# EMERGING CRITICAL ISSUES IN WATER RESOURCES OF ARIZONA AND THE SOUTHWEST

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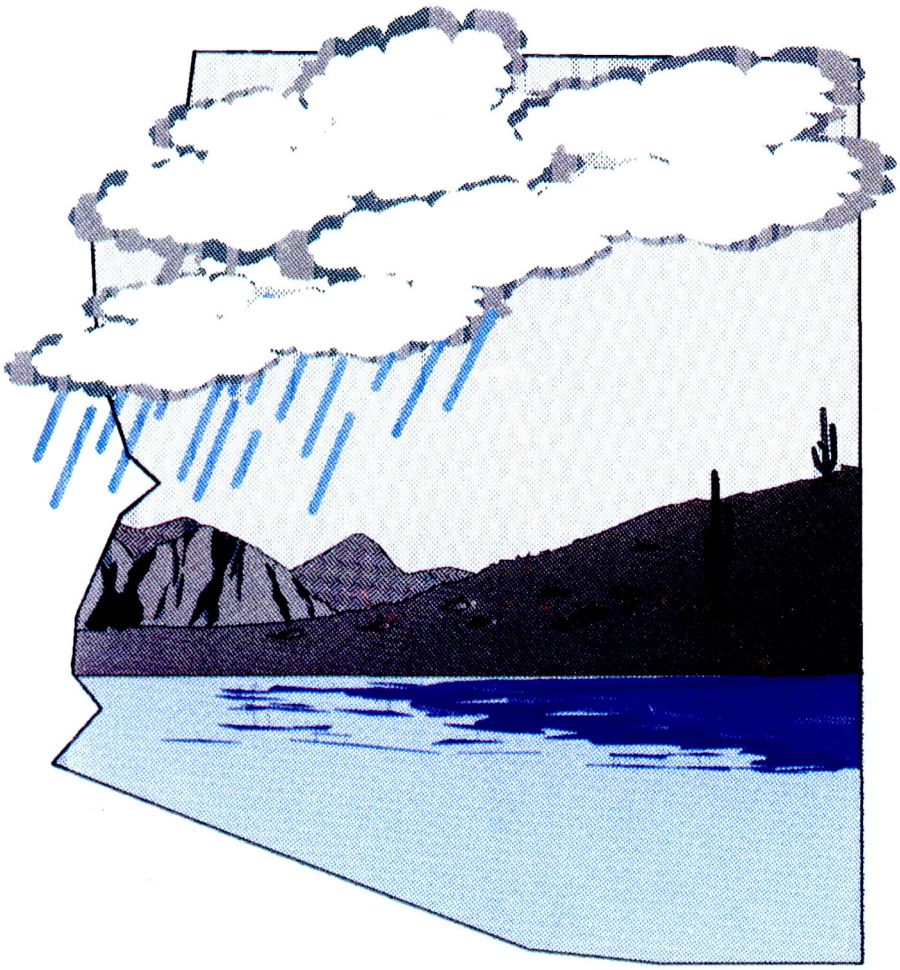

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REMARKS

# EMERGING CRITICAL ISSUES IN WATER RESOURCES OF ARIZONA AND THE SOUTHWEST

PROCEEDINGS OF THE
SIXTH ANNUAL SYMPOSIUM
ARIZONA HYDROLOGICAL SOCIETY

Holiday Inn
Casa Grande, Arizona
SEPTEMBER 23-24, 1993

# EMERGING CRITICAL ISSUES IN WATER RESOURCES OF ARIZONA AND THE SOUTHWEST

## PROCEEDINGS OF THE SIXTH ANNUAL SYMPOSIUM

Edited by

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ARIZONA HYDROLOGICAL SOCIETY
SIXTH ANNUAL SYMPOSIUM

ON

EMERGING CRITICAL ISSUES IN WATER RESOURCES
OF ARIZONA AND THE SOUTHWEST

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# PREFACE

The Arizona Hydrological Society (AHS) is an organization that draws together, as members, individuals and groups who are interested and/or involved in advancing the science of hydrology and the development, management and use of water resources in the State of Arizona and other areas in the Southwest. These members include consultants, administrators, policy makers and lawyers in governmental agencies and the private sector, and academicians engaged in the teaching and research of all aspects of water resources. The AHS annual symposium is an important event for its members and other water resources interest groups. It serves as an important forum for discussion on the status of hydrology, its applications and other related issues in Arizona and the Southwest.

The theme of this year's (1993) annual symposium was "Emerging Critical Issues in Water Resources of Arizona and the Southwest." It was selected to address the many critical water resources related issues facing Arizona and the U.S. Southwest. The issues include the most obvious water quality and quantity problems, and the not so obvious but equally important legal, policy, economic and administrative aspects of water resources problems in the area.

Recently, many parts of the arid and semi-arid Southwest have been experiencing critical water shortage problems with occasional dosage of excess water in some places at times. Shortage of water occurs when the needed amount of quality water is not available at the right time and place of need. This can be due to either a physical shortage of available water in a particular place and time, or contamination of the available water in an area or both. In some places, available water is getting degraded to the extent of becoming unsafe for human consumption. Even the Central Arizona Project (CAP) water needs some treatment before it is used for human consumption. The seriousness of such water quality problems in the southwest can be summarized by Mr. William Wiley's luncheon address, "Water, water everywhere, but nothing to drink".

Arizona and the entire Southwest also occasionally experience excess amount of water at least on temporarily basis. This occurs following unusually heavy precipitation event or a series of events like the ones which occurred in Arizona during the winter or in the midwest in the summer of this year. In those case, reservoirs were filled, farms flooded, bridges and roads destroyed, and many citizens temporarily rendered homeless. The completion of the CAP has also resulted in the availability of excess water in Arizona, at least in the short term. These are problems that need to be taken seriously in the State of Arizona and the Southwest.

All this means hydrologists, water resource managers and other water resources-interest groups need to sharpen their technical skills to protect the existing clean water, and improve the quality of any degraded water resource in the area. This may require developing and adopting new ways of technically, legally and administratively handling our water resources. The need for and importance of such an approach was eloquently put forth by Ms. Rita Pearson in her luncheon address on "learning about the changing face of our water policy."

Most of the critical water resource issues facing Arizona and the southwest were captured to a certain extent by the different topics discussed in the various sessions of the Symposium. Altogether, there were 52 presenters addressing diverse issues such as quantity, quality, legal, policy and management aspects of water resources, other specific regional topics like the CAP, and Indian water rights, and some technical aspects of handling water resources problems such as water resources modeling, flood hazard analysis and remediating water quality problems. Twenty of the papers presented were submitted for publication.

The submitted papers are sorted and then grouped into six categories on the basis of the type of hydrological or water resource-related issues addressed in each paper. The six categories constitute the first six parts of the Proceedings while the last part consists of abstracts submitted without complete papers and a list of the speakers who submitted neither abstracts nor papers.

Parts I and II of the Proceedings discuss on the problems, opportunities and possible constraints with aquifer restoration and water quality sampling activities, respectively. Topics on wastewater reclamation through subsurface recharge as an emerging water management technology are presented in Part III, while surface water analysis techniques and utilization of hydrological models to solve water resources problems are presented in Parts IV and V, respectively. The sixth part consists of papers that address critical legal and regulatory issues in water resources.

In general, all the papers in the Proceedings address mostly practical, real world water resource problems which attempt to provide practical and relevant solutions. The other main contribution of the symposium lies in its service as a neutral forum for inter-disciplinary discussions on critical regional water resource issues, problems and solutions. As such I hope that all water resource related agencies and other concerned individuals and groups in the area will realize this service of the AHS and take full advantage of it in the future.

Aregai Tecle, Editor
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In addition to the members of the Symposium Planning Committee, the chairman of the AHS Annual Symposium thanks the following individuals and organizations for their important support and active participation in the symposium:

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# KEYNOTE ADDRESS:

## EMERGING CRITICAL ISSUES IN WATER RESOURCES OF ARIZONA AND THE SOUTHWEST

by

PROFESSOR LAWRENCE D. GARRETT
DEAN, SCHOOL OF FORESTRY
NORTHERN ARIZONA UNIVERSITY

# EMERGING CRITICAL ISSUES IN WATER RESOURCES OF ARIZONA AND THE SOUTHWEST[1]

Lawrence D. Garrett[2]

ABSTRACT: Several critical water resource issues face scientists, policy makers and managers in the Southwest. The past four decades have produced significant enhancements in reservoirs, transfer systems and pumping technology. Although improvements will continue in these areas, they will be less pronounced. Environmental issues will be extensive, including riparian management, ground water degradation and wastewater reclamation. Financing the CAP project and appropriate groundwater use levels will be significant economic issues. Legal issues will be prominent, including Indian water rights and rights to waters originating in wilderness areas and public lands in general.

One of the most complex issues will relate to the management of public lands and how it impacts water quality and quantity both on and off public lands. Ecosystem management will be the primary guideline on these lands for several decades. In this regard, science, policy making and management guidelines are needed now to address issues of forest overstory density and forest ecosystem health and diversity.

## INTRODUCTION

I appreciate the opportunity to visit with you today regarding "Emerging Critical Issues in Water Resources of Arizona and the Southwest." I am impressed with your list of speakers in the various concurrent sessions. It is good to see broad coverage of important issues such as Colorado River water utilization, Indian water rights, groundwater and surface water opportunities, water reclamation and water quality. I am pleased that difficult issues like riparian management and protection and groundwater contamination are being addressed in the program. Also, I note that your society has chosen to involve representatives from Arizona's Comparative Environmental Risk Project! I feel that project, with its comprehensive approach, will cause all of us to think more globally in environmental assessments, especially as regards what segments could be at risk and potentially causing others to be at risk.

I am strongly involved in the comparative risk project or ACERP, as we call it. I am also involved in G-SPED, directed at economic development and trade, the Governor's oversight committee on public forest land management, and a Southwest University Consortium Forest Study. I mention all of these because I think each effort in its own way is trying to do something very important. I will pick

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[1]Keynote address, Arizona Hydrological Society Sixth Annual Symposium, Casa Grande, Arizona, September 23-24, 1993.

[2]Lawrence D. Garrett is Dean of the School of Forestry, Northern Arizona University, Flagstaff, Arizona.

a phrase you have heard a lot to explain it. "Think Globally, Act Locally." Most of our issues today transcend our local communities, states and regions. In many cases even our countries. Water resources are no exception. Yet, a great part of our solution must be attained at the local level.

As you well know, much of Arizona's water supply, consumption, degradation, and recreation problems are not simply a result of people living in Arizona. It is my full belief, and I think probably yours as well, that more and more of Arizona's future water issues and problems will be driven out of a more regional and national environment.

I would like to take a few minutes this morning to expand on your topic of "Emerging Critical Issues in Water Resources of Arizona" and hopefully give each of you some food for thought, as you enter your two days of meetings.

I will preface my comments with a statement on the tenor of my talk. It will at times seem almost Malthusian in tone. That relates simply to the need to put reality into the picture. Today's problems in water resources are both difficult and complex. To argue differently would be misleading. On the other hand, I believe our society has the capacity for solving the most complex and difficult problems, even water resource issues in the Southwest.

## CRITICAL WATER RESOURCE ISSUES

There are several key critical water resource issues that I feel have emerged and are emerging. I would like to mention several of them. Then I would like to relate by an example how difficult and time consuming our solutions have become. Finally, I will mention one study NAU is involved in that takes a more comprehensive approach to solution.

Before I start, lets revisit where we are in Arizona regarding water resources.

Arizona's water situation, in some ways, is not unlike our neighboring state of California. Measured on a decadal basis, demand, especially urban demand, will be an ever-increasing function with shifts occurring from one sector to another. Significant changes in real physical supply, for all practical purposes, is somewhat fixed. I say this knowing of opportunities in conservation and in weather and vegetation management.

In the distant past, we did not have the level of water resource access that we have today. The primary factors that have increased our access to water resources has been the development of large reservoirs, transfer systems, and efficient pumping systems. In many ways, these man-made infrastructures have allowed us to transfer water from its source locations to locations we have chosen to live in and develop, namely, the central and southern desert regions of Arizona.

It is probably reasonable to assume that development of extensive reservoirs like Lake Powell, transfer systems like CAP, and more efficient pumping systems have been fairly maximized at least for the next two decades. For the period 1995-2015, we will likely not radically increase real water supplies to the state.

In the last half century, agricultural and urban development in Arizona had to resort to groundwater pumping to accommodate increased demand for water. As a consequence, extensive

overdrafts have occurred for many years. The very progressive groundwater legislation of 1980 established regulation and conservation practices as well as management direction for rectifying the groundwater overdraft problem in the state. However, this particular problem continues to plague the state's water conservation practices.

Through the decade of the 1980's, total water consumption in the state from deep well pumping contributed almost half of our total consumption. The overdraft has been significant. Some water tables have dropped hundreds of feet with associated land subsidence.

Surface water supplies to the state in the 1980's contributed approximately the other half of the state's total consumption. A significant source of surface water supplies emanate from the Colorado River system. The remaining surface water supplies are from Arizona river systems, primarily the Salt and Verde Rivers, and managed by the Salt River Project.

Colorado River water availability was greatly enhanced by movement of Colorado River water through the Central Arizona Project to the Phoenix metro area in 1985 and recently to the Tucson metro area in. Access to the Colorado River through the CAP, with the tremendous storage catchments in Lake Mead and Lake Powell, create both stable supplies and potential stable pricing. I say potential because there are CAP payment issues yet to be resolved. Likewise, development of extensive catchments on the Salt and the Verde River Systems by the Salt River Project have created fairly stable supplies and stable prices.

Although Arizona's fairly fixed future water supplies could seemingly be problematic, transfers from agricultural uses to urban and industrial uses will likely continue to occur due to pricing mechanisms, conservation practices, and declining agricultural uses. The current large uses in the agricultural sector may therefore tend to mitigate somewhat, problems of increased urban use.

And as everyone in this room knows, potential declining agricultural use of water will likely be taken up by increasing uses for urbanization. Although we might hope that predictions of doubling Arizona's population early in the 21st century is a fantasy, there are real expectations it is likely to occur.

This doubling of Arizona's population and associated growth will occur not only in the urban areas of Phoenix and Tucson, but in areas like Kingman, Bullhead City, Flagstaff, Williams, Yuma and Pinetop as well as increasing distributed populations in many rural areas.

It is that increasing diverse population and its needs, demands and interests, that will both drive future water issues and problems, and bring increased complexity and difficulty to any resolutions sought. What are some of those issues likely to be?

**Environmental Issues**

Many of the issues that will be brought on by increasing and more diverse populations will be environmental issues. In Arizona I think two primary issues will likely impact water resources significantly in the next three decades.

One issue is riparian zone restoration. It will move from the current state focus of loss and degradation of riparian ecosystems over the last 50 years to a more focused emphasis on specific areas of protection. This has begun with current proposed legislation for protected zones on many rivers and streams in the state. As population increases in both rural and urban areas there will be focused localized attention on protection of individual riparian ecosystems that will in turn translocate themselves upstream and downstream to other riparian zones.

Groundwater degradation will become a major issue in urban communities, and growing rural communities. These issues and problems will impact wastewater disposal, reclamation projects, waste management systems and land management practices.

**Economic Issues**

We will obviously have, in the next three decades, economic issues surrounding effective financing of the CAP Project and appropriate pricing for maintaining agricultural industry. I think these will be particularly difficult times because price increases will be greater than have been experienced in the last three decades.

However, I think some of our greatest economic arguments may be in the public sector relating to continued use of groundwater. Potential inability to meet the mandates of the groundwater law could expose Arizona to penalty pricing mechanisms similar to those witnessed in private industry regarding air quality.

Wrapped into economic issues will be the continued economic/legal aspects of land purchase for water rights. This will continue to be a critical western water problem.

**Legal Issues**

I think two legal issues regarding water resources have only begun to be debated. One is obviously Indian rights and will definitely take the forefront in the next few years. That issue will move quickly into a second quasi political/legal arena relating to water rights associated with public lands, initially wilderness areas. This issue will be staged from public, state and private rights perspectives and from environmental perspectives. I think the issue will eventually move politically to all public lands, and be extended into areas of effective public land management for not only protecting the environment, but fostering continued quality water to states and municipalities.

Western congressional leaders have begun to debate this issue on specific case approaches. A most recent case is in wilderness designations just north of us in Colorado.

**Public Land Management**

There is another critical emerging issue affecting water resources in the intermountain west and southwest, and that is forest watershed management. I have left it to last for two reasons. First, it by itself affects most other water resource issues over the long term, and secondly, I wish to use it as an example of the complexity and difficulty we face in the area of water resource management.

All of us in the inner basin west and southwest realize that our long term solutions in water supplies relate to how we manage and protect higher elevation forested watersheds. This relates to the fact that that is where most of our surface water and water to recharge overdraft comes from. The Salt, Verde and Colorado River systems emanate from high altitude coniferous forests in Arizona and Colorado.

A critical issue facing resource managers and water resources is the present and future condition of these watersheds. Their condition affects evapotranspiration and soil moisture, seeps and springs, instream flows, erosion, riparian ecologies, reservoir siltation, decadal release levels and eventually water pricing.

The complex interrelated issue of forest watershed management involves policy, environment, economics and integrated resource management concerns. The science needs are extensive.

Many natural resource professionals believe we may already have significant forest ecosystem problems that could affect selected drainages and watersheds in the west. I would appreciate your indulgence while I use the coniferous forest ecosystems of Arizona to highlight this issue.

## EVOLVING FOREST ECOSYSTEM MANAGEMENT

All of the issues I have spoken to today will involve years and even decades to resolve. The issue of forest watershed management or what we call today forest ecosystem management, can easily involve 25 years and even reach toward 50 years for solution. This relates simply to the time interval required to convince the general public through science that change is needed, planning for that change and then implementing that change through policy and laws. Remember that the watershed for the Colorado River approaches a quarter million square miles and change would have to occur over much of the watershed to see a water resource quality change at the upper end of Lake Powell. The same argument holds for the Salt and Verde systems.

In reality we have discovered that significant changes in the upper watersheds of the Salt and Verde River systems have been occurring over the last 100 years. After intensive timber harvests and grazing in the 1850-1910 period, we began to control wildfire in these ecosystems, fire that normally passed through stands at 3-15 year intervals. The original pre-European settlement forest existed as open clumps of 25-50 trees per acre. These open park-like older forests with extensive grasses, forbs and shrubs and associated insects, birds and mammals have been replaced with younger forests of closed crowns and fairly sparse understories, in some areas no understory at all.

This change has significantly affected the biophysical resource base. Further, the fact that it would happen and its consequences is not new science. Writers such as Leopold could project the natural progression in the 1920's and in fact predicted it, as did authors in the 1940's and 1950's. More recently, many forest ecologists of the inner mountain west such as Drs. Covington and Moore at NAU, have characterized the dramatic forest ecosystem changes that have occurred.

Are these changes in and of themselves bad? Perhaps not, it really depends upon our objectives.

The comprehensive 275,000 acre Beaver Creek Research Project of treated and measured watersheds were evaluated from 1958-1984. It was concluded from that project that the ponderosa pine forest ecosystem created greater biophysical diversity, stability, and diversities of outputs at 50-70 sq. ft. basal area than at densities of 120-150 sq. ft. basal areas. Much of our forest densities today exceed 100 sq. ft. basal area.

Many forest ecologists and entomologists in the west feel that these significantly altered forest ecosystems are continuing to lose diversity, are both unnatural and unhealthy, and probably cannot be sustained. And, some natural resource managers feel that even with reduced management constraints, entire watersheds could not be restored in less than 30-50 years.

Questions are complex and extensive. With the high levels of evapotranspiration in the southwest and tenfold increases in overstories, what has happened to soil and subsoil moisture; and how has soil moisture influenced springs, seeps, instream flows and riparian ecologies. What are the probabilities and risks of catastrophic events if we continue current trends of increased densities? Could insect and disease, combined with wildfire eliminate most of the overstory in an entire watershed, such as Wet Beaver Creek? What would the short and long term environmental and social impacts of that event be on the upper Verde River system?

## SEEKING SOLUTIONS

I have addressed some water resource issues that I think will demand our attention over the next several decades. All are critical. I have ended with a short example of protection and management issues relating to Arizona's forest watersheds. I ended there because for most of us in the west, that's where our water starts.

If we are to sustain our human societies through time, part of our effort must be toward sustaining these watersheds in good condition. To that end, Northern Arizona School of Forestry and five other southwest schools are conducting cooperatively with the U.S. Forest Service a Southwest Forest Study to evaluate alternative public forest land management directions. Involved are Utah State University, Arizona State University, University of Arizona, Western New Mexico University and New Mexico State University, the Southwest Regional Office and Rocky Mountain Forest Experiment Station of the U.S. Forest Service.

Our approaches, although not global, are regional. Our focused solutions will be local, at a forest district level.

The entire study is designed to look over space and through time at the intricate biophysical relationships in the southwest ponderosa pine forest ecosystem. How does changing overstory density affect soil moisture, instream flows and riparian ecologies?

We also are studying how changing management of forest ecosystems affects social and economic systems, with a focus on rural western communities. The management of large ownerships of western forest lands by public agencies directly impacts rural community social and economic structures.

Physical areas of study will include the Dixie National Forest in Utah, the Kaibab and Coconino National Forests in Arizona and Santa Fe National Forest in New Mexico.

We are also using these research findings to develop system design models for managers and policy makers. The intent is to define, through computer algorithms, the relationships found.

## THE IMPORTANCE OF PROFESSIONAL SOCIETIES

In closing my comments today, I would like to thank you for the invitation to your annual society meeting. I, like many of you, am involved in several professional societies. They play a critical role in focusing professional and public attention on critical issues, as you are doing here today.

I encourage you to continue your important work. Anyone who comes to the Southwest quickly realizes water will always be a key resource to Arizona's future.

# Part I

# AQUIFER RESTORATION: SOME CRITICAL PROBLEMS AND EMERGING OPPORTUNITIES

# MAXIMIZING REMEDIATION EFFICIENCY AT THE HUGHES/AIR FORCE PLANT NO. 44 GROUNDWATER REMEDIATION PROJECT, TUCSON, ARIZONA[1]

Timothy J. Allen[2]

## ABSTRACT

The groundwater remediation project at Hughes/Air Force Plant No. 44 (AFP 44) has been in operation for over 6 years. Significant progress has been made in decreasing the concentrations of TCE, DCE and chromium in the south half of the Tucson Airport Area Superfund site plume. The project is a pump and treat system with reinjection, covering an area of about 2 square miles. The well field is currently pumping 3,200 gallons per minute from an average depth of 120 feet. There are currently 24 extraction wells, 19 recharge wells and 74 regional aquifer monitor wells in the well field.

An active management strategy has been used to control the remediation, varying the extraction and recharge rates as needed throughout the plume. Water levels and water quality are monitored at least quarterly throughout the well field. The data is used to continuously adjust the extraction and recharge flows to maintain maximum contaminant mass removal and to assure that plume containment is being achieved. Well field modifications are made, as necessary, to adapt the pumping and recharge patterns to changing conditions in the aquifer.

## INTRODUCTION

The AFP 44 remediation project was designed to contain and remediate the south half of the Tucson International Airport Area superfund site contaminant plume (see figure 1). By agreement with the Environmental Protection Agency (EPA), AFP 44 is responsible for remediating the portion of the plume south of Los Reales Rd. The north half of the plume will be remediated under the Tucson Airport Remediation Project (TARP), managed by Tucson Water. Groundwater remediation carries a high priority in the Tucson area because, until the

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[1]Paper presented at the Sixth Annual Symposium of the Arizona Hydrological Society, Casa Grande, Arizona, September 23-24, 1993.

[2]Timothy J. Allen is Hydrogeologist for the Hughes Missile Systems Company, Tucson, Arizona.

recent introduction of Central Arizona Project water, groundwater was the sole source of drinking water for the city.

The AFP 44 groundwater remediation project involves extracting, treating and reinjecting water from what was originally 2 square miles of contaminant plume in the regional aquifer. The plume contains chlorinated solvents, predominantly trichloroethylene (TCE), with lesser amounts of 1,1-dichloroethylene (DCE) present. A smaller plume of chromium, contained within the boundaries of the plant site, has been almost completely removed.

