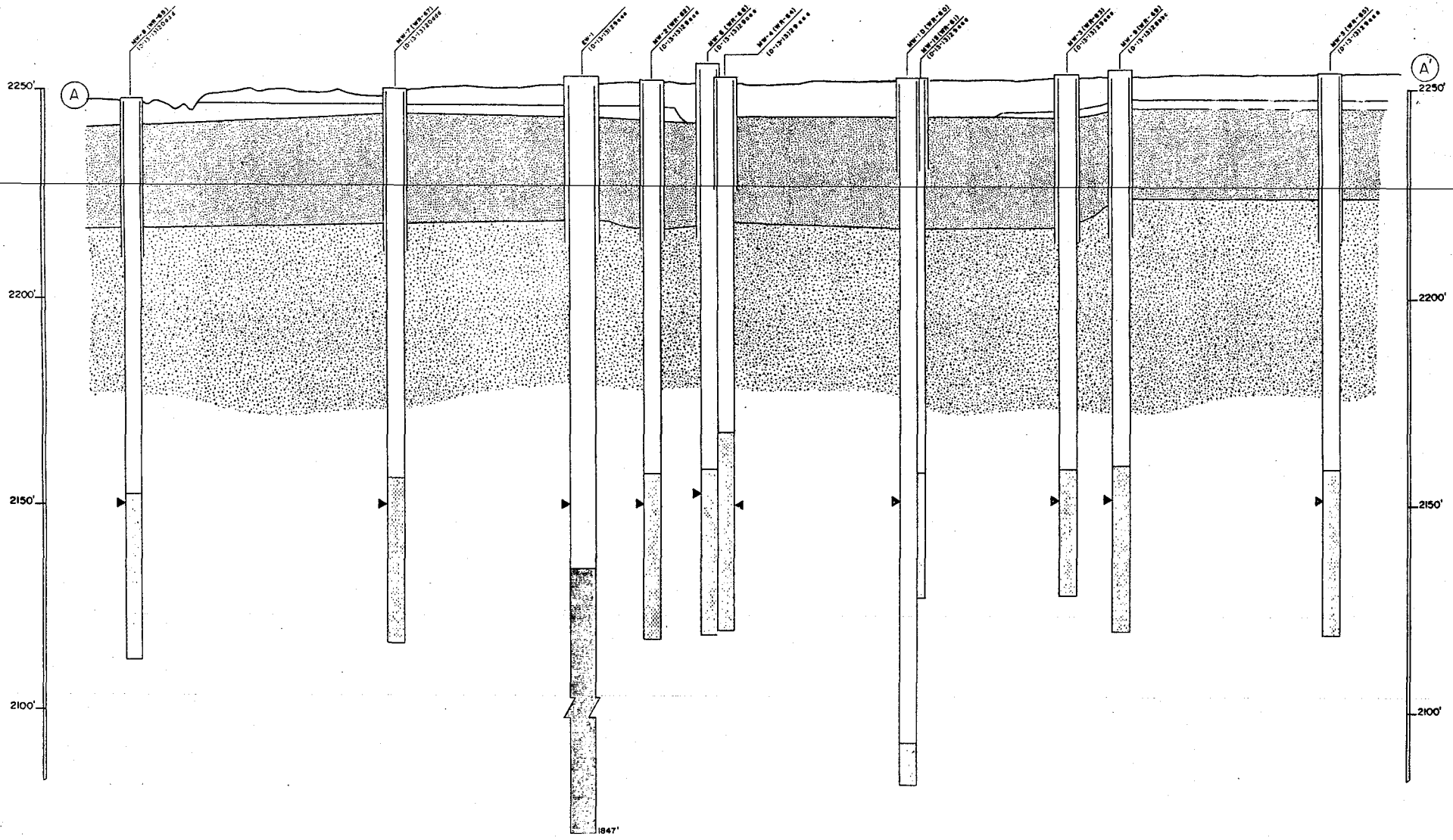
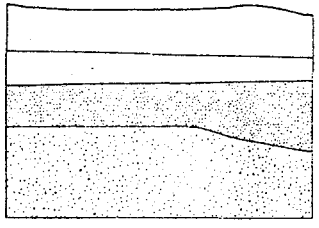