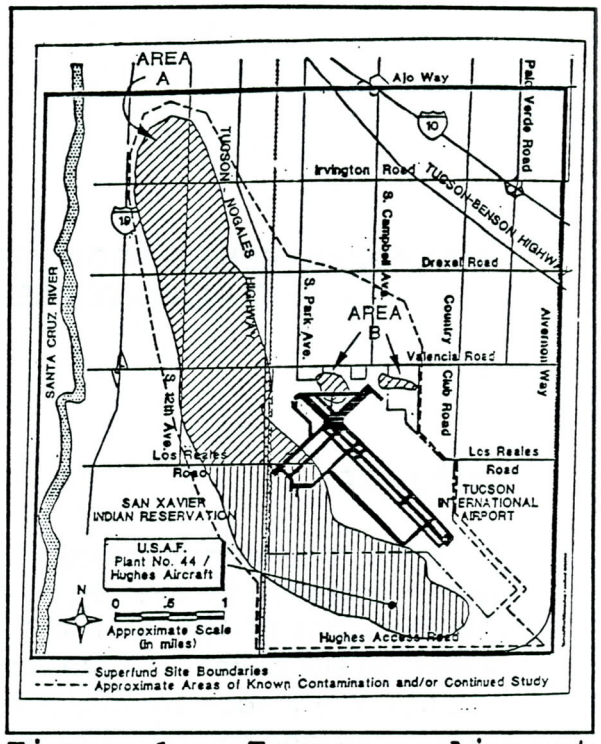



**Figure 1** Tucson Airport Superfund Site Plume

In the first six years of operation the project has pumped, treated and reinjected back into the aquifer over 9.2 billion gallons of groundwater. A 190 acre plume of groundwater contaminated with chromium in excess of drinking water limits has been reduced to less than 1% of its original area. The TCE plume within the zone of capture of the remediation wellfield has been reduced to about 60% of its original area. Concentrations within the plume have been lowered significantly. The mass of TCE and DCE removed from the treated water is approximately 75% of the amount of solvent estimated to be present as dissolved phase in the remediation area.

The relative success of the project is due to several factors. There are clear goals and objectives. The primary goal of the remediation project is to restore the contaminated groundwater to drinking water quality in the shortest possible time-frame. The main objectives are to contain the plume and to continuously maintain contaminant removal at the maximum possible rate. AFP 44 has an extensive database of hydrogeological and stratigraphic information on the project area, which provides a clear picture of the subsurface conditions. Regular monitoring is done and water table elevations and contaminant concentrations are mapped. The remediation is actively managed. This means that the pumping and recharge patterns and rates are continuously adapted to the current conditions and requirements. Pumping or recharge is avoided in areas that don't produce a beneficial effect. Finally, remediation efforts are being focused on the source areas that represent potential ongoing sources of contamination to the aquifer. Enhanced extraction and remediation of contaminants in source areas is pivotal to achieving our goal in the shortest possible time at the lowest cost.

## SITE DESCRIPTION AND HISTORY

AFP 44 is located on a 1380 acre site immediately south of the Tucson International Airport. AFP 44 is owned by the U. S. Air Force and operated by Hughes Missile Systems Company. The plant was constructed in 1951 for production of the Falcon air to air missile. AFP 44 has been in continuous operation since that time, producing a variety of missiles and weapons systems for all of the armed forces.

Contamination of the groundwater beneath AFP 44 was the result of historical on-site treatment and land-disposal of industrial wastes from 1952 to 1977. Solvent bearing wastes and plating waste waters were disposed at a variety of sites on AFP 44 property. Three of the disposal sites were later identified as the major source areas for the on-site groundwater contamination. The three sites were: the former Final Assembly and Check-out (FACO) area dump site, the former solvent disposal pit and the former sludge drying beds (see figure 2). The sludge drying beds were the major source of chromium contamination in groundwater. The FACO dump and the solvent disposal pit were the major source areas for the chlorinated solvent contamination.

Waste disposal operations conducted at various industrial sites on the Tucson Airport property also contributed to groundwater contamination within the boundaries of the AFP 44 remediation project (Rampe, 1985).

Groundwater contamination was identified in the vicinity of the Tucson International Airport Area in 1981 by an investigation conducted by the EPA and the Arizona Department of Health Services (ADHS). The primary contaminants identified were chromium and chlorinated solvents. This resulted in the closure of several Tucson Water drinking water supply wells found to contain TCE in excess of the drinking water maximum contaminant level (MCL), which is 5 parts per billion (ppb). One of the wells, SC-7, was located across the road from the northwest corner of the AFP 44 property. During subsequent investigations numerous monitor wells were drilled in the area and a plume of TCE contamination was identified. AFP 44 was included as part of the Tucson Airport Area site which was placed on the National Priority List (Superfund) in 1983.

The Air Force reached an agreement with the EPA and the ADHS in 1984 to be responsible for remediation of groundwater in the area south of Los Reales Rd. The remediation would be conducted as part of the Air Force's Installation Restoration Program. This program is authorized to conduct remediation projects on Air Force installations. A pilot scale pump and treat groundwater remediation system was constructed and activated in 1985. The pilot system included extraction and reinjection wells, air stripping to remove volatile organic compounds (VOC's) and an anion exchange process for chromium removal. The pilot system was operated from March 1985 to May 1986.

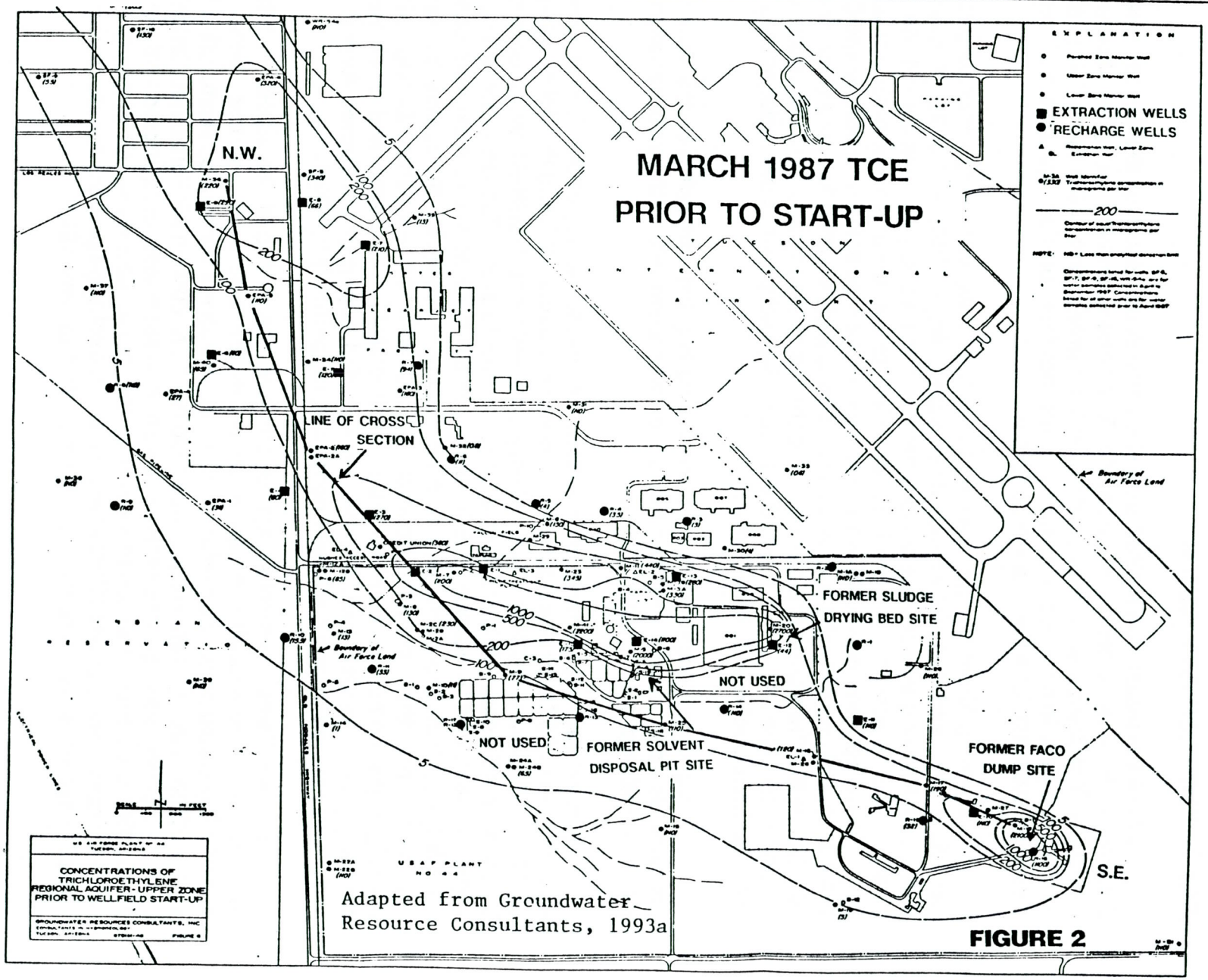

MARCH 1987 TCE
PRIOR TO START-UP
EXPLANATION
EXTRACTION WELLS
RECHARGE WELLS
N.W.
S.E.
LINE OF CROSS SECTION
FORMER SLUDGE DRYING BED SITE
NOT USED
NOT USED
FORMER SOLVENT DISPOSAL PIT SITE
FORMER FACO DUMP SITE
Boundary of Air Force Land
CONCENTRATIONS OF TRICHLOROETHYLENE REGIONAL AQUIFER-UPPER ZONE PRIOR TO WELLFIELD START-UP
Adapted from Groundwater Resource Consultants, 1993a

FIGURE 2

Construction of the full scale groundwater treatment plant and well field was completed in early 1987. Start-up of a portion of the full-scale groundwater remediation began in April, 1987. The full-time operation of the entire system began in January, 1988. The groundwater plant and well field have been in almost continuous operation since that time. The remediation was on-line for 6 years and 3 months as of June, 1993.

## SITE HYDROGEOLOGY

Groundwater occurs at depths of 90 to 140 feet below ground surface beneath the remediation area, within alluvial sediments of the Tucson Basin. The unsaturated zone above the regional aquifer is made up of discontinuous lenses of sand and gravel, interbedded with layers of sandy clay, clayey sand and clay. The material is unconsolidated, except where cemented with caliche. A continuous strata of sandy clay and clay is found under the northwest part of the AFP 44 property, between 60 and 105 feet below ground surface. Perched groundwater is present above and within this unit at several sites. Figure 3 shows a geologic cross-section of the remediation area.

The regional aquifer locally consists of an upper and a lower zone, separated by a thick, laterally extensive, clay aquitard. The upper zone, along with much of the overlying unsaturated zone, is correlative with Ft. Lowell Formation sediments (Leake and Hanson, 1987). The clay aquitard separating the upper and lower zones is correlated with a lacustrine facies of the Upper Tinaja beds. The lower zone appears to be correlative with either Lower Tinaja or Pantano Formation.

The upper zone of the regional aquifer is the primary focus of the groundwater remediation project. It is the most productive zone of the regional aquifer in the area and represents the bulk of the TCE contamination. An elongated contaminant plume formed as the result of continuing contributions of TCE from source areas below former disposal sites and relatively high flow rates of groundwater in the upper zone. Regional groundwater flow in the upper zone is in a northwest to northerly direction across the remediation area, causing the plume to grow in that direction.

The upper zone extends from the regional water table surface downward to the contact with the clay aquitard at depths of 180 to 225 feet below ground surface. The average thickness throughout the remediation area is 70 feet. The upper zone consists of unconsolidated, highly permeable sand and gravel layers interbedded with layers of clayey, impermeable sediments. The stratigraphy is similar to that of the unsaturated zone. Water within the individual sand and gravel beds occurs under unconfined to semi-confined conditions. In some parts of the area the individual sand and gravel beds appear to be hydraulically isolated from beds above and below at the same location.

Transmissivity values for the upper zone of the regional aquifer, estimated from pump test data, range from 400 to 200,000 gallons per day per foot (gpd/ft), making the upper zone about one to two orders of magnitude more permeable than the lower zone. The wide range of transmissivity values is closely related to varying net thickness of sand and gravel beds within the upper zone sediments. Upper zone transmissivity values tend to be greatest in the northwest, where the coarse-grained, permeable beds are predominant. The upper zone in the southeast part of the remediation area consists almost entirely of fine grained material, and has correspondingly low transmissivity values.

The aquitard is a thick sequence of clayey sediments extending from the base of the upper zone, to a depth of about 300 to 350 feet below ground surface, isolating the upper zone from the lower zone. The aquitard is made up primarily of clay and sandy clay, with infrequent thin interbedded lenses of sand and gravel.

Isolated areas of contamination exist in the lower zone of the regional aquifer at the vicinity of the historical wells that were screened in the upper and lower zones. Groundwater remediation is performed at those areas.

The lower zone of the regional aquifer begins at about 300 to 350 feet below ground surface at the base of the confining clay. The lower zone sediments consist of clayey sand

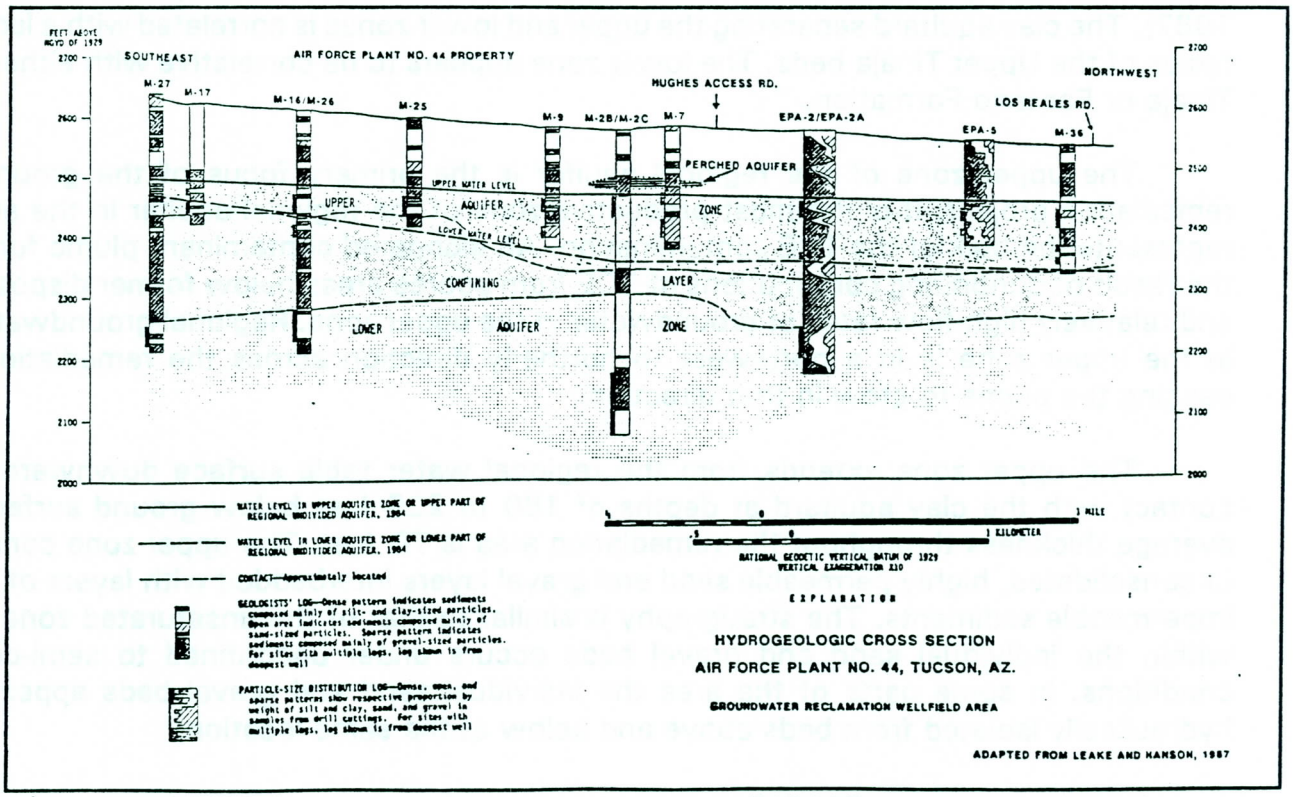



**Figure 3** AIR FORCE PLANT NO. 44 HYDROGEOLOGIC CROSS SECTION

and sandy clay, with occasional thin lenses of gravelly sand. The lower zone is known to extend down to a depth of 620 feet in the remediation area, but the entire thickness of the unit has not been penetrated. Hydraulic heads had historically been deeper in the lower zone than in the upper. Water levels in monitor wells completed in the lower zone are typically from 7 to 115 feet deeper than upper zone monitor wells at the same locations. Measured transmissivity values in the lower zone range from 200 to 3000 gpd/ft. As stated above, the lower zone transmissivities are about one to two orders of magnitude lower than the upper zone. The lower zone is much less permeable because it contains more clay, is more poorly sorted and is more heavily cemented than the upper zone sediments.

## CHEMICAL CHARACTER OF THE GROUNDWATER

The chemistry of the groundwater in the upper and lower zones are well defined within the remediation area. All monitor wells are sampled for common ions and trace metals annually. In the upper zone, listed in order of abundance, calcium and sodium are the dominant cations and bicarbonate and sulfate represent the dominant anions. In the lower zone groundwater, also listed in order of abundance, sodium and calcium are dominant cations and bicarbonate and sulfate are dominant anions. Upper zone water tends to be somewhat higher in TDS, chloride and nitrate and lower in fluoride and pH than lower zone water. Table 1 shows the range of typical common ion values for the upper and lower zone wells. Trace metals are generally not present in detectable concentrations except for chromium, which occurs as a contaminant. The organic contaminants are discussed in the next section of this paper.

TABLE 1. COMMON IONS IN GROUNDWATER

| COMMON IONS | UPPER ZONE WELLS | LOWER ZONE WELLS |
|---|---|---|
| ANIONS: | | |
| Alkalinity | 100-180 mg/l | 25-160 mg/l |
| Sulfate | 40-225 mg/l | 40-195 mg/l |
| Chloride | 5-60 mg/l | 6-25 mg/l |
| Nitrate | .5-2 mg/l | .1-2 mg/l |
| Fluoride | .3-.6 mg/l | .3-2.5 mg/l |
| CATIONS: | | |
| Calcium | 30-110 mg/l | 8-60 mg/l |
| Sodium | 25-60 mg/l | 40-75 mg/l |
| Magnesium | 7-25 mg/l | .2-8 mg/l |
| Potassium | 1-3 mg/l | 1-2.9 mg/l |
| TDS | 230-500 mg/l | 220-280 mg/l |

## CONTAMINANT DISTRIBUTION

The development of the contaminant plume in the upper zone was controlled by the location of the contaminant source areas (former disposal sites) and the groundwater flow direction. TCE entered upper zone groundwater at all three of the former disposal sites discussed earlier; the former FACO dump site, the former solvent disposal pit and the former sludge drying beds. The TCE plume originating at the FACO site migrated northwesterly in the direction of groundwater flow and merged with the TCE plume emanating from the other two sites. The plume continued to migrate north and west and merge with the TCE plume originating on the west side of the airport property. Average migration rate is estimated to be 500 feet per year.

DCE is detected in association with TCE over most of the remediation area. In most areas it occurs in concentrations equaling less than 20 % of the TCE concentrations. It is not present in any significant quantities beneath or immediately downgradient of the FACO site (figure 2). There are no records of DCE use or disposal on-site. We believe that the DCE is a breakdown product of TCA rather than TCE since DCE is only present down-gradient of the sites where TCA was disposed.

Two groups of "nested", selectively screened upper zone monitor wells were installed at the at the FACO dump site and solvent disposal pit locations to study the vertical distribution of VOC's in the aquifer. At both locations the highest concentrations of VOC's were present in the shallowest wells. TCE was detected in these wells in the parts per million range. VOC concentrations decreased by about one order of magnitude in each deeper sand. The data indicates that non-aqueous phase liquid TCE concentrations are probably present at or near the top of the water table in the upper-most sand, acting as continuing sources of contamination.

The bulk of the chromium contamination in the groundwater originated from disposal of plating waste at the former sludge drying beds, in the vicinity of monitor well M-20. The chromium plume developed in a northwesterly direction from this location, in response to regional groundwater flow. Other metals such as copper, nickel, cadmium, lead and zinc were probably present in the same waste stream as the chromium but these are not present in the groundwater beneath the site. We believe that concentrations of other metals were attenuated in the vadose zone by cation exchange in clays and by precipitation as insoluble hydroxides due to high soil pH's. Chromium, travelling in the anionic chromate form, was not as susceptible to these processes, and was mobile enough to reach the water table.

Contamination in the lower zone occurs in isolated pockets and is restricted to the areas around previously existing wells which allowed contaminated water to migrate downward. Contaminated water migrated from the upper zone, downward through the well casings and out into the lower zone. Since groundwater movement in the lower zone is relatively slow, the contaminants migrated very slowly and remained fairly close to the areas

where they entered the lower zone.

## TREATMENT PLANT

The Groundwater Treatment Plant was designed to treat up to 5,000 gallons per minute (GPM) of groundwater contaminated with chromium and VOC's. Contaminant removal is accomplished as follows, according to the numbered treatment steps shown on the plant flow diagram on figure 4. The chromium bearing water is pumped through pre-filters (#1) to remove particulates. The water then enters ion exchange vessels (#2) where the actual chromium removal takes place through an anionic exchange process.

After chromium removal, the water is air-stripped to remove VOC's (TCE and 1,1-DCE). The air-stripping takes place in three parallel banks of stripping towers. Each bank consists of a primary (#3) and a secondary tower (#4), connected in series. The water leaving the ion exchange system enters one bank of towers. Water not requiring chromium removal enters the other two banks of stripping towers directly from the well field.

The primary air-towers remove approximately 85% to 90% of the VOC's from the water. The air emitted from the primary towers is ducted to activated carbon beds where the VOC's are removed from the air stream. The secondary air stripping towers are used as a polishing step in the treatment. Water leaving the secondary towers typically contains no detectable TCE or DCE. Air from the secondary towers contains very low levels of VOC's and is vented directly to the atmosphere.

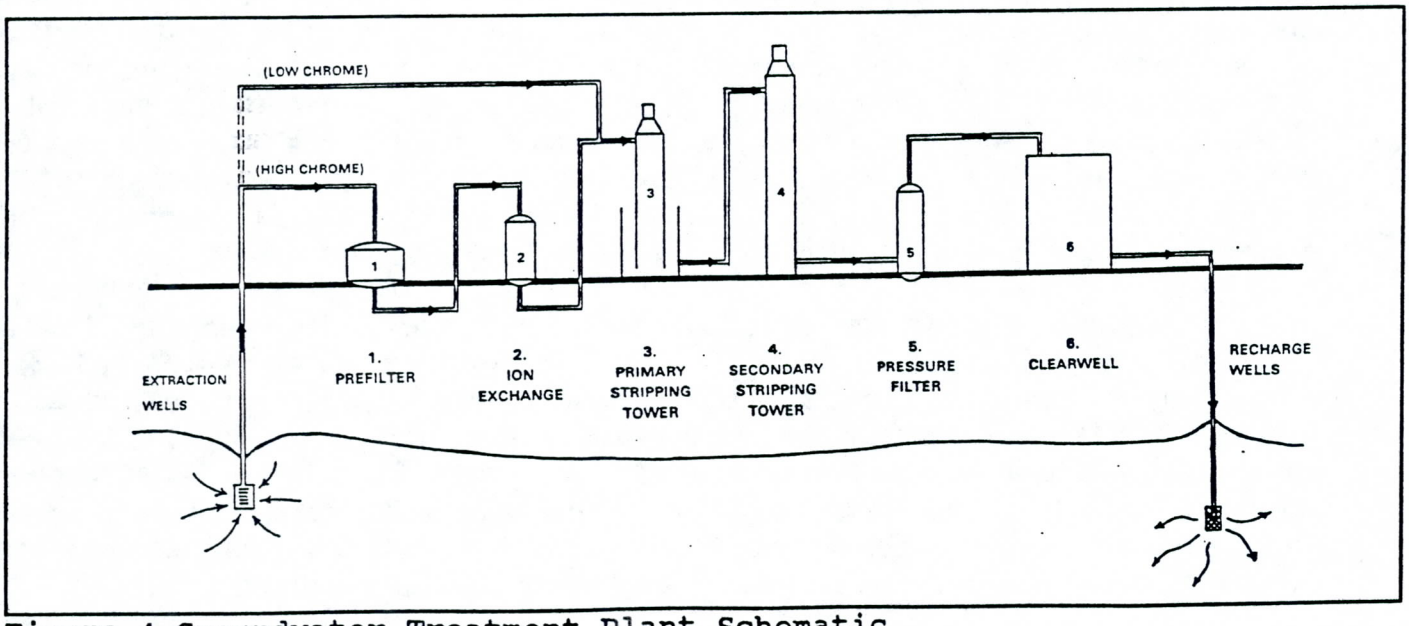



**Figure 4** Groundwater Treatment Plant Schematic

Treated water leaving the stripping towers is neutralized using sulfuric acid, to offse the increase in pH that occurs during the air-stripping process. The water is then filtered through sand pressure filters (#5) and is then placed in a 655,000 gallon clearwell (#6). The treated water is pumped from the clearwell to the recharge wells where it is returned to the aquifer.

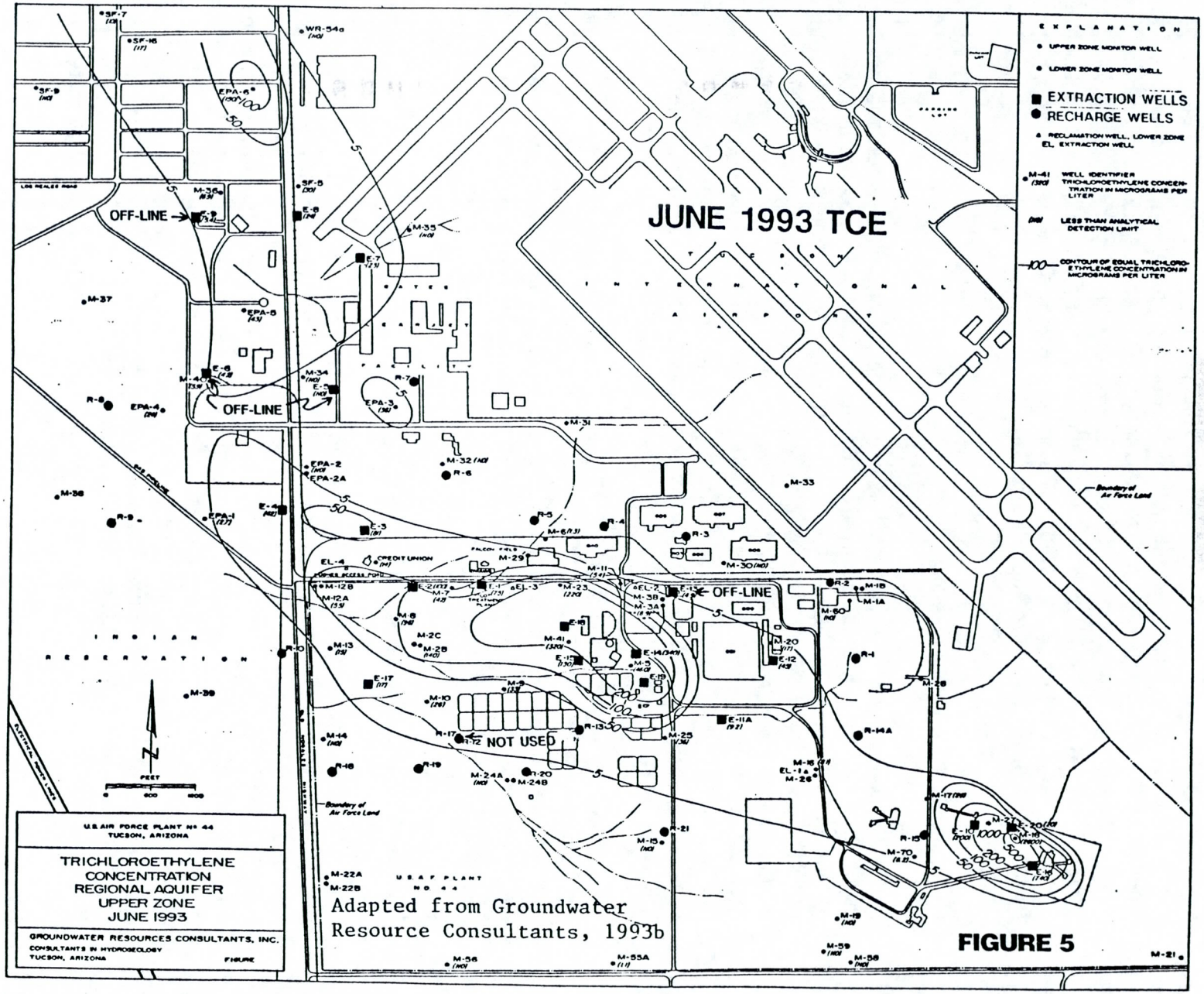
Virtually all phases of the groundwater treatment plant and well field operations are managed by a computer control system. The computer can vary flow rates in the plant and well field and can perform an orderly shutdown of the plant and well field if malfunctions occur in any critical part of the system. Computer control allows continuous operation of the remediation system without the need for 24 hour a day staffing.

## THE REMEDIATION WELL FIELD

The remediation well field (figure 2) was completed in 1987 and originally consisted of 15 upper zone and 4 lower zone extraction wells, and 17 upper zone recharge wells. The well field has been modified by the addition of new wells and by conversion of existing wells from recharge to extraction and from extraction to recharge. It currently consists of 20 upper zone and 4 lower zone extraction wells, and 19 upper zone recharge wells (figure 5). The well field was designed to implement a very aggressive remediation strategy, emphasizing both containment and rapid reduction of contaminant levels.

The extraction wells are distributed throughout the interior of the plume so that contaminated water can be removed along the plume centerline. Pumping the wells creates a lowering of the water table in the interior of the plume, forcing clean water along the plume margins to flow to the center, to replace the water that is pumped. Recharge wells are located along the plume margins to return the treated water to the aquifer. The recharge creates pressure ridges of injected water along the plume margins. By lowering water levels in the center of the plume and raising them along the margins, the net effect is the creation of a steep flow gradient toward the center of the plume from both sides, which provides containment of the contaminant plume, accelerates the inward flow of contaminated groundwater and facilitates its removal. The well field has been modified somewhat from the original design but retains the basic pumping and recharge strategy.

All extraction and recharge wells drilled for the project are constructed with 8" or 12" steel casing, .060" to .125" slot steel screen (Johnson Hi-Cap) and are gravel packed. Most of the well sites contain 2" diameter observation wells, used for water level measurements, located about 10 feet from the main well. Pump sizes on extraction wells vary from 5 to 60 HP and all but 6 have variable frequency drives. The variable frequency drives allow pump discharge rates to be controlled remotely by the same computer which controls the treatment plant. Extraction wells are also equipped with flow meters and pressure transducer type water level sensors. Flow and water level information is monitored remotely by the


JUNE 1993 TCE
EXPLANATION
UPPER ZONE MONITOR WELL
LOWER ZONE MONITOR WELL
EXTRACTION WELLS
RECHARGE WELLS
RECLAMATION WELL, LOWER ZONE
EL EXTRACTION WELL
WELL IDENTIFIER
TRICHLOROETHYLENE CONCENTRATION IN MICROGRAMS PER LITER
LESS THAN ANALYTICAL DETECTION LIMIT
CONTOUR OF EQUAL TRICHLOROETHYLENE CONCENTRATION IN MICROGRAMS PER LITER
OFF-LINE
OFF-LINE
OFF-LINE
NOT USED
INTERNATIONAL AIRPORT
INDIAN RESERVATION
Boundary of Air Force Land
U.S. AIR FORCE PLANT No 44
TUCSON, ARIZONA
TRICHLOROETHYLENE
CONCENTRATION
REGIONAL AQUIFER
UPPER ZONE
JUNE 1993
GROUNDWATER RESOURCES CONSULTANTS, INC.
CONSULTANTS IN HYDROGEOLOGY
TUCSON, ARIZONA
FIGURE
Adapted from Groundwater
Resource Consultants, 1993b
FIGURE 5

computer.

Recharge wells have 4" diameter injection pipe extending below the water table and operate under pipeline pressure. Gravity feed, used in the original design, was discontinued after it was found that pressurized recharge produced superior performance. Injection rates were increased up to 50% and well redevelopment, which had previously been done annually, was virtually eliminated. Well head pressures are monitored and are kept well below the calculated hydrofracture gradient.

## GROUNDWATER MONITORING

A network of 74 monitor wells is used to define and map water level and water quality conditions within the remediation area. Of these, 64 are completed in the upper zone and 10 are completed in the lower zone. All extraction and monitor wells are monitored on a regular basis for TCE, DCE and chromium. Also collected are measurements of pH, conductivity, temperature and water level. Extraction wells are sampled monthly and 62 monitor wells are sampled quarterly. The remaining 12 monitor wells are located off the plume margins, and have always contained less than detectable amounts of TCE and 1,1 DCE. These wells are sampled annually. Samples are collected from all monitor wells and are analyzed for common ions and trace metals annually.

Data collected during the monitoring is used to generate quarterly project maps. Concentrations of TCE, DCE and chromium are mapped and contoured for the upper zone Water table elevation maps are contoured for the upper and lower zones. Having these maps available on a regular basis has been a key factor in our ability to actively manage the groundwater remediation.

## REMEDIATION STRATEGY

The basic strategy for operating and managing the groundwater remediation at AFP 44 is centered on the goals of containing the plume and continuously maximizing the contaminant removal rate. To do this, an active management strategy is used in operating the well field. Monthly and quarterly water quality and water level monitoring provides the basic information necessary. The contaminant concentration and water table elevation maps produced from the monitoring data present the information in an easily understood format. The newest maps are compared to maps from previous quarters to get a picture of how plume and flow conditions have changed through time in response to earlier adjustments made in the well field. As new data is collected it is used to continuously reassess the effectiveness of the remediation and to adjust the pumping and recharge patterns to maintain plume containment and high contaminant removal rates.

If the data indicates that our present pumping and recharge strategy is no longer fully effective, the simplest method of changing conditions in the wellfield is to modify pumping and recharge rates in specific wells. By varying the rates, and by turning wells on and off, we can control flow of groundwater and the movement of contaminants within the plume. Changing pumping and recharge rates includes shutting down wells, when appropriate to the pumping strategy.

Adjusting pumping and recharge rates are not always enough to achieve containment and contaminant removal goals. In the past we have modified extraction and recharge patterns through converting recharge wells into extraction wells and vice versa, to achieve pumping or recharge in areas where it was needed. Thus far, three recharge wells have been converted into extraction wells R-14 to E-11a, R-16 to E-16 and R-11 to E-17. These wells are listed by their old numbers on figure 2 and the new numbers on figure 5. All were located in areas where use for recharge was inappropriate but were suitable as extraction points. One extraction well, E-11, which was drilled beyond the southeast edge of the plume, was converted to recharge well R-14a. The three former recharge wells currently account for 500 GPM of pumpage. Our future plans include converting E-6 and E-9 to recharge wells to enhance easterly migration of contaminants in the northwest part of the plume. These wells are now in an area which is remediated to below the MCL levels for TCE concentration and are off-line as part of our pumping strategy.

New recharge and extraction wells are drilled as needed to enhance remediation efficiency. Four new recharge wells (R-18 through R-21) were added in 1993. These wells were added to prevent south-ward migration of the plume boundary in the central plant area (figure 5). Previously existing monitor wells R-12, R-13 and R-17 could not be used because they were located too far within the plume. Injection in these wells would have pushed TCE contaminated water south-ward, out of the reach of the extraction wells.

Additional extraction wells E-18, E-19 and E-20 were added to replace inflow to the treatment plant that was lost when clean extraction wells were shut down. Each of the new wells was placed in locations where high concentrations of TCE were present and where additional pumpage would help maintain high contaminant removal rates (figure 5). As the contaminant plume continues to shrink in the future, our plan is to maintain high pumping rates from progressively smaller contaminant zones until the remediation is complete. This approach should lead to a more rapid decrease in plume area.

A key element of our future strategy is remediation of the soils and aquifer below several of the former disposal sites. These sites represent potential continuing sources of contamination to the regional aquifer. Based on well field experiments conducted in those areas we have observed the phenomenon called "rebound" in several extraction wells. Rebound is a rapid increase in contaminant concentration which occurs after an extraction well is shut down for some period and then pumped. Rebound is often cited as "proof" by critics of pump and treat technology that pump and treat "doesn't work".

Tests were conducted in 1992 with four of the extraction wells located in or adjacen to the source areas for the VOC's in the groundwater. These wells are E-14 and E-15 in the central plant area and E-10 and E-16 in the FACO area. The test involved sampling VOC levels while the wells were in continuous operation, then shutting the wells down for a period of 40 hours, then restarting the wells. VOC samples were again collected at two hour intervals after start-up. Observed concentrations of TCE and DCE were two to five times higher after the wells were restarted. After about 12 hours of continuous operation, the concentrations returned to the levels observed before the test. We believe rebound occurs as a result of the presence of higher concentrations of sorbed solvent in the aquifer below the water table, or in the dewatered portion of the aquifer adjacent to the wells. When the wells pump, the solvent below the water table desorbs at a constant rate. Solvent left above the water table remains sorbed. When the wells are shut down, the water level rises, putting the water in contact with more solvent. Since the water is not moving, the solvent desorb into a limited amount of water causing much higher concentrations.

Rebound has not been observed in extraction wells that are not adjacent to forme disposal sites. We shut down extraction wells E-5 and E-6 in November 1990 and May 1991 respectively, when TCE concentrations had stabilized at or below drinking water MCL's. This was done as part of our pumping strategy, to enhance migration of contaminants to extraction wells located to the north and south. Since this time, TCE levels have remained low and no rebound was observed. Wells E-9 and E-13 were shut down in August 1992 for strategy reasons and TCE levels have continued to decline at those sites also. This should dispel the notion the critics of pump and treat have propagated that rebound always occurs when wells are shut down. We now know that rebound is only likely to occur in relatively small localized, portions of the remediation area.

To eliminate potential continuing sources of VOC contamination to groundwater, it is necessary to separately remediate the disposal sites. This is essential to timely completion of the groundwater remediation. Since pump and treat methods are not effective for removal of free-phase VOC's from the aquifer or the adjacent soils, other remediation techniques must be used. Vapor extraction appears to be the most promising technique for eliminating large amounts of concentrated solvents. Pilot studies were conducted on site by an independent contractor to the Air Force, using a technique called "dual extraction". This method involves vapor extraction through the casings of pumping extraction wells, which allows vapor extraction of solvents from the dewatered portion of the aquifer around the well bore and from the soils above the aquifer. Although the final report is not yet available, we estimate (based on activated carbon consumption) that several hundred pounds of TCE and DCE were removed from the former solvent disposal pit site during approximately one month of pilot operation. We currently have a portable vapor extraction unit on order which we plan to put into full time operation this year.

## PROGRESS OF THE REMEDIATION

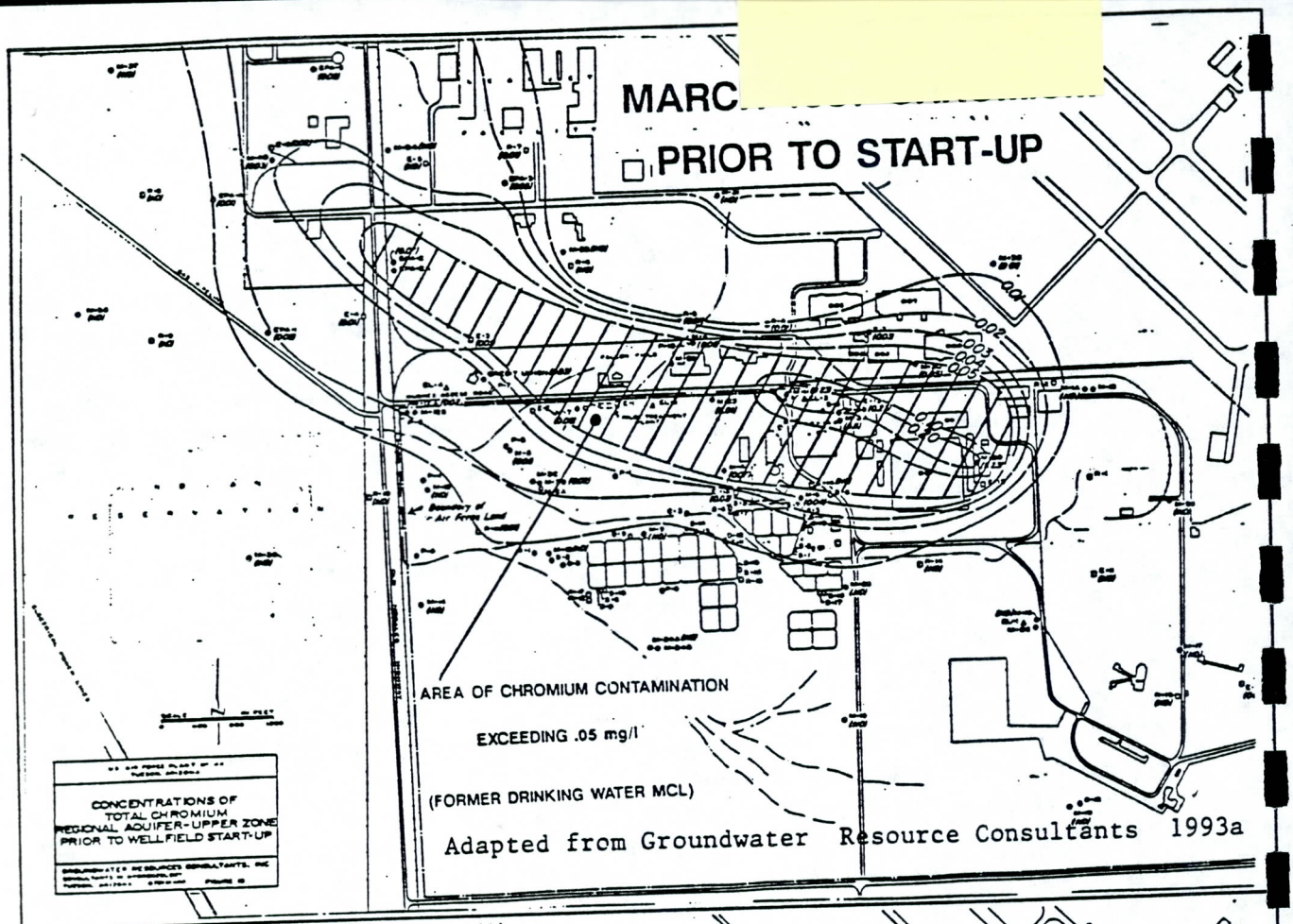
As of June, 1993, the groundwater remediation project at AFP 44 has been on-line for 6 years and 3 months. During this time 9,253,000,000 gallons of groundwater has been pumped from the aquifer and remediated. As of June 1993, we have removed 11,961 lbs. of TCE, 1,488 lbs of DCE and 312 lbs of chromium from the groundwater. The quantities were calculated based on influent concentrations and flow rates into the groundwater treatment plant. The progress made in the remediation of the plume becomes apparent when comparing maps of contaminant concentrations from early 1987, when the project started, and June, 1993.

The biggest success was the remediation of the chromium plume. At the time the remediation began, the drinking water MCL for chromium was .05 mg/l and this number was used as the cleanup standard. In 1987 the area of the chromium plume where concentrations were greater than .05 mg/l was 190 acres (figure 6). By September, 1990, the mappable chromium plume had all but disappeared. As of June, 1993 the only area where the chromium concentration was consistently elevated, was near extraction well E-12, which is located about 100 feet downgradient of the former sludge drying bed site, which is the source of the chromium. The high solubility and mobility of the chromate ion are probable contributing factors in the rapid disappearance of the chromium plume after a relatively short period of pumping.

Significant progress has also been made in reducing both the area of contamination and the concentration levels of VOC's in the aquifer. Since the concentrations of DCE are far lower than those of TCE in any given well and since the drinking water MCL's are similar (5 ppb for TCE and 7 ppb for DCE), the TCE plume concentrations become the deciding factor in determining when the remediation is complete. A comparison of the TCE concentration maps from the start of the project in early 1987 (figure 2) and the most current map from June, 1993, (figure 3) shows the progress made in decreasing plume area and reducing TCE concentration levels. The areas were measured for the portion of the TCE plume within the zone of capture of the AFP 44 wells. We estimate this zone to extend 1/4 mile north of Los Reales Rd. Table 2 shows how plume areas exceeding various concentrations have changed:

TABLE 2. CHANGES IN TCE PLUME AREA
MARCH 1987 TO JUNE 1993

| CONCENTRATIONS | % CHANGE |
|---|---|
| > 5 ppb | -41% |
| > 100 ppb | -81 % |
| >500 ppb | -97% |
| >1000 ppb | -99.4% |


MARC
PRIOR TO START-UP
AREA OF CHROMIUM CONTAMINATION
EXCEEDING .05 mg/l
(FORMER DRINKING WATER MCL)
Adapted from Groundwater Resource Consultants 1993a
CONCENTRATIONS OF
TOTAL CHROMIUM
REGIONAL AQUIFER-UPPER ZONE
PRIOR TO WELLFIELD START-UP