EXPLANATION



Lithologic Descriptions

Channel and Overbank Deposits

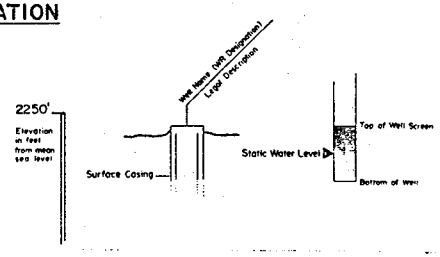
I a Loose, moderately sorted, sandy, silty loam

I b. Loose, dark to reddish brown, generally well sorted, medium quartz sand to moderately sorted, silty sand with minor subrounded gravel

I c. Loose, well to poorly sorted, coarse, rounded gravelly quartz sands and sandy gravels containing cobbles and small boulders; some interbedding of clay seams. Sandy zones often grade into more coarse, cobbley gravel or into poorly sorted zones of cobbley, sandy gravel containing clay

Basin Fill

II Moderately to poorly sorted, subangular volcanic sands and gravelly sands interbedded with 0.5' to 1' thick sandy clay seams



DEMONSTRATION RECHARGE PROJECT
GENERALIZED N-S CROSS SECTION

tucson water

Chief Hydrologist Bruce Johnson

FIGURE 2

Vert. Scale 1" = 10'

Horiz. Scale 1" = 60'

Date February 14, 1985

sand. From 10 to 37 feet we found a loose, coarse, volcanic sand with cobbles and below 37 feet we encountered a tighter more angular volcanic gravelly sand with cobbles and minor clays. Analysis to date indicates a favorable environment for conducting the proposed demonstration project.

An extended aquifer test was conducted using the extraction well as a pumping well and six monitor wells to obtain on-site data for determination of aquifer parameters of transmissivity and the storage coefficient. Test data is still under analysis, however, the values for transmissivity ranged from a low of about 175,000 gallons per day per foot to a high of about 250,000 gallons per day per foot. These values will be used to calculate the expected mounding of the recharged water and to calculate the rate of movement of the recharged water upon its arrival at the regional water table.