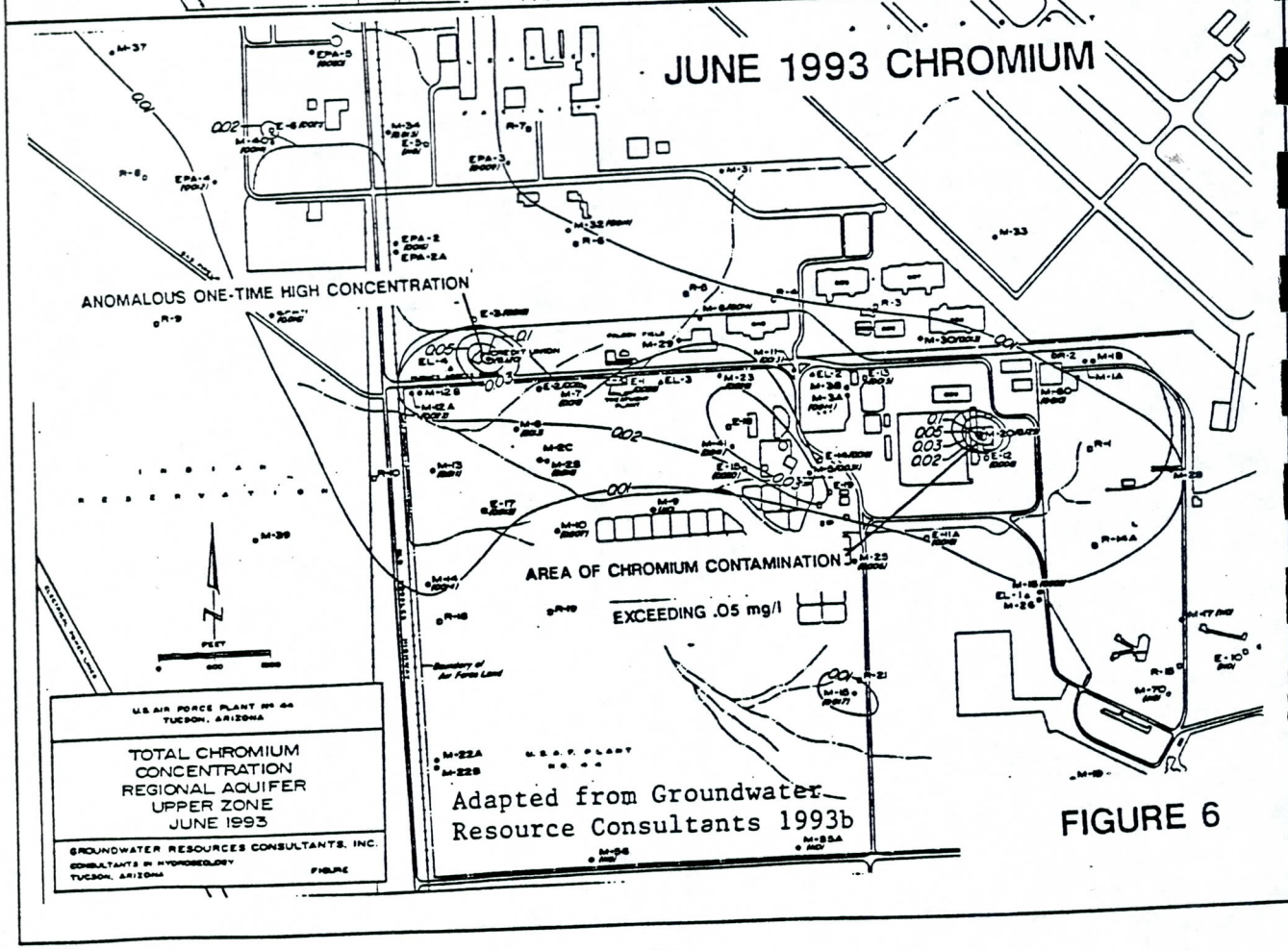
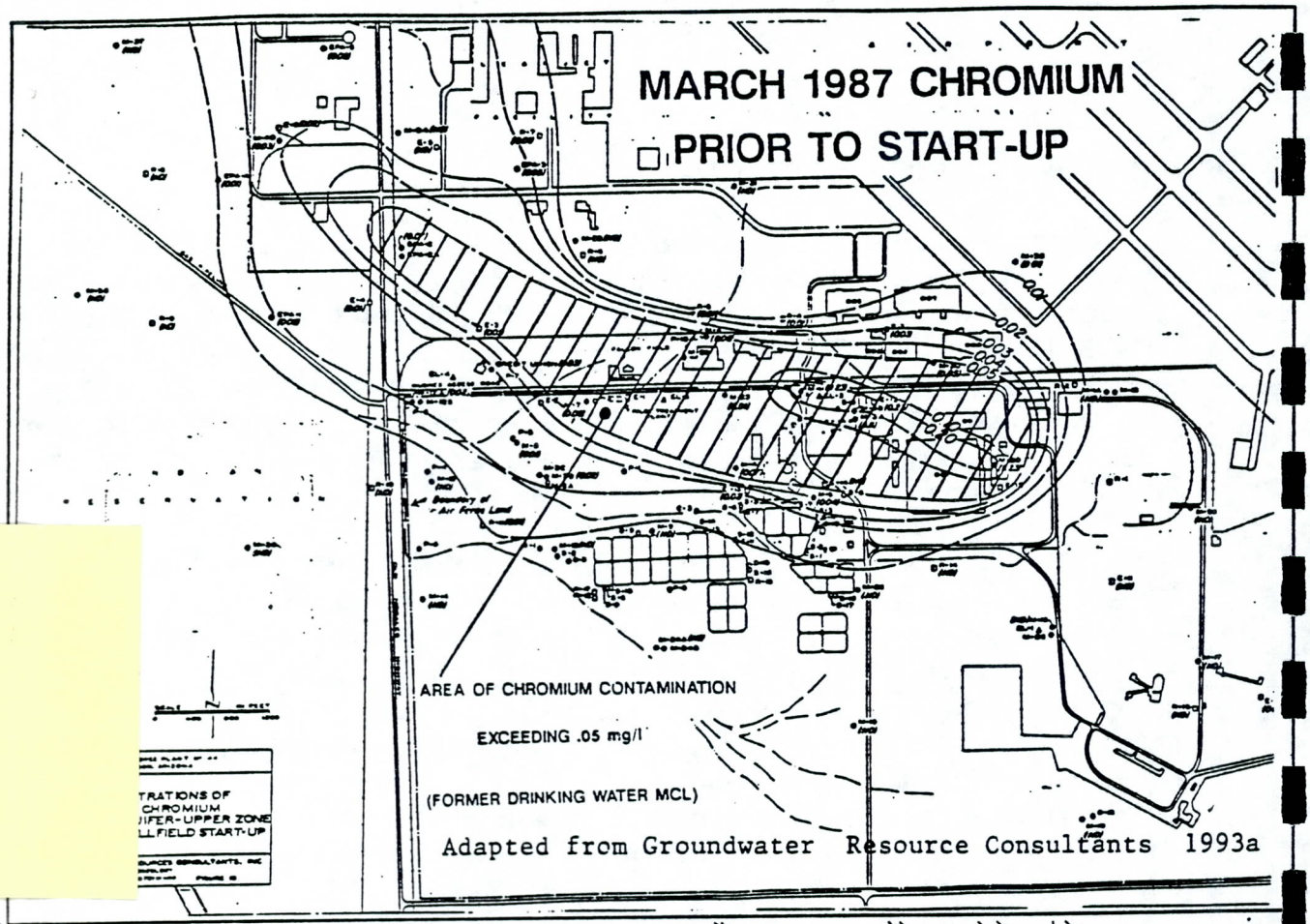

JUNE 1993 CHROMIUM
ANOMALOUS ONE-TIME HIGH CONCENTRATION
AREA OF CHROMIUM CONTAMINATION
EXCEEDING .05 mg/l
Adapted from Groundwater
Resource Consultants 1993b
U.S. AIR FORCE PLANT
TUCSON, ARIZONA
TOTAL CHROMIUM
CONCENTRATION
REGIONAL AQUIFER
UPPER ZONE
JUNE 1993
GROUNDWATER RESOURCES CONSULTANTS, INC.
TUCSON, ARIZONA

FIGURE 6


MARCH 1987 CHROMIUM
PRIOR TO START-UP
AREA OF CHROMIUM CONTAMINATION
EXCEEDING .05 mg/l
(FORMER DRINKING WATER MCL)
Adapted from Groundwater Resource Consultants 1993a

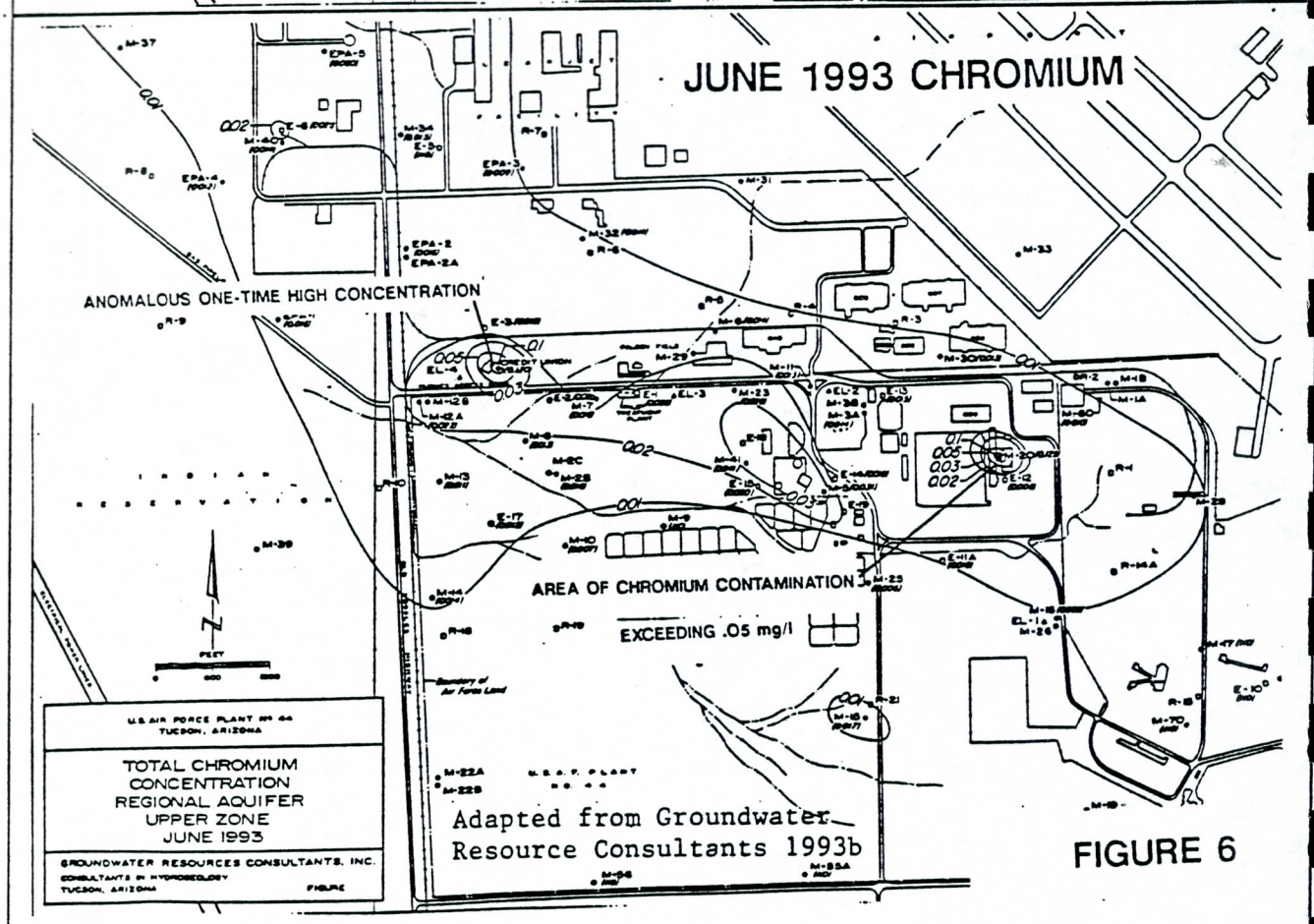
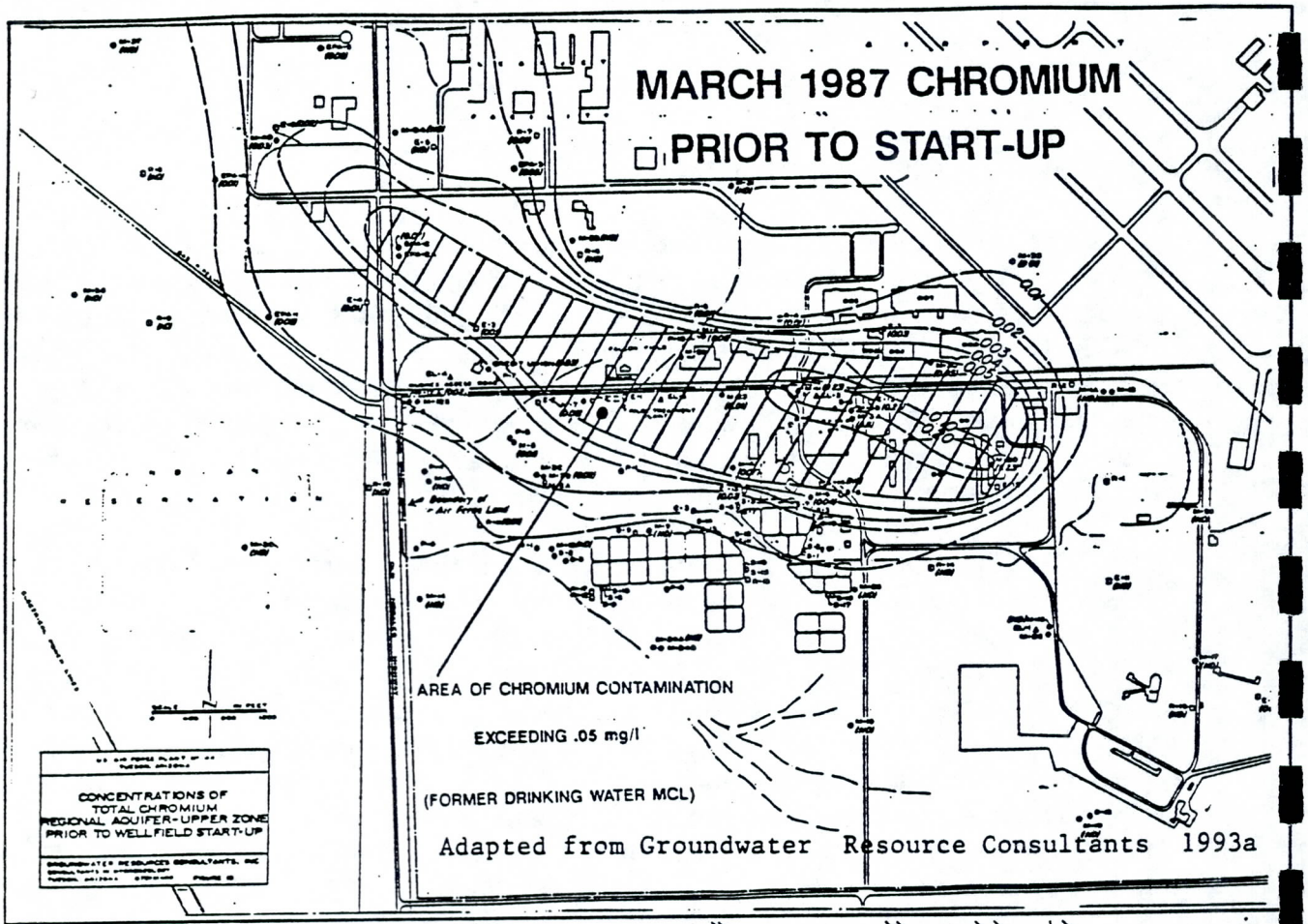
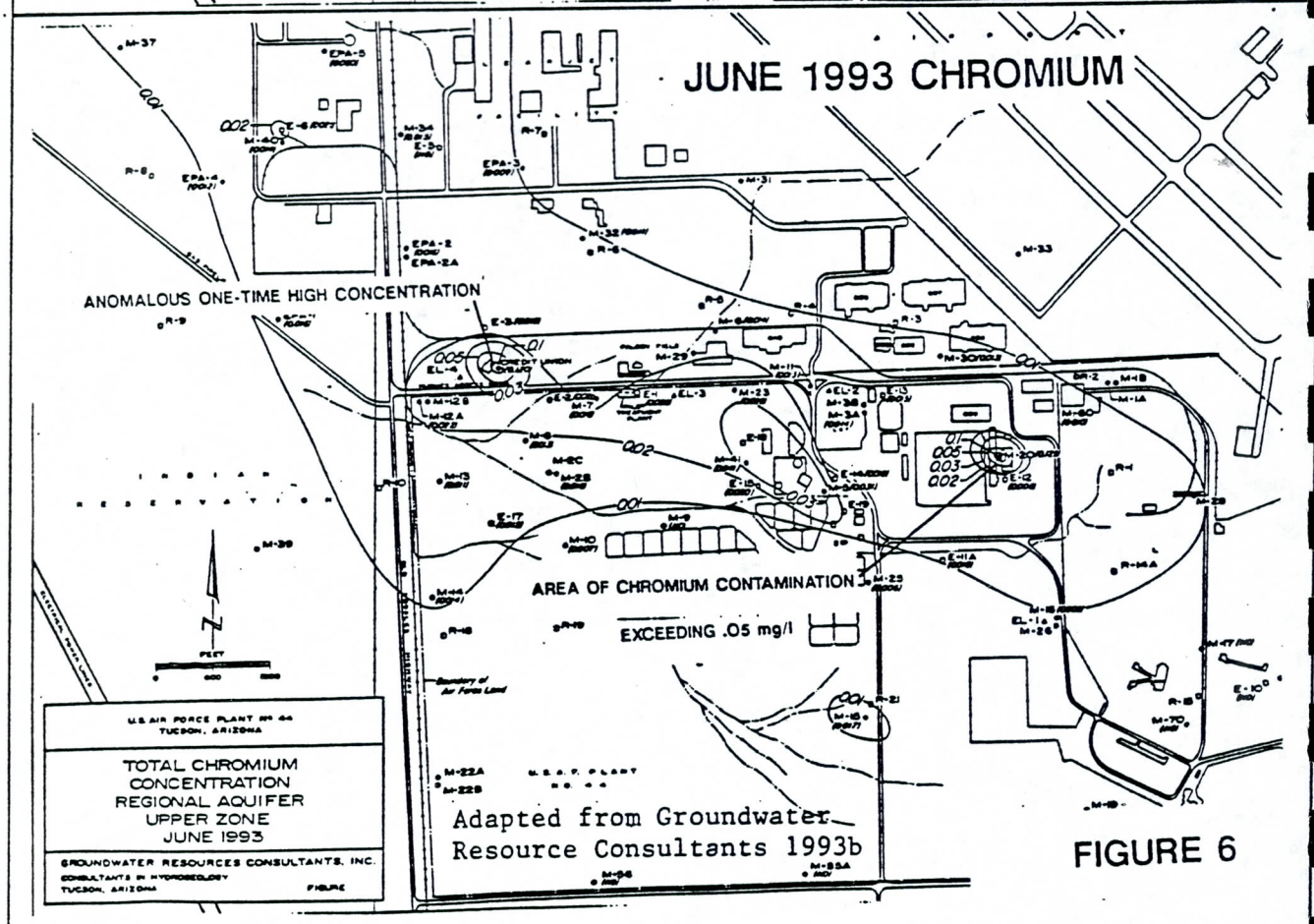

JUNE 1993 CHROMIUM
ANOMALOUS ONE-TIME HIGH CONCENTRATION
AREA OF CHROMIUM CONTAMINATION
EXCEEDING .05 mg/l
U.S. AIR FORCE PLANT
TUCSON, ARIZONA
TOTAL CHROMIUM
CONCENTRATION
REGIONAL AQUIFER
UPPER ZONE
JUNE 1993
GROUNDWATER RESOURCES CONSULTANTS, INC.
CONSULTANTS IN HYDROGEOLOGY
TUCSON, ARIZONA
Adapted from Groundwater
Resource Consultants 1993b

FIGURE 6




Adapted from Groundwater Resource Consultants 1993a




Adapted from Groundwater Resource Consultants 1993b

FIGURE 6

Mass balance calculations based on volumetric estimates indicate that the mass of TCE and DCE in the aquifer has been reduced by about 75% (figure 7). The change only represent the amount of VOC's dissolved in the water and doesn't include amounts that may be present as free-phase liquid in the vadose zone or as DNAPL's in the aquifer. The calculated amount of TCE and DCE removed, based on the map estimates, agrees within about 8% with estimated removal based on the flow volumes and influent concentrations entering the treatment plant. Data from the first 5 years of operation shows that the VOC removal rate becomes progressively less each year. Projections of future contaminant removal rates show the treatment system will have to be operated for a minimum of 10 more years to remove the remaining VOC's, if additional remedial measures are not implemented.

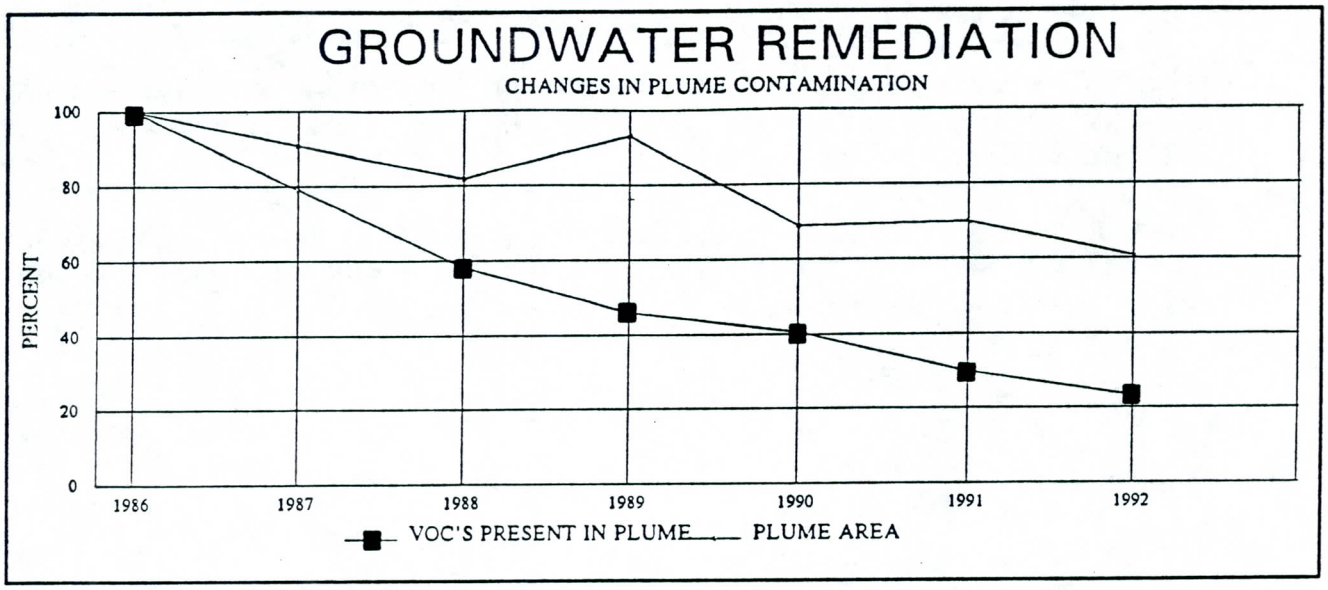



Figure 7

## CONCLUSIONS

Pump and treat groundwater remediation can be a very efficient method of reducing contaminant concentrations and containing plumes in groundwater if certain principles are followed. Clear project goals and objectives are needed. These must be kept in mind when designing and operating remediation systems. Sufficient hydrogeological data should be collected to accurately characterize the subsurface conditions at the site. Groundwater monitoring should be conducted on a regular basis, and often enough to detect significant changes in aquifer conditions as they occur. Contaminant concentration and water table elevation data should be routinely mapped to get a clear picture of aquifer conditions. The

most important principle is to actively manage the project and adapt the pumping patterns to changing aquifer conditions. Finally, any potentially continuing sources of contamination to the groundwater need to be removed if the project is to be completed in a timely manner.

## REFERENCES CITED


Groundwater Resource Consultants, 1993a, Summary of Wellfield Reclamation Operations and Changes in Groundwater Conditions, April 1987 through December 1992, U.S. Air Force Plant No. 44: March 1, 1993.

Groundwater Resource Consultants, 1993b, Summary of Wellfield Reclamation Operations and Changes in Groundwater Conditions, December 1992 through June 1993, U.S. Air Force Plant No. 44: September 1, 1993.

Leake, S.A. and Hanson, R.T., 1987, Distribution and movement of Trichloroethylene in ground water in the Tucson area, Arizona: U.S. Geological Survey Water Resources Investigations Report 86-4313, 40 p.

Rampe, John J., 1985, Results of the Tucson Airport Area Remedial Investigation, Phase I, Volume III An Evaluation of the Potential Sources of Groundwater Contamination Near the Tucson International Airport, Tucson Arizona.

# PERFORMANCE EVALUATION OF THE MOTOROLA 52ND ST. OPERABLE UNIT EXTRACTION WELL SYSTEM[1]

**R. Douglas Bartlett, P.G.[2], Gregory Fisher[3], James R. Hussey, P.E.[2], L. Todd Cruse[2], and Morley J. Weitzman[2]**

**ABSTRACT:** An Operable Unit (OU) extraction well system consisting of nine extraction wells pumping at a total average rate of 600 gpm was installed in 1991 and 1992 to contain a portion of a dissolved solvent plume originating from the Motorola 52nd St. CERCLA site. The OU extraction system began limited operation in May 1992 and full operation in July 1992. Two- and three-dimensional finite-difference ground-water models were used to design the system. The performance of the extraction system has been assessed using monthly water level measurements in conventional and multi-port Westbay wells. This paper presents an assessment of the first six months of operation and a comparison between modeled and observed performance of the OU extraction system.

The OU system creates a capture zone in the alluvium spanning the width of the plume and is more effective than predicted in bedrock where capture is observed to a depth of 300 feet. Model predictions of flow rate and drawdown agree closely with observations except in deep bedrock ports where drawdowns are observed to exceed model predictions.

## 1.0 INTRODUCTION

Since 1983, Dames & Moore has conducted extensive investigations of ground-water contamination in the area of the Motorola 52nd St. Facility. These investigations were conducted under oversight of the Arizona Department of Environmental Quality (ADEQ) as part of the WQARF (Water Quality Assurance Revolving Fund) and the U.S. Environmental Protection Agency (EPA) under CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act). The site was nominated for the National Priority List (NPL) in 1983 and placed on the list in 1989.

The investigations have revealed a plume of volatile organic compounds (VOCs) originating from the 52nd St. facility and migrating toward the southwest.

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[1] Paper presented at the Sixth Annual Symposium of the Arizona Hydrological Society, Casa Grande, Arizona, September 23-24, 1993.