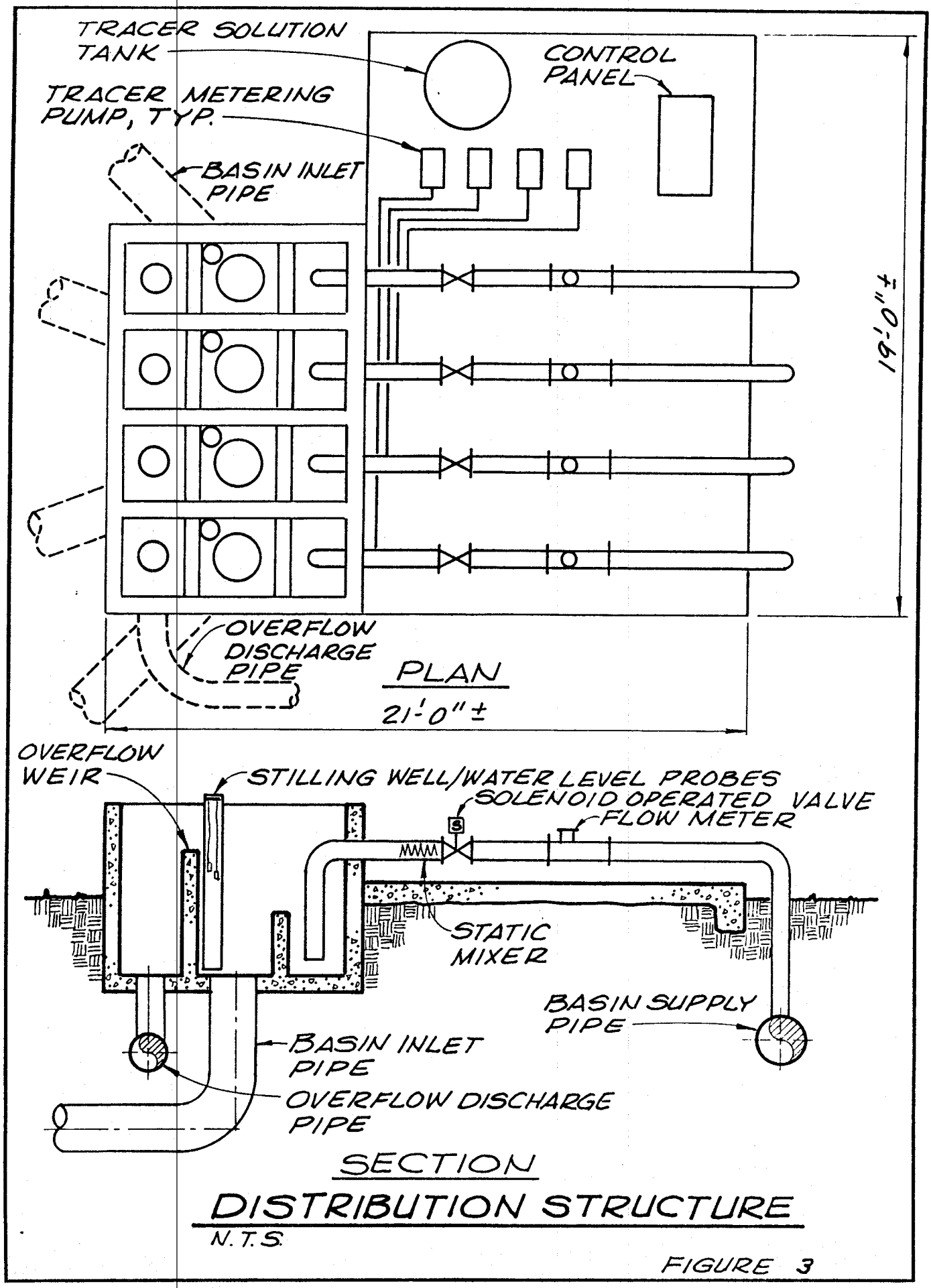
Providing adequate, reliable monitoring of recharged water as it moves through the vadose zone remains the single greatest challenge of this or any proposed recharge program. Due to the significant depth to the water table (105 to 110 feet), many techniques commonly relied upon to provide percolation data in the vadose zone are impractical. Accordingly, it is proposed that a network of neutron access holes be constructed throughout the site and that periodic repetitive measurements be taken with a neutron logger to develop meaningful moisture profiles. From this data it is believed that acutal flow of recharged water can be traced through the vadose zone. Additionally, perching of recharged water can be monitored and evaluated in terms of subsequent recovery during extraction operations.

Project Design

As depicted on Figure 1, the primary features of the demonstration recharge facility are the four 3/4 acre infiltration basins. The basins are constructed using 3 foot high dikes. The basins are designed to be aesthetically pleasing and readily expandable to over twice their present size if warranted. A centrally located distribution facility will regulate the water level in each of the basins. A conceptual design of the distribution structure is shown on Figure 3.

Projected inundation depths are from 6 to 18 inches with optimal depth of inundation being one of the primary operational testing goals of the demonstration phase.

Filtered, disinfected secondary effluent (reclaimed wastewater) will be provided to the recharge facility from the Roger Road Wastewater Reclamation Facility through a pipeline crossing the Santa Cruz River channel. The same channel crossing will contain parallel piping to convey the recovered recharge water to the storage reservoir for the City's reclaimed wastewater distribution system. Water pumped from the recharge site will be mixed with reclaimed wastewater in the reservoir and pumped to golf courses and other users connected to the City's reclaimed wastewater distribution system. It is anticipated that the quality of the water pumped from the recovery well will be equal to or better than the quality of the water from the wastewater reclamation facility.



DISTRIBUTION STRUCTURE

N.T.S.

FIGURE 3

Construction

The construction of the project was divided into two contracts. One contract for the pipelines to the recharge site and another for the basins and distribution facility. The contractor for the basins will be responsible for the start-up and an initial 7-day operational test of the facilities. Construction is expected to be completed in the fall of 1985.

Freshwater Testing

Initially the recharge basins will be operated for three months using potable water only. The purpose of this test is to gain experience in the operation of the basins and to assess the potential for developing perched water tables within the unsaturated zone. An intensive study using the neutron probe will be accomplished. The objective will be to determine the maximum infiltration rate that can be used without creating a perched water table.

An additional objective of freshwater testing is to monitor the disposition of recharged water after it reaches the water table. To accomplish this, frequent (daily) measurements of the depth to water in the monitoring wells will be taken. Additionally, samples will be periodically withdrawn from the monitoring wells and tested for index constituents that will identify recharged water. The objective is to understand how the "hydrogeologic system" functions under recharge conditions before reclaimed wastewater is introduced.

Operation with Reclaimed Wastewater

Following completion of the freshwater testing phase, reclaimed wastewater will be introduced into the basins. The rate and wetting-drying schedule will be selected on the basis of the results of the freshwater testing.

During the course of the reclaimed wastewater recharge phase, the following objectives will be met:

- The quantity of recharge water effluent that must be pumped to prevent it from mixing with the native water in the vicinity of the recharge site will be determined.
- The effect of different wetting-drying cycles on percolation rates, operation of the basins, and the degree of treatment in the unsaturated zone will be evaluated.
- The removal of bacteria, viruses, and trace organics will be measured.

An intensive monitoring program will be performed and data will be periodically reviewed as they become available. Much of the monitoring and data acquisition will be accomplished by a computerized data logging system. A programmable controller at the recharge site will be linked with a personal computer at the City's wastewater reclamation facility control room.

The system will control and log flow to each recharge basin and control and monitor operation of the extraction well. The computer will also be used to

record the water levels in all monitoring wells on site and to generate periodic reports and trend charts as required.

It is anticipated that two to five years of operation will be required before the City can reach a conclusion regarding the feasibility and economic benefits of aquifer storage and recovery using reclaimed wastewater.

SUMMARY

Tucson is implementing a wastewater reuse program in an effort to preserve high quality groundwater for potable and other priority uses. The feasibility of using reclaimed wastewater in an aquifer storage and recovery application is being evaluated through a demonstration recharge project. If feasible, aquifer storage and recovery can reduce the size of conventional wastewater reclamation and storage facilities by 30 to 50 percent, improve the quality of reclaimed wastewater, and greatly contribute toward achieving a balance in aquifer recharge and withdrawals.

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Closing Remarks

L.G. Wilson

Water Resources Research Center

I hope that you will bear with me if I relate a story that I once heard that summarizes my thoughts at the end of this symposium. There once was a little country church with a devoted minister who aspired to literary greatness. On one Sunday he gave what he thought was a particularly good sermon. As he was shaking hands with the members of the congregation at the end of the service, a little old lady commented to him that his sermon was "superfluous, simply superfluous". He said, "why thank you, I'm thinking of publishing it posthumously". She said "thats an excellent idea, and the sooner the better".

The point that I'm trying to make with this little story is that this symposium was excellent and anything but superfluous, and in my case I hope that the transactions will not be published posthumously. As I indicated in my opening remarks, the intent of this symposium was to provide an overview of current technical developments in the field of artificial recharge as well provide a review of legal, economic, and financial issues. The case studies were intended to demonstrate how these different elements are being tied together to solve real world problems. The speakers are to be congratulated in helping us to attain the symposium objective, and I will try to briefly overview the key elements of the program.

Following the keynote address by Reid Teeples and the overview paper by Don Maughan, the first session dealt with the technical details of artificial recharge, including methods and problems and a review of case studies. It was shown that artificial recharge has been carried out successfully in many locations, most notably in California. Special management techniques are required when recharge is coupled with an effluent reuse program. Also there are problems with most facilities in sustaining favorable intake rates that require appropriate management approaches. Nevertheless, the fact that recharge methods have been successful elsewhere gives us confidence that they will be successful here in Arizona.