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As part of the WQARF/CERCLA process, Motorola entered an agreement (the 1989 Motoro 52nd St. Consent Order) to contain and control contaminant migration. This resulted in the construction of an Operable Unit to pump-and-treat contaminated ground water. A 13-well ground-water extraction system designed to contain the ground-water plume has been installed both onsite in the Courtyard a offsite at the Old Crosscut Canal (OCC). Partial operation of the system began in 1986 and fu operation started in 1992. The system is intended to contain contaminated ground water migrating fro the 52nd St. facility at the OCC in the alluvial aquifer. This paper provides an evaluation of t Motorola 52nd St. OU system and compares the results of the first six months of operation to predicte performance. The primary focus of the paper is hydraulic containment. The effect of the OU on wat quality is addressed elsewhere.

## 2.0 BACKGROUND

### 2.1 History of the Motorola 52nd St. Ground-Water Investigation

The Motorola 52nd St. Facility is located in the eastern part of the City of Phoenix and is show relative to the surrounding area on the Vicinity Map, Figure 1. Motorola commenced manufacturing operations in this facility in 1956.

In November 1982, Motorola discovered a leaking underground TCA (1,1,1-trichloroethane) tank. The Arizona Department of Health Services (ADHS) was notified and Motorola voluntarily initiated investigation of soil and ground-water contamination. As a result of the preliminary investigation, oth volatile organic compounds (VOCs) including TCE were also discovered in the ground water.

A Remedial Investigation/Feasibility Study (RI/FS) was initiated by Motorola in 1983, and w conducted under regulatory oversight of ADHS (prior to October 1986), ADEQ (after October 1986), the Arizona Department of Water Resources and the U.S. Environmental Protection Agency. While t RI/FS was being prepared, Motorola voluntarily designed and constructed an on-site ground-wat treatment plant. This plant, referred to as the Pilot Treatment Plant (PTP), has been in operation since 1986, treating ground water at approximately 20 gpm from two wells.

In June 1987, Draft RI and FS reports (Dames & Moore, 1987) were prepared for regulatory review and public comment. These documents represented an extensive investigation of potential sourc of contamination at the Motorola 52nd St. Facility, characterization of the hydrogeological environmen prediction of the extent of contaminant migration in ground water and a review of remedial action alternatives.

Dames & Moore prepared a Draft Remedial Action Plan (RAP), dated June 24, 1988, (Dames & Moore, 1988). Motorola submitted the RAP to the ADEQ and the EPA for review. A remedi action was proposed as an interim remedy in accordance with CERCLA criteria for an Operable Uni and WQARF criteria for a remedial action. Remedial action alternatives were reviewed in a public meeting in Phoenix on July 11, 1988, and an alternative was chosen by ADEQ and EPA.

Responsiveness Summary was prepared by ADEQ/EPA to address comments on the RI/FS and the Draft RAP, and EPA issued a Record of Decision (ROD).

In 1989, the State of Arizona and Motorola executed an agreement to implement the recommendations of the RAP. This agreement, executed on July 26, 1989, is referred to as the Motorola 52nd St. Consent Order (AG, 1989). The Consent Order defines the scope of the Operable Unit (OU), the schedule for work and administrative provisions for conducting the work.

Construction of the OU system, consisting of onsite and offsite components, began in 1991 after a delay caused by canal realignment associated with the Papago Freeway construction. The offsite system was completed in Spring 1992. Startup of the system began in May 1992. Full operation commenced in July 1992.

## 2.2 Regional and Local Hydrogeologic Setting

The Motorola 52nd St. Facility is located near the western edge of the Papago Buttes, a prominent physiographic feature that represents part of the eastern boundary of the West Salt River Valley alluvial basin. Five distinct rock units crop out at the Papago Buttes: (1) Precambrian granite, (2) Precambrian metarhyolite, (3) Tertiary Camels Head Formation, (4) Tertiary Tempe Beds, and (5) Tertiary volcanics. These rock units, which collectively comprise the bedrock unit, are covered by Quaternary alluvium in the vicinity of the facility.

Ground water flows toward the southwest at the Motorola 52nd St. site with an average gradient of 0.011 ft/ft. Local anomalies in ground-water flow and hydraulic gradient near the facility reflect the influence of shallow bedrock. West of the Old Crosscut Canal, the hydraulic gradient decreases to about 0.005 ft/ft.

Two distinct geologic units have been identified as the primary water-bearing formations - the alluvium and the bedrock (Dames & Moore 1992). The alluvium is more transmissive and permeable than the bedrock. The less permeable bedrock occurs at shallow depths at some locations, reducing the saturated thickness of the alluvium.

The bedrock geometry is illustrated in Figure 2. Shallow bedrock occurs just west of the 52nd St. Facility along a northwest-southeast oriented fault block of Precambrian granite. Bedrock in this area may be as shallow as 20 feet. Shallow granite at a depth of about 90 feet is also present south of the Papago Freeway between 40th and 46th Streets.

## 2.3 Alluvial Aquifer

The upper stratigraphic unit onsite and offsite is comprised of unconsolidated alluvium. It consists of sediments that range in size from clay-sized particles to boulders, and varies in thickness from less than 20 feet at 52nd Street to greater than 300 feet west of 24th Street. These sediments form the alluvial aquifer, the upper surface of which is the water table.

Ground water is unconfined in the alluvium. The bottom of the alluvial aquifer is underlain by the less permeable bedrock strata. Where leakage occurs across this lower boundary, the alluvial aquifer is termed leaky phreatic. The hydraulic conductivity of the alluvial aquifer varies between 40 and about 200 feet/day (Dames & Moore, 1992).

### 2.4 Bedrock System

The bedrock is comprised of Precambrian metarhyolite and granite, and Tertiary volcanics and indurated sediments. These rocks have undergone ten or more separate deformational events, including faulting, rotation, and vertical and horizontal displacement.

At least two periods of faulting produced the fault and fracture patterns observed in rock core collected during drilling at the site: mid-Tertiary extensional block faulting and late Tertiary Basin and Range Faulting (Dames & Moore 1992). Based on these observations, at least two dominant fracture, fault, and lineament trends were noted: a northwest - southeast trend, and a northeast - southwest trend.

Correlation of packer tests for the analysis of hydraulic conductivity with fracture frequency support the concept of a double-porosity model for the bedrock system. Under these conditions, ground water in the fractured bedrock moves predominantly through the secondary porosity system that is controlled by the distribution of fractures and faults, and the degree to which the fracture zones communicate hydraulically with each other. Hydraulic conductivity in the bedrock increases with the fracture frequency and with the degree of hydraulic communication between adjacent fracture sets.

The storage capacity of the secondary porosity system is small relative to the primary porosity system of the intact rock mass. Ground water moves from storage within the primary porosity system into the more permeable fractures as each fracture system drains. Consequently, the storage capacity of the primary porosity can significantly influence the rate of movement of the ground water.

## 3.0 OPERABLE UNIT

### 3.1 Purpose and Objectives of OU System

The selected remedial action specified in the Remedial Action Plan (Dames & Moore, 1988) is a partial remedy ("Operable Unit" or "OU") as defined by the EPA. The OU consists of ground-water extraction onsite and offsite, and treatment. Additional onsite Soil Vapor Extraction (SVE) is included as part of the Remedial Action requirements of the Consent Order. The SVE system is not discussed in this paper.

The primary objective of the OU as stated in the 1989 Consent Order is that the OU system contain and control migration of contaminated ground water. Specifically the OU should "hydraulically contain groundwater contamination by volatile organic compounds from the facility to the east bank of the OCC. A zone of capture will be established by pumping from wells at the OCC." Further, the OU system shall be designed to "have a beneficial impact on the quality of groundwater within the bedrock

## 3.2 Construction and Operation

The OU extraction system is comprised of two components; an onsite system of four extraction wells in the vicinity of the Courtyard, and an offsite system of nine extraction wells at the OCC. The water withdrawn from the wells is piped onsite and treated onsite in an Integrated Ground-Water Treatment Plant (IGWTP), and put to beneficial use in the high purity water system at the Motorola 52nd St. facility. The configuration of the OU system is shown on Figure 1.

The four extraction wells (DM 301 through DM 304) installed onsite in the Courtyard area are intended to reduce ground-water contaminant migration in the alluvium and bedrock near the area of suspected sources of contamination. Two of the onsite wells (DM 301 and DM 302) were installed in 1986 as part of the Pilot Treatment Plant. Both have been operated nearly continuously since 1986. The combined total pumpage from all four wells was designed to be 60 gpm, and averaged about 45 gpm between April and December 1992.

The nine offsite extraction wells, DM 305 through DM 313, were installed between September and November 1991. They range in depth from 105 to 167 feet and were completed in the base of the alluvial aquifer and into the upper 20 to 30 feet of bedrock. The extraction wells are constructed using 6-inch diameter stainless steel casing and wire-wrap screen. The nine offsite pumping wells were originally designed to pump at rates of about 85 gpm with a total extraction rate of 755 gpm. After step-drawdown testing, the design flow rates were modified. The revised extraction rates for individual wells range from 10 to 130 gpm and total about 600 gpm. The reduction in flow rate resulted from shallower-than-expected bedrock in the southern portion of the line of wells.

The offsite and onsite extraction wells are monitored and controlled remotely. Each well head in the offsite system includes a magnetic flow meter and submersible pressure transducer. Data from the meters is transmitted via phone line to a control building located onsite near the treatment plant. Each extraction well is continuously monitored for flow rate and depth to water. These data are displayed in the control building and stored electronically for later evaluation.

A ground-water monitoring system of 14 wells supports this operation. Water level data are obtained monthly and water quality data quarterly from a combination of conventional wells installed in the alluvium and multiport, Westbay wells installed in the alluvium and bedrock.

Ground-water extraction from the offsite extraction wells began on an 8-hour-per-day basis during May 1992, and was extended to a 24-hour-per-day basis in July 1992. The total pumping rate from the OCC increased during May and June to approximately 650 gpm and then decreased to between 400 and 500 gpm for the remainder of 1992.

# 4.0 EVALUATION OF OU OPERATION

Ground-water level elevations and ground-water quality data collected during the first 6 months of operation were used to: 1) demonstrate the zone of capture; 2) assess the potential impacts of

drawdown; 3) demonstrate the effectiveness of the OU extraction well system on reducing VOC concentrations in ground water; and 4), provide recommendations for continued water level and water quality monitoring. Due to space limitations this paper will focus on the hydraulic containment objective only.

The period between March and May 1992 was used as a baseline because the extraction system was not in operation and monitor wells had been installed. To assess the OU performance, data collected during 6 months of continuous pumping, were compared to baseline data collected in the March to May 1992 interval. A total of 13 extraction wells and 14 monitor wells with a total of 33 monitor intervals were used to evaluate the system. Ground-water model predictions were compared to actual observations. Predictions of hydraulic head were compared to actual water-level measurements taken during the period of March to December 1992.

### 4.1 Capture Zone

Flow nets were constructed in plan and cross section to assess hydraulic capture. The baseline flow nets (Figures 3 and 4) illustrate that prior to pumping, ground water flowed horizontally toward the southwest with the exception of two cones-of-depression at the Motorola 52nd St. facility. Two onsite extraction well systems were operated to produce local remediation at the Motorola 52nd St. site during the baseline period: a two-well onsite extraction system in the Courtyard, and an 11-well extraction system in the Southwest Parking Lot. The performance of these systems does not directly impact this analysis and, is not discussed here.

Plan (Figure 5) and cross-section (Figure 6) flow nets for the end of the 6-month pumping period, October to December 1992, were used to assess the impact of the offsite extraction system. A heavy dashed line in each figure indicates the location of the capture zone. The solid line shown on Figure 5 represents the model-predicted capture zone.

The observed capture zone for the OU extraction system extends approximately 900 feet west of DM 309, 1,500 feet north of DM 301 and 1,300 feet south of DM 313. Figure 6 illustrates that during full-scale operations, the combined OU extraction system was withdrawing ground water within the zone of capture to a depth of approximately 300 feet below land surface.

Upward hydraulic gradients were observed in multi-port wells along the OCC. At monitor well DM 603, the upward gradient increased from 0.0005 ft/ft in April-May 1992 to 0.005 ft/ft in October-December 1992. Pumping along the OCC had a measurable influence on vertical hydraulic gradients in monitor well DM 502 located about 3,000 feet southwest of the OCC. Prior to full scale operations, ground water at DM 502 was moving downward with a vertical gradient of 0.0008 ft/ft in the alluvium, while deeper in the bedrock, the vertical gradient was upward at 0.003 ft/ft. During full-scale operations on October 24, 1992, the extraction system produced a gradient reversal at DM 502 resulting in an upward vertical gradient of 0.064 ft/ft in the alluvium, and a downward gradient in the bedrock of 0.004 ft/ft.

## 4.2 Drawdown

Apparent drawdowns observed in wells over the period March to December 1992 are shown on Figures 7 and 8, in plan and section, respectively. Declines in water levels are interpreted as apparent drawdown because regional water-level trends were not incorporated in the analysis. The following discussion summarizes observations of "apparent" drawdowns, uncorrected for regional water-level trends. Regional trends were judged not to affect the conclusions reached in this analysis.

Water-level declines were calculated as positive drawdowns and are represented by solid contours on Figures 7 and 8. Water-level increases were calculated as negative drawdowns and are represented as dashed contours. The point of zero drawdown marks the apparent effective influence of the OU extraction system and lies outside the zones of capture shown on Figures 5 and 6.

Drawdown in extraction wells was observed to be as high as 50 feet but included linear and non-linear head loss caused by well and aquifer inefficiencies. Monitor wells exhibited less drawdown, ranging from over 12 feet in well DM 603, 300 feet west of the OCC, to less than 5 feet in well DM 115, 1000 feet east of the OCC. More than one foot of drawdown was observed at well DM 504 about one mile west of the OCC.

Figure 7 illustrates that the offsite OU system has a radius-of-influence extending as much as one mile from the extraction wells. The pattern of drawdown reflects the overall orientation of shallow bedrock in the area. Note the northwest-southeast and northeast-southwest patterns. The bedrock high east of the OCC is oriented northwest-southeast and is as shallow as 20 feet. A bedrock ridge located in the vicinity of DM 503 and DM 122 is oriented northeast-southwest and is within about 90 feet of the surface. Alluvium thickens to greater than 150 feet west and north of DM 503. Drawdown decreases rapidly east of the OCC as shown on the cross section (Figure 8). At well DM 606, 1200 feet east of the OCC, about 2 feet of drawdown was observed. Approximately 3,000 feet west of the OCC, however, drawdown exceeded 5 feet in well DM 502. Drawdowns observed in bedrock (Figure 7) confirmed that the extraction system has a significant influence to depths in excess of 300 feet.

# 5.0 GROUND-WATER MODEL DEVELOPMENT

Ground-water flow and contaminant transport modeling was first used in 1983 to evaluate ground-water flow conditions at the Motorola 52nd St. site. Since then, modeling has been used to evaluate contaminant migration and to design the OU system.

Dames & Moore developed two ground-water models to design the OU system; a two-dimensional finite-difference model of the alluvial aquifer at the plant site, and a three-dimensional finite-difference model of the alluvial-bedrock aquifer system. Only the results of the three-dimensional model will be discussed in this paper. Both models were developed using a proprietary computer code known as "TARGET" developed by Dames & Moore. TARGET is a family of five vertically-integrated 2- and 3-dimensional finite difference models capable of simulating saturated and unsaturated flow and transport of a dissolved, reactive chemical compound in a porous media.

A three-dimensional model originally developed for the RI/FS (Dames & Moore, 1987) wa modified to allow simulation of the 9 offsite extraction wells. The model covers an area of about 6 square miles. Modifications included reduction in the size of model cells located in the vicinity of the OCC and incorporation of updated depths to bedrock. The resulting model included about 35,000 cel ranging in size from 100 by 100 by 15 feet to 1000 by 1000 by 50 feet.

Material property distributions input to the model were developed through evaluation of field dat including cuttings and rock core from monitor wells, aquifer tests, packer tests in bedrock borings and wells, and rising-head tests conducted in Westbay monitor wells. Calibration of the model was don through comparison of predicted and observed hydraulic heads in a system of ground-water monito wells shown in Figure 1.

A steady state flow model was used to simulate the ground-water flow field. The steady stat assumption (as opposed to transient flow) was considered valid for this site because historical data from wells in the area indicated that the ground-water flow gradient and direction have not significantl changed since the early 1960's. Water-level measurements obtained in June 1991 were used to calibrat the flow model.

The ground-water model was used to simulate the operation of the OU extraction system for period of 20 years (1992 to 2012). The predicted capture zone developed by interpretation of velocity vector plots is illustrated on Figure 5. The modeling results for the OU system can be summarized a follows:

The maximum drawdown at the offsite extraction wells was predicted to range from 10 to 3 feet.

The average drawdown in the bedrock was predicted to exceed 10 feet.

The capture zone created by the offsite extraction wells may extend as far as 1,500 feet downgradient of the OCC.

## 6.0 COMPARISON OF PREDICTED AND OBSERVED OU PERFORMANCE

In general, actual drawdowns agree closely with the predicted drawdowns and support the use of the model in predicting the response of the alluvial aquifer to pumping. Figure 5 shows the predicted and observed capture zones. The predicted capture zone was developed by interpretation of velocit vector plots.

Observed drawdowns alluvium agreed closely to predicted drawdowns. Figure 9 illustrates th drawdown observed in DM 603 at the 68-foot deep port in alluvium. Predicted and observed drawdowns coincide. Contrast the 68-foot port with the port at 245 feet in the same well (Figure 9). Observed drawdown greatly exceeds the predicted drawdown in bedrock. Similar observations can be made fo a number of the multi-port wells near the OCC.

One explanation for the difference between predicted and observed drawdown in bedrock could be that the value of storage used in the ground-water model was too large. Measurement of storage in bedrock is difficult due to the low permeability of bedrock. Values of storage for bedrock input to the model were inferred from the bedrock permeability measured using packer and rising head tests.

The overestimation of storage by inference from permeability measurements resulted in an underestimation of bedrock drawdown in the ground-water model. Thus, model predictions conservatively underestimated the influence of the OU system on drawdown in bedrock.

## 7.0 CONCLUSIONS

The OU extraction well system installed along the OCC has been shown to create a capture zone in the alluvial aquifer that spans the known width of the solvent contaminant plume associated with the Motorola 52nd St. site. Effective capture is achieved to a distance of about 900 feet west of the OCC and 1,300 to 1,500 feet north and south of the extraction well system. In addition, the OU system creates a capture zone extending about 300 feet below the OCC, into the bedrock.

Full-scale operation of the OU extraction system has a radius of influence that extends about one mile downgradient from the OCC. The drawdown pattern developed from the extraction system reflects the pattern of shallow bedrock in the area. Drawdown is greatest in areas where the alluvium is relatively thick.

Actual drawdowns observed in monitor wells agree with model-predicted drawdowns within the alluvium. Actual drawdowns observed in bedrock tend to exceed model-predicted drawdowns. OU pumping has a greater effect on drawdown in bedrock than predicted by the ground-water model. The difference between the model predicted and observed drawdown may be due to an overestimate of bedrock storage.

The ground-water model developed for the Motorola 52nd St. site is an effective tool for evaluating the OU extraction system in the alluvium. Prediction of the effectiveness of an extraction system in a bedrock setting using a porous media model should be made cautiously. In this instance, the model predictions conservatively underestimate the effectiveness of the extraction system in bedrock.

The OU extraction system is functioning as planned. Hydraulic containment was achieved as predicted. Pumping rates of 500 gpm are sufficient to achieve contaminant capture.

## 8.0 REFERENCES

AG (Attorney General's Office), 1989. 52nd St./Complaint, Consent Order and Settlement Agreement, Civil Action No. 89-16807. June 20, 1989.

Dames & Moore, 1987. Draft Remedial Investigation Report, 52nd St. RI/FS, Phoenix, Arizona for Motorola Inc., June.

Dames & Moore, 1988. Draft Remedial Action Plan. June 24, 1988.

Dames & Moore, 1992. Final Remedy Remedial Investigation Report, Motorola 52nd St., February 1992. Transmitted March 15, 1992.

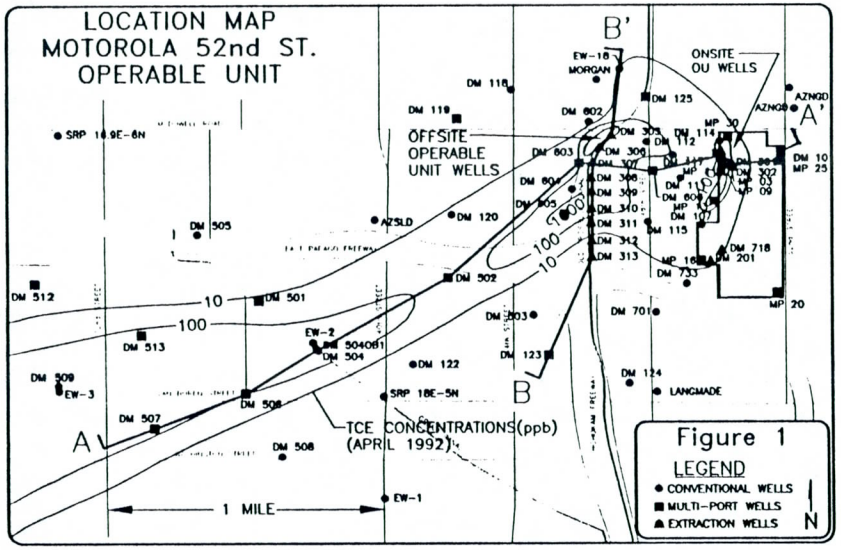



Figure 1

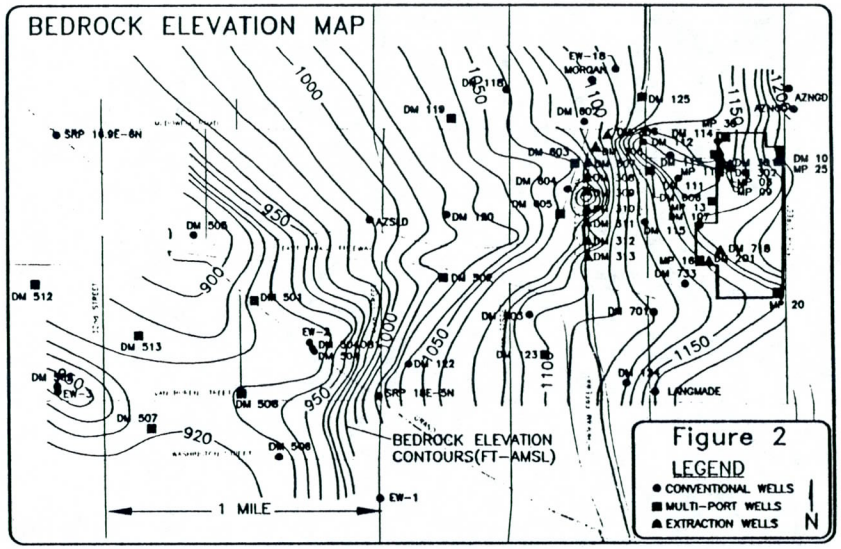



Figure 2

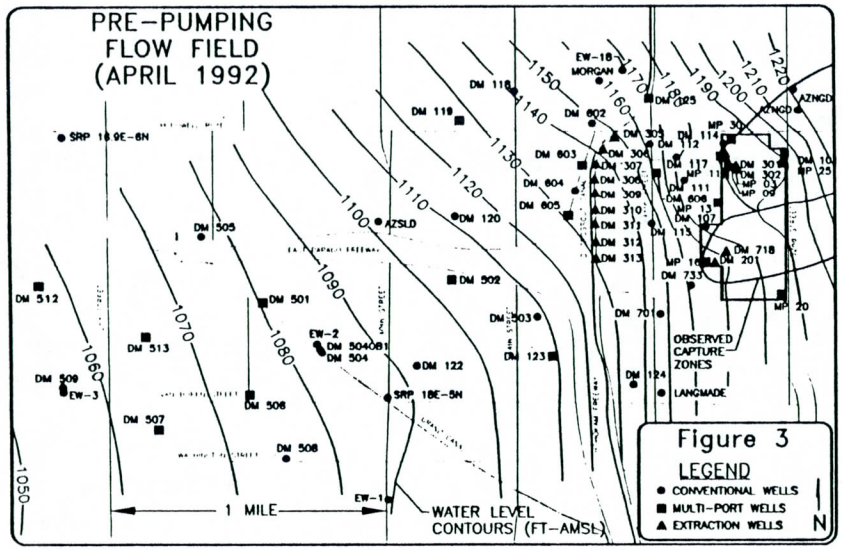



Figure 3

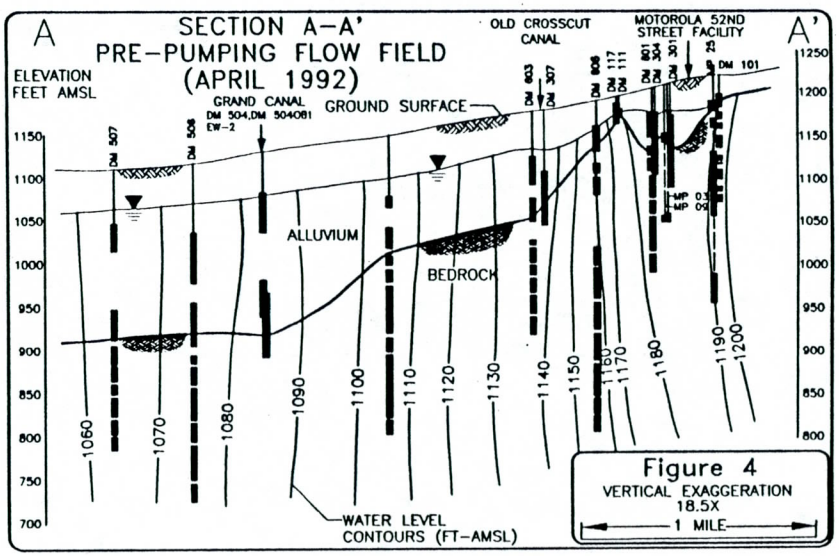



Figure 4

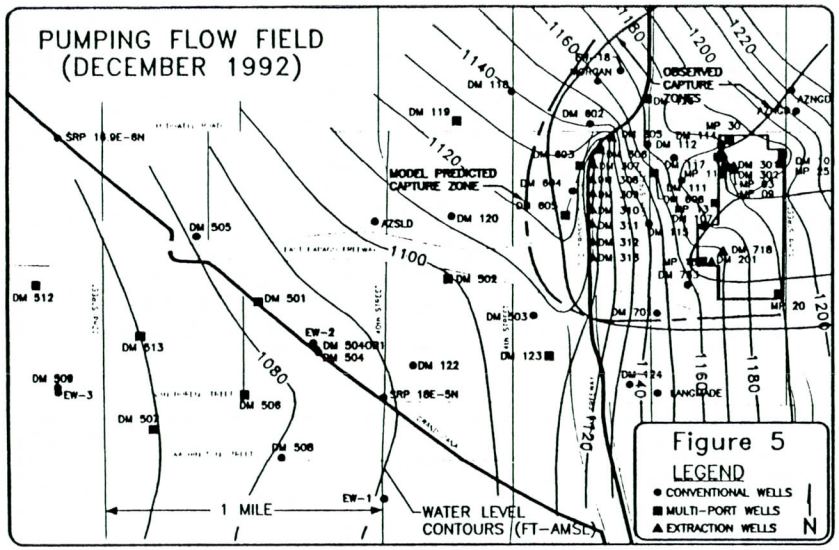



Figure 5

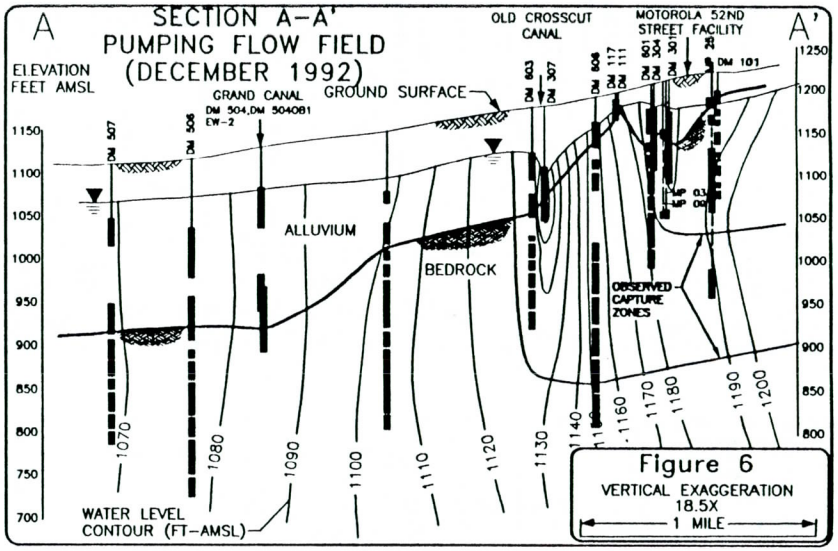



Figure 6

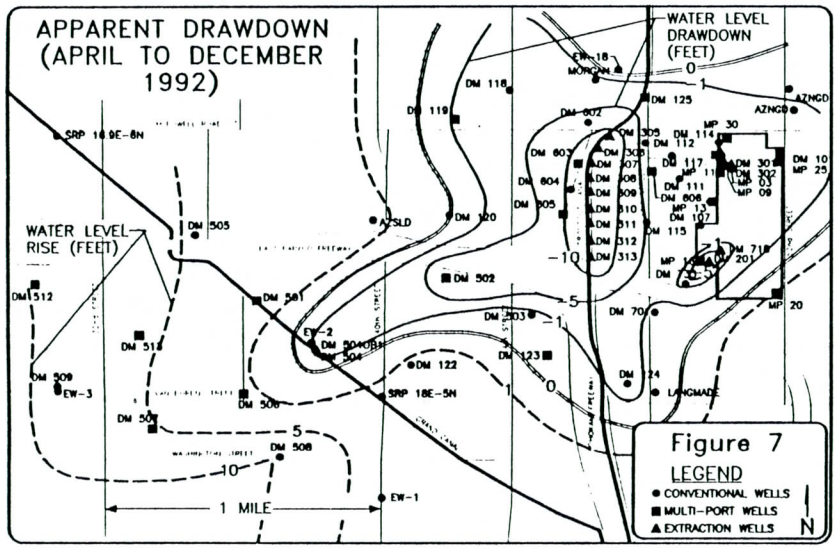



Figure 7

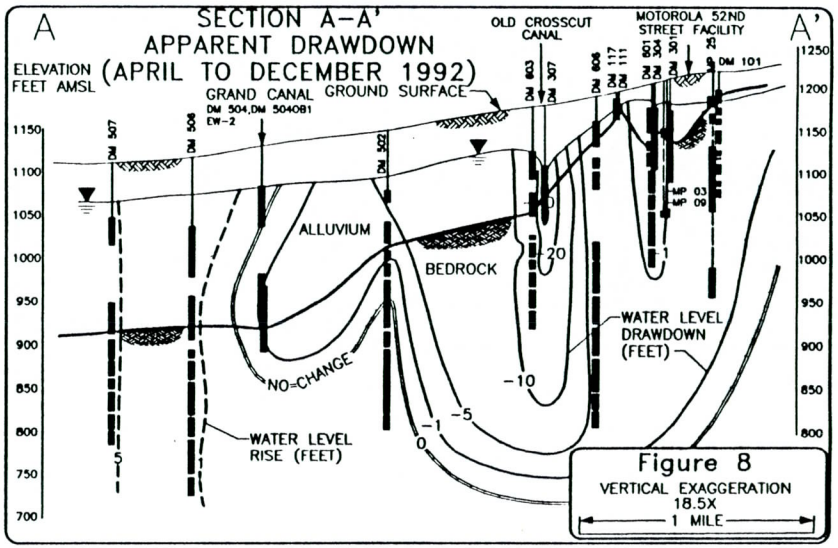
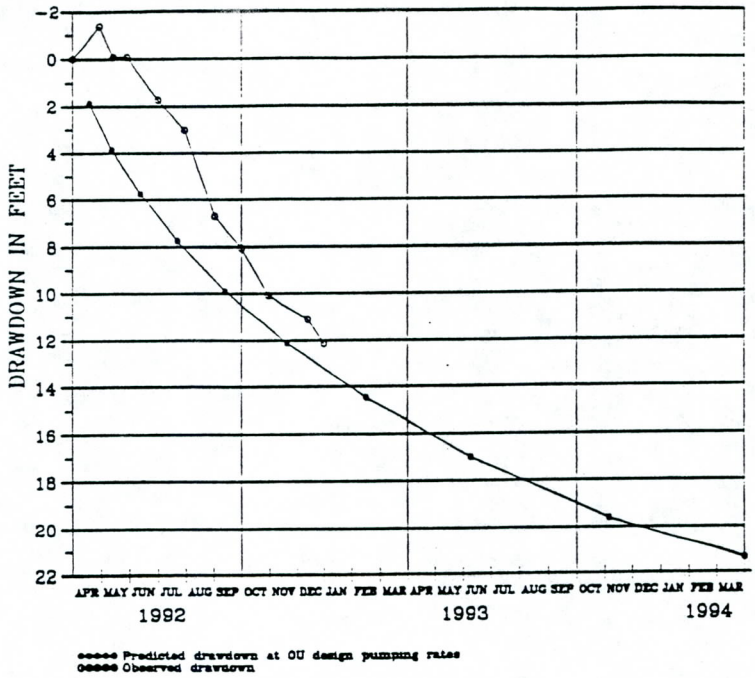
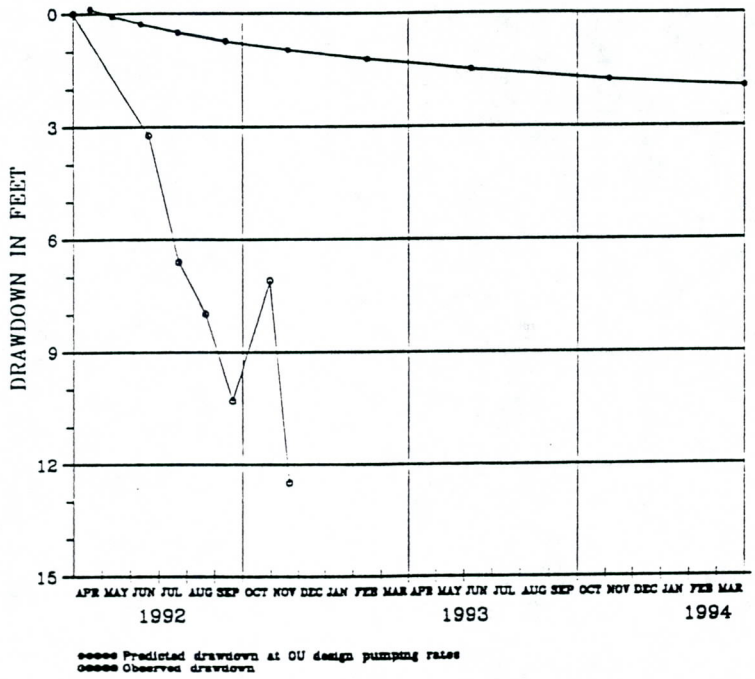



Figure 8




PREDICTED vs. ACTUAL
DRAWDOWN FOR
DM 603-68
DM 603-245

Figure 9

DAMES & MOORE

# WHAT'S NEW IN BIOREMEDIATION?[1]

Jeremiah D. Jackson, PhD, PE[2]

ABSTRACT: This paper explores recent technology trends in the bioremediation of contaminated soils and groundwater. Technologies discussed include: the use of non-aqueous nitrogen as a macronutrient; the dewatering of a contaminated aquifer to create an artificial vadose zone; and air sparging to aerobically enhance bioremediation. Basic theory is covered, along with design basics, leading to a conceptual remedial design. For each application, the governing design constraints are identified, and then resolved using the new technology.

## INTRODUCTION

This paper is the fourth in a series of papers on bioremediation presented at the annual Symposia of the Arizona Hydrological Society. Previous papers have discussed ex-situ soil bioremediation basics (Jackson 1990), bioremediation kinetics (Jackson 1991), and in-situ soil bioremediation (Jackson 1992). The purpose of this paper is to introduce emerging developments in bioremediation technology, with the intention being to report in more detail their design and performances at upcoming symposia.

## OVERVIEW BIOREMEDIATION STRATEGY

Previous work by this author (Jackson 1990 and 1992) and others has shown that successful bioremediation of soils and groundwater contaminated with fuel hydrocarbons requires satisfying three basic biological needs:

1) air
2) water
3) food.

Fuel hydrocarbons, especially those that are semi- or non-volatile such as diesel, are readily biodegraded under aerobic conditions. Consequently, it is important to aerate and thus maintain aerobic conditions within contaminated subsurface soils and groundwater.

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[1]Paper presented at the Sixth Annual Symposium of the Arizona Hydrological Society, Casa Grande, Arizona, September 23-24, 1993.

[2]Jeremiah D. Jackson is a Principal and Senior Vice President, Kleinfelder, Inc., San Diego, CA.

Since bioremediation relies on living microorganisms to accomplish the degradation of fuel hydrocarbons, the contaminated media need to have sufficient moisture. Contaminated groundwater does not, of course, suffer from water deficiency; however, contaminated soils need a moisture content of approximately 20 percent for successful bioremediation.

Microbial food requirements are satisfied by the fuel hydrocarbon contamination itself (as organic carbon), and primarily two other macronutrients: nitrogen and phosphorus. These other macronutrients must be "biologically available", typically in an aqueous solution of ammonia and phosphate. This author as well as others have found that successful biodegradation occurs with a carbon-to-nitrogen-to-phosphorus (C:N:P) ratio of 100:5:1 by weight.

## UNSATURATED SOILS

A common contamination scenario in the arid Southwest involves the release and movement of fuel hydrocarbons through permeable unsaturated soils. Generally, since the depth-to-water is often great, the hydrocarbon contamination does not reach, but ultimately threatens, underlying groundwater.

The remediation strategy for the above scenario would follow the overview strategy of satisfying the three basic biological needs, by:

- replenishing consumed interstitial oxygen by moving exhaust gases (viz., carbon dioxide) out and fresh air in, via a soil ventilation system
- adding water to increase soil moisture
- adding an ammonium phosphate solution to satisfy C:N:P requirements.

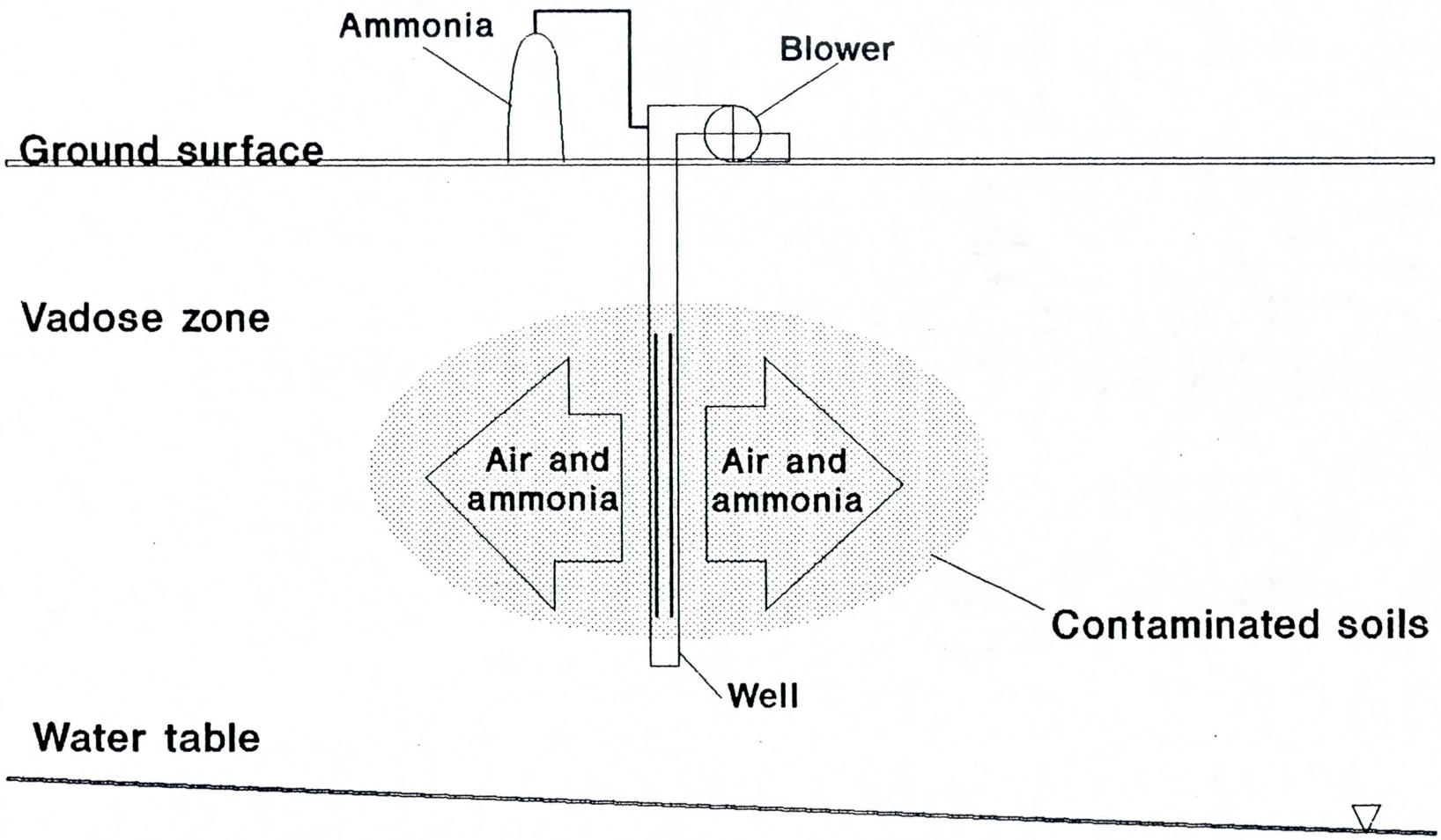
A common regulatory obstacle to the above remediation strategy is the concern that aqueous ammonium will migrate downward, reach the underlying groundwater as a nitrate, and ultimately pollute the aquifer with the threat of methemoglobinemia. Consequently, it is often difficult, if not impossible, to obtain regulatory approval for in-situ bioremediation of contaminated soils when aqueous ammonia is proposed as a source of added nitrogen.

An interesting alternative to the above which may be more acceptable, is the use of anhydrous ammonia instead of the aqueous ammonium solution. Work by Dineen et al. (1990) has shown the successful application of such an approach for bioremediating petroleum hydrocarbon contaminated soils. Their application involved the injection of low concentrations (e.g., 100 ppm) of ammonia gas into a pressurized air stream being blown into and through the subsurface contaminated soils (see Figure 1). Dineen et al. found that bacterial densities responded favorably to such an approach, and concluded that it was an effective mechanism for providing the necessary nitrogen.

## SATURATED FINE SOILS

Fuel hydrocarbons which do eventually reach the water table will generally back up and float on the water's surface. (Some will be dissolved in the underlying water, but due to the low dissolution of fuel hydrocarbons in water, the resulting concentration is small.) If the water table should rise -- which it significantly has this year in many parts of Arizona due to the record rainfalls and river flows -- the floating contaminant "plume" will largely

# Figure 1: Conceptual Remedial Design for Unsaturated Soils



be trapped resulting in a difficult remediation problem: highly contaminated *saturated* soils. Depending on whether these soils are "fine" and exhibit low permeability (e.g., silts), or whether they are "coarse" with high permeability (e.g., sands or gravels) leads to two different remediation approaches. Both remediation approaches, however, are based on the same strategy:

- remediation requires creating and maintaining aerobic conditions by adding air
- saturated conditions eliminate the need for increasing soil moisture
- existing residual macronutrient concentrations in the groundwater typically exceed requirements of the relatively low concentrations of trapped and dissolved hydrocarbons.

Both approaches also suffer from the same major problem:

- saturated soil conditions make it difficult to maintain aerobic conditions.

An emerging technology for accomplishing the above strategy while overcoming the inherent difficulty of aerating saturated soils, is to *dewater* the contaminated saturated zone to result in an "artificial" vadose zone. The dewatered contaminated soils are then bioremediated using standard in-situ technologies, such as those discussed by Jackson (1992). This approach works best for fine soils, since for a given pumping rate, drawdown is greater in less permeable aquifers. A conceptualization of this remedial design is given as Figure 2.

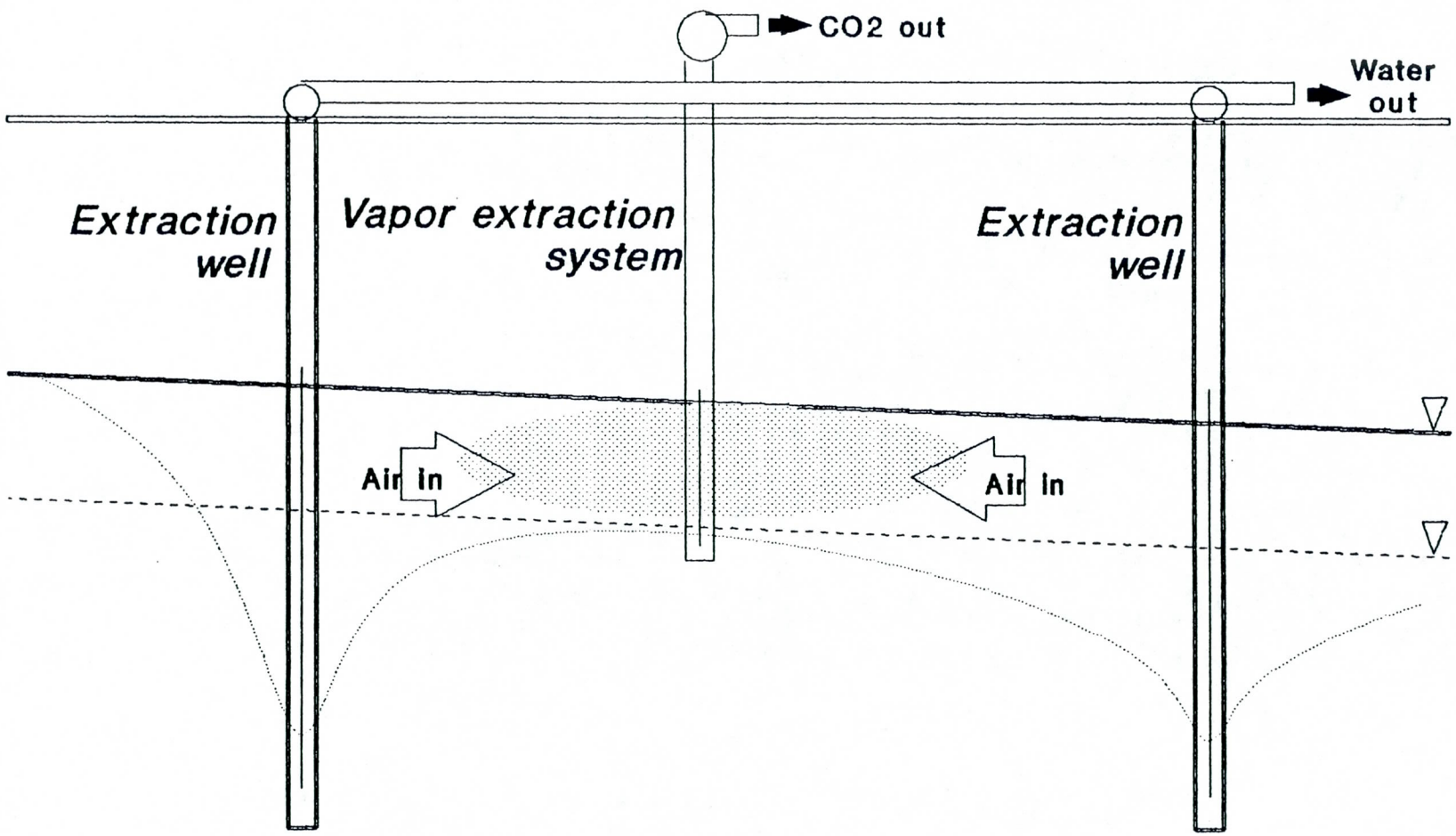
## SATURATED COARSE SOILS

As noted above, saturated coarse soils have the same strategy and dominant problem as saturated fine soils. Both scenarios require aeration, yet -- due to water saturation of the contaminated soils -- aeration and the goals of creating and maintaining an aerobic environment are difficult to accomplish.