The second session dealt with institutional, legal and political issues of recharge. As you might expect these are volatile issues, and a lot of activity is occurring at this time. The session moderator noted that Arizona is in the forefront in having legislation promoting ground-water management. Based on this precedent, the charge was issued to overcome existing institutional barriers to recharge and conjunctive management through a positive attitude and a progressive approach. Two of the speakers addressed the present legal framework and proposed legislation for recharge in Arizona. There is a real opportunity at this time to develop meaningful legislation to address recharge, and as Leonard Dueker pointed out we need to maintain an upbeat approach and "get on with it". There was concern expressed that the pending legislation on sewage effluent recharge may lock us into the kind of legislation that will limit recharge of other water sources. We also heard the idea that the use of CAP water for recharge may not be recommended or even permitted in some cases. Again the experience in California may guide us in our approach to governing recharge in the state. Specifically, California has tried both the statutory and judicial responses to the issue of artificial recharge. The experience is that the judicial approach is both lengthy and uncertain in outcome. Consequently, Arizona may be wise to use the legislative approach. The State Legislature will

be addressing the need for recharge legislation during study sessions this summer or fall. I'm sure that comments from attendees at this symposium will be welcomed.

Included in the session on legal-institutional issues was a review of current agency planning for recharge at the federal and state levels. Specifically, the role of the Bureau of Reclamation in overseeing pending federal legislation that would fund recharge projects in the reclamation states was summarized. Similarly, activities of the U.S. Army Corps of Engineers in the recharge arena were reviewed with an overview of the study for a demonstration project in the East Basin of the Salt River. A speaker from the state health department services brought out the interesting point that seepage from waste disposal impoundments could be viewed as artificial recharge with potentially dire consequences for ground-water quality. Finally a speaker from the state land department summarized that agency's interest in recharge vis a vis the land departments allocation of CAP water.

The third session dealt with the economic and financial aspects of recharge. The session began with a comprehensive overview of the elements of an economic analysis for a recharge project. Far more than a simple totalling of costs and benefits is required. Equity issues linked to the distribution of gains and losses and indirect effects of the project must be addressed. A model was presented which linked hydrologic relations with economic factors to determine the optimal size and mode of operation of a project. The plans for a demonstration recharge project in the Tucson Active Management Area were presented with special emphasis on the financing requirements. In essence, financial support from the TAMA's augmentation fees will be used to pursuade another party to operate a demonstration project in a selected location and to operate it in a manner to maximize the useful research data produced. The California approach to dealing with economic, financial, and institutional barriers to bringing a project on line was reviewed, and it was shown that creative solutions to these complex issues can be found. Finally, a review of the privatization concept for financing a recharge project was presented. This approach is currently being strongly considered for the proposed Butler Valley project, described in the afternoon session.

Several speakers expressed the need for demonstration recharge projects to clarify many of the associated uncertainties. However, they cautioned that alternatives to supply side augmentation must also be considered, including water management.

The last session of the symposium included case studies on artificial recharge in Arizona. The first study was the Butler Valley Project. Preliminary aspects of this project are being undertaken as a University of Arizona research project, affording the opportunity to examine not only technical issues for the valley but also legal, institutional and economic issues common to all potential recharge projects in the State. In other words, this case study brings to the forefront issues that are common to any recharge project in the State. Possible recharge schemes for the valley were also reviewed. The second paper dealt with plans for a recharge project operated by the City of Phoenix, using CAP water. Similarly the third paper examined the potential for recharge in Scottsdale. The speaker for this paper brought up a number of interesting issues related to legislation for recharge and recommended that recharged water should be classified as "stored" water rather than ground water. The final paper focused on a project

under construction by the City of Tucson to recharge reclaimed wastewater which has undergone advanced treatment, for ultimate recovery for golfcourse irrigation.

The last formal activity of the symposium was to poll the audience to determine the interval for a third symposium. The majority of the audience felt that two years was an appropriate interval. Finally, acknowledgments were made to those who contributed to organizing and carrying out the symposium, including Floyd Marsh, Herman Bouwer, Gary Small, and secretaries from the U.S. Water Conservation Laboratory, University of Arizona graduate students, and Salt River Project personnel who assisted in transcribing the program.

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