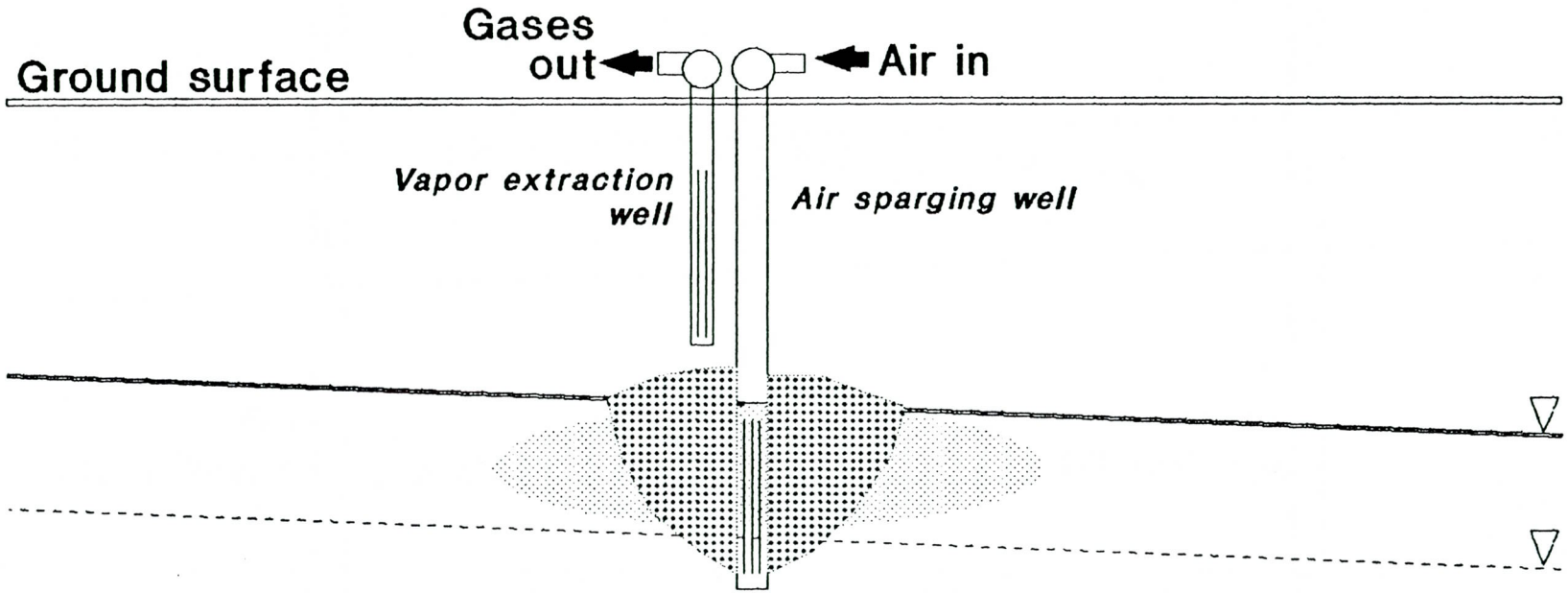
Dewatering coarse soils is not as cost-effective as dewatering fine soils, since a much greater volume of water must be pumped to obtain a similar drawdown of water level. For soils such as coarse sands or gravels, pumping may even be cost-prohibitive. Thus, an alternative approach is needed to aerate contaminated saturated coarse soils.

A successful approach recently used by Kleinfelder to aerate contaminated saturated coarse soils is to "sparge" air through the contaminated zone via pressurized wells. This "air sparging" supersaturates the water-saturated contamination, and provides abundant oxygen to satisfy the aerobic respiration demand of the microorganisms. A conventional soil ventilation system installed in the overlying vadose zone is then used to remove exhausted biogases (e.g., carbon dioxide) and any volatile compounds (e.g., benzene) contained in the fuel and air stripped by the air sparging wells. These gases can be monitored at the soil ventilation system wellhead to estimate biodegradation effectiveness. Figure 3 is a conceptual remedial design of this use of air sparging and vapor extraction for bioremediation of contaminated saturated coarse soils.

# Figure 2: Conceptual Remedial Design for Saturated Fine Soils



# Figure 3: Conceptual Remedial Design for Saturated Coarse Soils



## REFERENCES

Dineen, Dennis, Jill P. Slater, Patrick Hicks, James Holland, and L. Denise Clendening, "In Situ Biological Remediation of Petroleum Hydrocarbons in Unsaturated Soils," in Petroleum Contaminated Soils, Volume 3, edited by Charles E. Bell, 1990.

Jackson, Jeremiah D., "Bioremediation of Diesel Contaminated Soils", presented at the 3rd Annual Symposium of the Arizona Hydrological Society, 1990.

Jackson, Jeremiah D., "Bioremediation Kinetics", presented at the 4th Annual Symposium of the Arizona Hydrological Society, 1991.

Jackson, Jeremiah D., "In-situ Bioremediation of Diesel Contaminated Soils", presented at the 5th Annual Symposium of the Arizona Hydrological Society, 1992.

# AQUIFER CONTAMINATION AND THE CITY OF PHOENIX WELL SYSTEM: PROBLEMS AND SOLUTIONS

Keith R. Larson

ABSTRACT: Over the last decade, City of Phoenix well system production capacity has decreased by over 60 percent due to groundwater contamination. In response, Phoenix has developed a Well Drilling and Remediation Action Plan aimed at increasing well system capacity by 60-70 million gallons per day by the year 2000. This paper summarizes the nature of aquifer contamination problems in Phoenix and strategies the city is implementing in new well development and existing well remediation. Strategies include drilling new wells in undeveloped areas not yet impacted by pollution, downhole well modification, and well blending. The latter two are relatively low-cost techniques being used to mitigate water quality problems at inactive wells that do not meet drinking water standards. High-cost wellhead treatment systems are considered only as a last resort for high priority production wells.

Over the last decade, aquifer contamination has resulted in a severe reduction in the production capacity of the City of Phoenix well system. In 1980, Phoenix had 115 active wells capable of producing about 125 million gallons per day (MGD) of potable water. Since then, 80 wells have been deactivated, capped, or abandoned, leaving the City with only 43 wells with a capacity of 43 MGD. Aquifer contamination by various pollutants coupled with more stringent drinking water quality standards was the cause of inactivation of the majority of wells.

Fortunately for Phoenix, the acquisition of Central Arizona Project (CAP) water in 1985 provided a major new surface water supply to compensate for the loss of well capacity. However, the loss of groundwater wells has left the city with insufficient backup supply to meet unrestricted water demands in the event of a major cutback in the city's CAP or Salt and Verde River water supplies due to severe drought or temporary canal outages.

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[1] Paper presented at the Sixth Annual Symposium of the Arizona Hydrological Society, Casa Grande, Arizona, September 23-24, 1993.

[2] Keith R. Larson is a Water Resources Planner with the Phoenix Water Services Department, Phoenix, Arizona.

Reduced well capacity has also made it more difficult to solve short-term water syster operation problems such as maintaining chlorine residuals and reservoir levels, and supplying water during main breaks or water treatment plant shutdowns. This paper describe- groundwater quality problems facing Phoenix and the steps being taken to increase we system capacity in the face of spreading groundwater contamination and more stringent drinking water quality standards.

## THE PROBLEM

The City of Phoenix' water quality policy is that wells are placed on inactive status whei contaminant concentrations reach 90 percent of an EPA maximum contaminant level (MCL, or state action level. In addition, if wells produce water that has any measurable amount of organic compounds, they are inactivated. Table 1 shows the number of wells that have beei taken off-line due contaminants as a result of these policies.

**Table 1**

| Wells Taken Out of Service | |
|---|---|
| **Reason** | **Number of Wells** |
| Nitrate | 40 |
| DBCP/EDB | 8 |
| TCE | 4 |
| Chromium | 7 |
| Other | 21 |
| **TOTAL** | 80 |

Nitrates are by far the most prevalent contaminant affecting the city's wells. Many Phoenix wells are located in areas that were farmed prior to being developed for urban use. Pas' overuse of nitrogen fertilizers is thought to be the primary cause of nitrate contamination ii these areas. Past use and disposal of the pesticides DBCP and EDB has impacted eight wells. To date, four wells have been shut down due to contamination by the industrial solver trichloroethylene (TCE), and seven wells have been impacted by chromium of natura occurrence in the aquifer materials underlying portions of northeast Phoenix. Finally, a total of twenty-one wells have been inactivated due to factors such as lead, fluoride, high tota dissolved solids, sand in pumped water, collapsed casings, or inefficient productioi characteristics.

## SOLUTIONS

In response to the likelihood of continued impacts to the City's well system, the Phoenix Water Services Department commissioned several studies aimed at defining the nature and extent of contamination and alternatives for increasing well system capacity to provide adequate backup water supplies. Following completion of the studies, staff developed a Well Drilling and Well Remediation Action Plan covering the 1993 to 2000 period. The program's objective is to add an additional 60-70 MGD of well capacity by the year 2000. To accomplish this goal, two or three new wells will be drilled and equipped each year, and an attempt will be made to solve water quality problems at three wells each year. The total cost of the eight-year program is estimated at $41 million. The following sections describe the strategies that will be used to accomplish these goals.

### New Wells

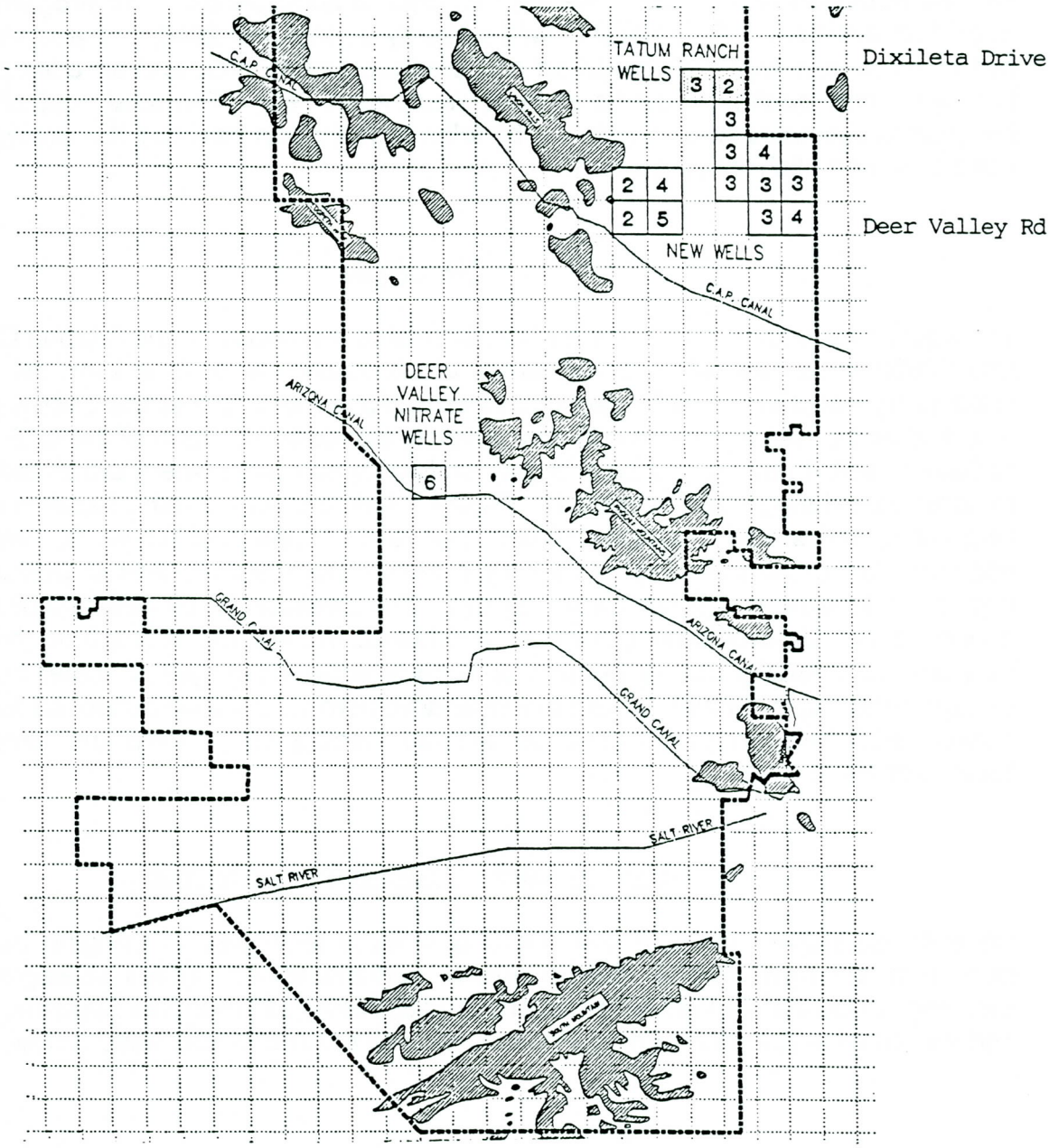
The aquifer underlying much of the Phoenix service area south of the Arizona Canal and in the Deer Valley area has either known areas of contamination or is at high risk for future well impacts by pollutants. Hydrogeologic investigations indicate that the best area to construct new well fields from a water quality and quantity standpoint is north of the CAP canal and east of Cave Creek Road. This area is largely undeveloped desert where urbanization is expected to accelerate during the next decade. Figure 1 indicates the general location of planned well field areas and specific sections of land that is recommended for wells. Well sites will be acquired from master developers as early in the development process as possible to minimize impacts to landowners as land is subdivided. The location of new wells will ultimately depend on the pattern of development of state-owned lands in the area. Water from the new wells will be pumped primarily during periods of surface water shortages or water system outages. Groundwater supplies that exceed the local area demands will be conveyed to the rest of the service area through the distribution system leading south from the Union Hills Water Treatment Plant.

### Bringing Inactive Wells Back into Service

Phoenix has studied the cost and feasibility of three strategies for bringing back into service wells that are now inactive due to aquifer contamination. These strategies are: 1) Well Blending, 2) Downhole Well Modifications, and 3) Wellhead Treatment Systems. Each strategy, and its potential role in returning Phoenix wells to service is discussed below.

Figure 1

Areas of New Well Construction



## Well Blending

Blending water to meet water quality objectives has been a common practice in the water industry for many years. Until 1992, water providers in Arizona, including Phoenix, would blend well water exceeding MCLs with surface water in the distribution system to dilute concentrations to below MCLs. Mass balance calculations were done to ensure that contaminants would be diluted to acceptable levels by the time the water reached the tap of the first downstream customer. In 1992, the Environmental Protection Agency (EPA) and the Arizona Department of Environmental Quality (ADEQ) adopted new regulations requiring that any water entering the distribution system meet all MCLs. Blending must now occur outside of the distribution system. In addition, contaminant levels in approved blending operations must be monitored on a continual basis using real-time water quality test equipment.

In response to the new ruling, Phoenix developed and submitted to ADEQ a blending plan for four nitrate-contaminated wells located near the Deer Valley Water Treatment Plant. The plan was approved by ADEQ and the wells, which are blended with treated surface water in a 20 million gallon finished water reservoir, have been placed back into service. Additional wells are being investigated for blending feasibility. Most wells, however, are not conveniently located near large reservoirs with a large water quality buffering capacity. Thus blending plans for additional Phoenix wells will likely require construction of a small reservoir (50,000 to 100,000 gallons) on the well site where well water can be blended with treated surface water withdrawn from the water distribution system. This strategy holds promise only for wellsites that are large enough to contain a reservoir and that are located near water mains providing sufficient blending water.

## Downhole Well Modification

Several water utilities in Arizona have successfully modified wells to improve the quality of pumped water. The major concepts of well modification are: 1) seal off aquifer zones of known poor quality water, and 2) eliminate cascading of poor quality water from the upper aquifer to the lower aquifer. Typically, a steel casing liner is installed and cemented into place using pressure grouting techniques. Other techniques that may work in some situations include: 1) installation of a cement plug in the filter pack to prevent downward movement of contaminated water through the well bore, 2) patching breaks in the well casing through which water is cascading, 3) deepening wells, 4) resetting pump bowl depths, and 5) redeveloping wells. Well modification can be used to lower the concentration of any contaminant, but has been used most extensively in Arizona to remediate nitrate problems.

Phoenix recently completed a pilot well modification program in which three wells that exceeded the nitrate MCL were modified. Test pumping is now underway to determine the effectiveness of the modifications in lowering nitrate concentrations to within the drinking water standard. If the program proves successful and cost-effective, more Phoenix wells will be

considered for modification, provided well and aquifer characteristics are favorable. It shoul be noted that well modification may only be a temporary fix to a water quality problem. Continued vertical migration of poor quality groundwater that is related to a regional sourc of contamination or regional groundwater flow patterns may, over time, overcome the wate quality improvements gained through modification. However, well modification is relatively inexpensive compared to other remediation options, and can be an appropriate alternative fo older wells with a limited useful life that are pumped infrequently as a backup supply sourc

Wellhead Treatment

Various physical and chemical wellhead treatment processes are effective in dealing with th range of organic and inorganic contaminants limiting groundwater use. Phoenix investigate ion-exchange treatment as a potential strategy for treating wells high in nitrate. A treatment plant was designed to treat water from the four wells located near the Deer Valley Wate Treatment Plant. A decision was made not to construct the system due to the estimated co of $4 million, and to implement the lower-cost well blending plans. Phoenix currently has no active production wells with operating wellhead treatment units. However, wellhead treatmer remains a viable strategy that may be used for high priority Phoenix wells whose operatio must be maintained, and where cost is a secondary consideration.

## Well Drilling and Remediation Action Plan Summary

Phoenix' overall approach to increasing groundwater production capacity over the next eigh years is to: 1) drill new wells in areas with no known land use history that could result in contamination of the aquifer, and 2) attempt first the lowest-cost alternatives for solving wate quality problems at inactive wells. Initially, efforts will focus on wells affected by nitrates an chromium, using a combination of well modification and well blending techniques. This decision was based largely on the following per well cost estimates for the remediatio alternatives:

Well Modification - $75,000 to $150,000
Well Blending - $150,000 to $250,000
Ion-exchange Treatment - $1,000,000
New Wells - $600,000 to $1,000,000

Wells impacted by organic pollutants will be addressed at a later date if additional well capacit is needed, and if remediation can be accomplished in a cost-effective manner. Because of it high cost, wellhead treatment for organic chemical, nitrates, or chromium will be considered as a last resort after other remediation alternatives have been investigated.

As a first step in the well program, inactive wells have been prioritized for remediation efforts based on production capacity, value to the water system operation, condition, construction details, age, water quality characteristics, and wellsite characteristics. High priority wells will be evaluated in more detail and decisions made on which alternative to pursue. About six inactive wells have been targeted for abandonment to date. Decisions to abandon others may be made following more study. As part of the prioritization, wells were evaluated regarding the potential for non-potable uses and trades or exchanges with non-potable water users.

## Dealing With Contamination: Decision Factors

The strategies a municipal water provider will choose to mitigate groundwater contamination problems will depend on its unique situation. Factors that will affect the decision include:

- The Extent of Aquifer Contamination: Is only small portion of the provider's service area underlain by contaminated groundwater or is the area of impact extensive?
- Water System Hydraulics - Will the water system accommodate wells in new locations? Are there other sources of water (i.e., surface water) available to the provider?
- Capital Improvement Program (CIP) budget priorities - How much money is available to solve the problem? Are there more pressing needs for available funds?
- Wellsite Constraints - Is there enough space at wellsites to accommodate reservoirs, treatment systems, or drilling rigs? Will the neighbors object to noise or visual impacts?
- Regulatory Concerns - What water quality, air quality, and noise standards and policies constrain alternatives?
- Public Concerns - What are the public's attitudes and expectations regarding water quality and exposure to chemicals?
- Media Attitudes - Does the media have a bias for or against certain alternatives?
- Politics - What are the local politics surrounding water quality decisions? Remember: City Councils ultimately determine the course of action!

## GROUNDWATER QUALITY TRENDS AND FUTURE IMPACTS

In the coming years, many municipal water suppliers in Arizona and elsewhere will be forced to, at least temporarily, remove wells from service because drinking water standards are not met. Two trends are at work here. First, new and more stringent water quality standards are being enacted all the time, with little relief on the horizon. The upcoming Radon and Arsenic MCLs are good examples of new standards that will result in the inactivation of many public supply wells across the U.S. Second, contamination within the aquifer is widespread, and contaminants are moving in response to groundwater flow gradients that are often dominated by municipal groundwater pumping. These trends suggest that virtually all existing and new public supply wells will, at some point in the future, require some form of remedial action to meet drinking water standards and maintain service levels.

With these trends in mind, is aquifer restoration (i.e., clean-up of known contaminant plumes to prevent future impacts to public water supplies) a meaningful concept for those now involved in municipal water supply planning? The answer may be a moot point. Expensive wellhead treatment systems will probably be required for most wells in the future regardless of whether EPA Superfund and state WQARF projects are effective in "cleaning up" the aquifer. Many groundwater scientists believe that some major contaminant plumes may require fifty to one-hundred years or more to clean up, or the chemical release may never be fully recovered. Thus many existing and new municipal wells may be affected by pollutants long before clean-up is achieved. Well system planners should attempt to minimize and delay the financial impacts of future remedial actions on production wells through the following strategies:

1) Locate new wells as far away from known contaminant sources as possible.

2) Design new wells with present and future water quality conditions in mind.

3) Plan wellsites to accommodate future wellhead treatment units, well modification equipment, or well blending facilities.

4) Consider a stepped approach toward well improvements, starting with the least-cost alternative, particularly when working with older wells.

5) Implement a "wellhead protection" program to minimize the potential for additional contamination of critical aquifer areas.

6) Manage groundwater withdrawals to contain known contaminant plumes.

# Part II

# WATER QUALITY SAMPLING: SOME CRITICAL PROBLEMS AND POSSIBLE SOLUTIONS

# Under Developed Monitoring Wells[1]
# How Representative Are Your Samples?

*by Gary L. Hix, R.G., CWD/PI* [2]

**ABSTRACT:** The author presents a working hypothesis that many of our existing monitoring wells do not yield values that are representative of the aquifers they penetrate. Yet our interpretations of depths to water, natural water quality, and the extent of contamination present in these wells are routinely used to determine the fate of large tracts of real property, who is and who is not a potentially responsible party, and the health of our future generations. Most monitoring well development methods are an extension of techniques developed for the water well industry. These same methods are being applied to monitoring wells, often without realizing their ineffectiveness in this vastly different environment. Physical limitations of the available equipment, plus constraints put on the environmental consults by the property owners and regulatory agencies, limit our ability to do a thorough job of well development. New equipment is being developed and marketed that will make developing small diameter monitoring wells easier. The latest in monitor well development equipment is reviewed, and a plan for scientifically testing the author's hypothesis is proposed.

One of the emerging critical issues regarding ground water in Arizona and the Southwest is water quality. In areas where we suspect the natural water quality has been compromised, we've installed monitoring wells to sample and test it. It's the author's contention, however, that maybe half of the monitoring wells being drilled, constructed, and sampled today do not yield values that are truly representative of the aquifers they penetrate. Yet our interpretation of depths to water, natural water quality, and extent of contamination present in these wells is used routinely to determine the fate of real properties, responsible parties, and the health of our future generations.

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[1] Paper presented at the Sixth Annual Symposium of the Arizona Hydrological Society, Casa Grande, Arizona, September 23-24, 1993.

[2] Gary L. Hix is a Registered Geologist in Arizona and California and a NGWA Certified Well Driller and Pump Installer. He is owner and operator of Saguaro Environmental Services Co.

A monitoring well should be a transparent, omni directional window into an aquifer that allows a ground water scientist to see and sense the subsurface environment without physically entering it. It would be great if we could get our eyes down to the bottom of brand new monitoring well and look out through the screens while we take our first water quality samples. If we could, we might be surprised to see only the inside of a long cylinder, several inches in diameter filled with fine grained sand pack mixed with mud and silt, and backed by a shell of clay. This cylinder referred to is the borehole filled with filter pack, and the clay shell is the mud cake and/or borehole damage we created while drilling it.

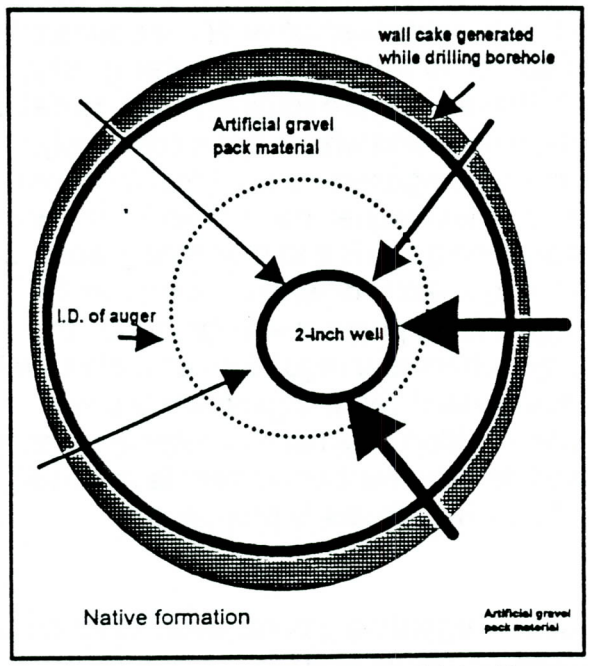


Figure 1. Monitoring well constructed slightly off center in the borehole to illustrate how one side of a well could be more thoroughly developed than the other.

Because we don't have eyes down in the well when we sample it, we can't see where the recharge is coming from, If we could, we might observe that recharge into the well during purging and sampling is entering the borehole radialy, and vertically, through preferentially developed zones in the clay shell. Once inside the shell, recharge must fight it's way through a fine grained sand pack partially blocked with silts and clays in order to enter the well casing through some very narrow slots. Yet it's sometimes assumed that one or two rounds of hand bailed samples from these wells gives a representative value of the aquifer's water quality for tens of feet from the well in all directions.

The author has participated in the drilling and development of many of these shallow depth monitoring wells. He has noted the unusually low well yields, and has heard from consultants the results of water quality values they have obtained over time. Surprisingly, a rather large number of small diameter monitoring wells constructed in shallow fine grained perched aquifers test contaminate free at first, but increase in levels over time. One obvious conclusion from the data is that the monitoring well was installed just in front of an advancing plume, and now the plume surrounds the well. But is this interpretation correct? Other explanations frequently given are laboratory error, cross contamination from another well carried with the sampling equipment, or outside influences from an unknown source.

Varying degrees of effort are spent on monitoring well development, depending upon the geologic formation, contaminates, project budgets and the drilling method used. It's the author's belief that fine grained materials are often left behind on the borehole walls and in the gravel pack that prevent or inhibit the free entry of water from all quadrants over the entire screened interval. These restrictions produce lower well yields and muddy water samples that are not representative of the aquifer. Subsequent sampling rounds with gradually increasing contaminate levels from these monitoring wells could be attributed to the fact that this new monitoring well is at last coming to equilibrium with it's environment, months, or even years after it was first installed.

It's the fine grained clayey shell generated while drilling the borehole which is not totally removed during the initial development that causes the greatest problem. It reduces well productivity, limits recharge, and skews water quality analyses. Eventually the clay shell breaks down, and the remaining silt in the sand pack is flushed out during subsequent purging and samplings. Admittedly this theory is not based upon defensible scientific data generated under controlled conditions. It's a hypothesis. One drawn, however, from several years of drilling, constructing and developing monitoring wells. If the author's hypothesis is correct, it may mean that many of our existing monitoring wells did not yield data that was truly representative, at least not initially. There may be other explanations for the apparent changes in values as well. Each project and each well is unique to that particular situation and all possibilities must be considered.

Never-the-less, if there's validity in the theory, the issue may become one of ever increasing importance in future years. Many past conclusions were drawn, and important decisions were made, based upon a few quick samples collected from monitoring wells of this type. As the evidence accumulates substantiating changes in water quality from monitor wells like these, a greater respect for the importance of through initial monitor well development will emerge. After a brief discussion of current well development practices, some previous investigations on the subject, and some personal perceptions about the effectiveness of various well development methods, the author proposes a means of testing his hypothesis.

**Our Perspective May Be "Out of Scale"**

The hydrology and well drilling text books we all studied and learned our trade from illustrated typical well development tools with exaggerated scale drawings. These drawings illustrated powerful movement of ground water around sand and gravel particles just outside the casing during development. We carried this perception over into monitor well development practices. The limited forces that we can generate inside a small diameter monitoring well, however, may not be as effective as they were in the much larger water wells.

Consider how difficult the task of properly developing a small diameter monitoring well is. We must physically reach perhaps a hundred feet or more down to the bottom of a two or four inch diameter well, out through 6% to 10% open area, through several inches of fine sand or gravel pack, reach the farthest edges of the borehole and physically remove a quarter to half an inch of mud cake to repair formation damage caused by the drilling. Let's further assume that there's only 15 to 17 feet of water in the bottom 20 feet of this one hundred foot deep monitoring well (assuming that the screened section straddles the water table).

Try to imaging the physical forces a contractor might be able to exert on the edge of the borehole while he's either pushing or pulling small quantities of ground water through the slots of the casing, plus through two to three inches of fine grained gravel pack. Remember too that the gravel pack was placed by gravity below the water table inside a slurry of mud and water generated during the drilling. If fresh water was not used to pump the sand pack into place, the sand pack is thoroughly mixed with a thick clay slurry left in the bottom of the borehole.

**More Difficult to Develop by Design**

As explained and illustrated above, monitoring wells are by design more difficult to develop than water wells. They are smaller in diameter than water wells, plus they typically will have very little saturated depth (a few tens of feet of water) compared to their total depth. They are often made of fragile PVC or Teflon ®. If this fifteen feet of saturated interval is a hundred feet down in a tight formation, it's not hard to see why it's a difficult task to develop these wells without damaging them. If the formation produces very little water to begin with, through development of wells like these can be a very slow and tedious process.

Many of the traditional well development methods gave little consideration to a monitoring well's basic design (small slot sizes, fine grained gravel packs, low submergence ratios, fragile materials, etc.) and not producing any more by-products than absolutely necessary. Added to these physical problems is the financial constraint of not wanting to spend too much time or budget working with a given monitor well. Whereas extra development time spent on a production water well can be justified in lower operating costs.

**Most Water Well Development Methods are Ineffective**

Bailers are frequently used as monitoring well development tools. Bailers and surge blocks are typically run on a cable, falling by gravity and pulled upwards with a winch. Physical agitation is supposedly provided by

movement of the surge blocks, while fluid and suspended sediments are removed with the bailer.

Surge blocks of various designs have been described and illustrated in well development literature. Schalla and Landick presented two unique prototype surging tools designed especially for monitoring wells (Schalla, 1986). Apparently, neither of these tools went past the development stage. The most common tools in use today are not much more than single swabs with insufficient mass to fall rapidly down through the water, getting only a moderately quick upward pull. How much force is generated on the borehole wall by this method is limited to how quickly the equipment and well design allows the tool to fall, and how quickly a contractor is willing to raise it.

A contractor must be very careful when working inside a plastic monitor well with a heavy steel bailer. Sand pump bailers can easily be stuck inside the narrow confines of a monitoring well by burrowing their way into sediments on the bottom. Dart valve bailers can knock the bottom out of a plastic well. Sticking a surge block inside a crooked well, plus the fear of breaking the screen if something gets dropped on top of the surge block, are two reasons contractors must be gentle when using these tools. Contractors work a lot by feel and past experience. When a contractor "feels" that a given section has been properly worked, the surge block is removed and the bailer sent in to remove the dirty water. In order to save time switching tools, some contractors will use a snug fitting bailer for both surging and bailing. The effectiveness of this method in breaking down wall cake is questionable.

A technical discussion of the forces that can be generated by bailers and one and two ring surge blocks can be found in the Roscoe Moss Handbook of Ground Water Development (Moss, 1991). This discussion, however, is primarily the results of laboratory and computer modeling studies. To the author's knowledge, these forces have never been physically measured inside either water wells or monitoring wells. How powerful, and therefore how effective, this surging action actually is at the edges of the borehole wall is the real question.

Another very real world limitation of using mechanical tools alone for developing monitoring wells is the length of time required to do a thorough job. The volume of water that can be removed with a dart valve bailer in a given time period is relatively small compared to most pumping methods. It's also difficult to remove all the suspended fines with the strictly mechanical method. Wells developed in this manner are re-muddied while purging and sampling with hand bailers because of the fine grained materials that have settled to the bottom of the well. Surging and bailing alone is not sufficient to develop some monitoring wells, yet a few hours of this action is all some wells receive. This could explain

why so many of them that have been developed this way yield muddy samples and changing analytical values for several months.

**Pumping and Over Pumping**

Over pumping has been used to develop water wells for decades. It's a different situation when developing monitoring wells. Two inch diameter monitoring wells don't allow much room for pumps with sufficient capacities to develop them by over pumping. One manufacturer, Grundfos, makes the variable speed Redi-flo2 ® submersible electric pump with good capacities that will fit in a 2-inch well. However, it wasn't meant to be used for well development. There are a couple of 3 inch diameter submersible pumps on the market also, but using them for well development is not a factory recommended practice either, and it will certainly void the warranty. Goulds has recently introduced a variable speed 4-inch diameter submersible pump, but the author knows of no one who is using it for well development. The "real world" situation is that a constant speed 4-inch submersible pump is carefully placed inside a 4 inch monitor well and held back by a manually operated ball or gate valve. This equipment works as long as the well casing is Schedule 40 PVC. Wells made of Schedule 80 PVC, whose ID measures 3.82 inches, are too small for 4 inch submersible pumps. This makes use of a bailer, or 3-inch pump mandatory.

Mc Ilvride and Weiss documented what dramatic effects drilling methods can have on well performance, and how difficult it can be to remove wall cake or clay smear from a borehole (Mc Ilvride, 1988). James Gibb presented one of the earliest discussions on what affects sampling methods have on water quality samples and the debate continues (Gibb, 1987). A National Symposium on the topic of ground water sampling held in Washington D.C. in November, 1992 presented the results of several new studies on the subject of sampling, but nothing new on well development methods (Grundfos, 1992). Meredith and Brice warned of the negative effects high entrance velocities can have on water quality samples when pumping small diameter monitoring wells (Meredith, 1992). They recommend low pumping rates for purging and sampling where entrance velocities do not exceed 0.3 ft/s.

**Over pumping can be a very effective way to develop a monitoring well if** your not limited to pumping 55 gallons of water. The cost of testing and disposing of well development water can easily exceed the cost of producing it. Limited submergence and fine grained formations that yield very little water often mean that the development pump must be held back to prevent it from breaking suction. Operated in this manner, a submersible electric motor doesn't get proper cooling from water flowing past it, and can easily be burned up. In the "real world" manufacturer's equipment warranties don't apply to pumps used for monitoring well development because of the way they're operated. Contractors who use them for monitor well development simply expect to sacrifice a pump and motor now and then.

## Surging, Air Lift Pumping

Monitoring wells often have a portion of their screen section exposed above the water table, a design which allows for changing static water levels and floating contaminates to enter the well. Air pressure at the bottom of the pipe in a well is proportional to the depth of submergence. When compressed air is vented at the bottom of a well, some of it has to enter the gravel pack before the expanding bubble exits the well. Any attempt to introduce air into the well casing to "blow", "unload" or otherwise air lift develop the well will introduce unwanted air into the gravel pack and surrounding formation. Small micro-bubbles of air can be trapped inside the gravel pack and may never escape. What level of confidence can be attached to water quality samples taken from a monitoring well that has a cylinder of tiny air bubbles trapped in the gravel pack surrounding the well screen?

Some contractors have had limited success using a dual pipe, or eductor, method of air lift development. The eductor pipe is lowered to near the bottom of a well. Using an airline, either suspended inside or attached outside, large volumes of air are released at the bottom of a pipe whose diameter is smaller than the ID of the well casing. Air rising inside the eductor pipe lifts water and sediments from the well without getting air into the screens or gravel pack. Eductor pipes capability to lift water are greatly diminished with high submergence to lift ratios. Considering the depth to water and limited saturated intervals in most monitoring wells, this practical water well development method is not ideal either.

## Washing and Jetting Methods

Early water well construction and development handbooks illustrated how the jetting technique can be used to flush fine grained material from the gravel pack. Various jetting tool designs can still be found in recently published reference books. The method can be very effective at removing mud cake and formation damage, especially at the top of the screens, as long as large volumes of water can be injected into the well. Many regulators, however, express grave concerns about introducing any water, materials or other products into a monitoring well. Stating that if a given quantity of water is introduced during development, two to three times this amount should be extracted before a valid water quality sample is taken.

Finding a source of clean water, plus the cost of testing and disposing of the additional volumes of purge water, severely limits the application of this method. Jetting with water from an outside source may never become an EPA approved method of developing monitoring wells because of these concerns, even though it may be the most effective method of removing wall cake.

In water well manuals jetting tools are shown being rotated, plus raised and lowered throughout the screened interval. These references also gave us tables showing the discharge pressures necessary to obtain jetting action at a given submergence. These pressure requirements can be as high as a couple of hundred pounds per square inch. Water injection rates can be a few tens of gallons per minute. Jetting with water and air is also performed in water wells, but for obvious reasons it's never used in monitoring wells. Despite the exaggerated scale drawings showing how well this method works, real world limitations on working room inside a typical monitoring well, plus disposal of large quantities of purge water, a practical application of this technique for monitor well development has not come forward.

Dougherty and Paczkowski presented a way to minimize fluids produced while jetting a monitor well (Dougherty, et.al., 1988). They showed how both a submersible pump and a jetting tool could be put into the screened section of a well, one on top of the other. With both of these tools in the well at the same time, water was primarily recirculated, with only minor amounts pumped to waste. No new water was introduced. The concept of jetting a monitoring well with it's own water sounds like a good one, if it can be made to work. This design appears to be a practical one for jetting small diameter monitoring wells, however, no one is currently manufacturing a tool of this design.

Flatwater Fleet has introduced a line of jetting nozzles for developing the screens of environmental and water wells. They're available in sizes from 2-inches in diameter on up, and are customized sized for jetting at varying velocities. Having off the shelf ready made tools for this development method could help bring this most efficient of well development methods to some form of practical application for monitoring wells.

**Vacuum Purging and Pumping**

One method of pumping environmental wells that has not been applied to water wells is vacuum pumping, a purging technique for monitoring wells used described by William Schaal (Schaal, 1992). Schaal claims that in California small diameter monitoring wells are regularly being vacuum purged prior to sampling. According to Schaal, vacuum purging continues to produce a cost savings over more conventional methods. Very low yielding wells can be vacuum purged and pumped without burning up submersible pumps, or spending a great deal of time with bailers. Schall has stated that the same technique can also be used to develop or rehabilitate monitor wells.

In this method the vacuum is supplied by a large vacuum truck, or specially designed high volume portable units. A "stinger" is dedicated to each well and stored within it when not in use. Stingers are most often made from 1

inch diameter PVC pipe. The stinger is connected to the vacuum hose and slowly lowered to within an inch or so of the water surface. Water is not lifted as a solid stream, but as a mist of water and air. According to Schaal, both air and water are pulled from the well as long as the stinger chatters with a characteristic "twitch." As the water level decreases, the stinger is lowered into the well to maintain optimum pumping. If the stinger is lowered to quickly, the twitching ceases, and the vacuum pumps begins to over rev. According to Schaal, removing 15 feet of standing water from a 25-foot deep 4-inch diameter well requires 5 to 8 minutes. Cost and availability of large vacuum trucks, plus the requirement to get the purge water out of the vacuum truck rather quickly, could limit use of this technique locally.

**Reverse Circulation Air Lift Pumping**

One tool that was designed specifically for developing monitoring wells is the Aqua Developer ® by the Aardvark Corporation. It was invented and introduced by Thomas Nuckols, and further described by Mike Craig (Nuckols, 1990, Craig, 1991). The Aqua Developer is a combined reverse circulation air lift pump, and surge block tool designed specifically for developing or rehabilitating 2, and 4-inch diameter monitoring wells. It works in reverse of most air lift pumping methods, which nets a tremendous savings in the volume of air required to operate it. This air lift pumping device removes drilling muds, foam, and fine grained material that may have settled to the bottom of the well, almost like a vacuum sweeper. Because this tool has no moving parts, it can lift and remove even coarse sand from the well without fear of locking up. Once the well has been cleaned to bottom, the open bottom tool is removed and replaced with the surge block development tool, which has a perforated intake section straddled by two rubbers rings. Figure 2 illustrates how the surge blocks and perforated intake section works inside a 4-inch monitor well.

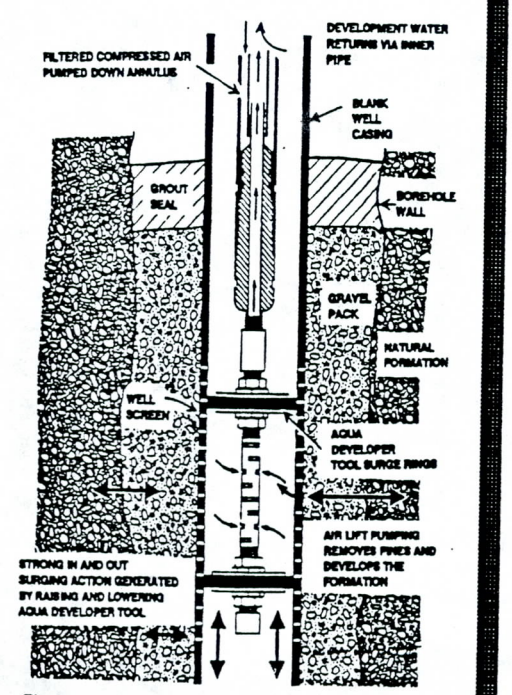

Figure 2. The Aardvaark Aqua Develooper inside a 4-inch diameter monitor well.

The surge block tool is typically raised and lowered using a pump hoist while it's operating. In and out movement of ground water through the gravel pack ( to what ever extent this is possible) is generated by the up and down motion of the surge blocks. Air lift pumping from between the surge rings removes fines while they're still in suspension. Because the surge blocks isolate small sections of screen, it's

possible to differentiate more productive zones from less productive zones. Discharge from the reverse circulation dual wall pipe is diverted through a mud cyclone. The cyclone vents the compressed air upwards while water and sediments fall into a bucket or drum. Flow rates can be measured, as can development progress. When used inside 4-inch wells, pumping water levels can be measured while air lift developing. This tool is readily available through the Aardvark Corporation, but it's mostly all stainless steel construction makes it one of the most expensive.

### Testing the Hypothesis

The author proposes testing his hypothesis by constructing several test wells within a large diameter pit that has been lined and backfilled with specified geologic materials, and saturated with known concentrations of a tracer representing contaminates. The test pit would be lined with an impervious material similar to that used to line landfills, plus a layer of bentonite clay on the bottom to be used as a marker bed indicating the bottom lining was nearby. Opposite sides of the pit would be fitted with large diameter wells used to inject water and maintain proper levels during the pumping tests. Several monitoring wells, to be used as baseline and control checks, would be constructed as the pit was backfilled and compacted. Figure 3 illustrates a possible layout and design of such a test pit.

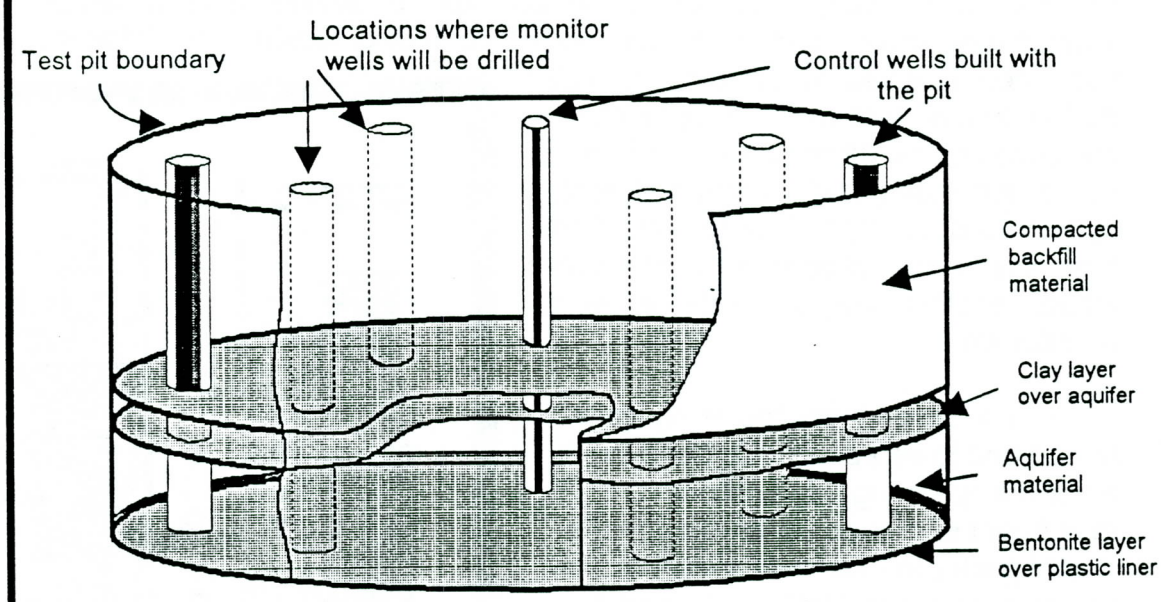


Figure 3 Drawing of proposed test pit with control wells and possible locations for drilling new monitor wells.

When baseline paramaters have been established in the control wells, various drilling methods would be used to drill monitoring wells within the test pit boundaries. Productivity and water quality results obtained from the newly drilled and constructed wells would be compared to the base line values.

By constructing wells within the confines of a lined test pit, control of many otherwise unknown field parameters can be maintained. Results obtained from the newly drilled, constructed and developed wells would be compared to results obtained from control wells. Tracers of known concentrations could be introduced into the aquifer surrounding the test wells at various levels and from different quadrants.

The extent of formation damage caused while drilling with various methods inside the pit could be directly observed and measured. Boreholes could be drilled through dense clays, and wells could be made in formations of, known hydrologic characteristics during the proposed investigation. Wells could receive different levels of development. Efficiencies of wells that are not fully developed should be lower than the efficiencies of control wells. Wells that were not fully developed might yield lower values of tracer contaminates. Analytical values obtained from the test wells that are different than the concentrations of tracers introduced into the pit (and recorded by the control wells) would reflect losses caused by either the drilling method or inadequate well development.

## SUMMARY

If test results confirm the author's hypothesis, then decisions based upon interpretations of some earlier analytical results may have to be re-evaluated. A valuable insight into the validity of our present practices could be obtained from such a study. Resolution of this issue may become one of the more critical issues in Water Resources of Arizona. The author invites comments, discussion, criticism and suggestions regarding implementation of the proposed field investigation.

## REFERENCES


Craig, M. 1991. Developing Monitoring Wells, Ground Water Age, Volume 25, No. 10.

Dougherty, P. J. and M. Paczkowski. 1988. A Technique to Minimize Contaminated Fluid Produced During Well Development. Proceedings of Second National Outdoor Action Conference, pp. 303-317.

Gibb, J. P. 1987. How Drilling Fluids of Grouting Materials Affect the Integrity of Ground Water Samples from Monitoring Wells, Ground Water Monitoring Review, Winter, 1987. pp. 33-42.

Grundfos Pumps Corporation, 1992, Proceedings of National Ground Water Sampling Symposium, Washington, DC. November 30, 1992. 111 p.

Iles, D. L., P. Hammond, and L. Schulz. 1992. Effects of Sampling Methods on Inorganic Water Chemistry Results, Proceedings from National Ground Water Sampling Symposium, Washington D. C. November, 1992. pp. 41-68.

Meredith, D. V. and D. Brice. 1992. Limitations on the Collection of Representative Samples From Small Diameter Monitoring Wells, Proceedings of Sixth National Outdoor Action Conference, pp. 429-439.

Mc Ilvride, W. A. and R. Weiss. 1988. Drilling Method Effects on Well Performance, Proceedings of Second National Outdoor Action Conference, pp. 277-287.

Nuckols, T. E. 1990. Development of Small Diameter Wells, Proceedings of Fourth National Outdoor Action Conference, pp. 193-207

Roscoe Moss. 1991, Handbook of Ground Water Development. Roscoe Moss Corporation.

Schaal, W. 1992. Is Well Purging with Vacuum A Reliable Cost-saving Technique When Testing for Volatile Organic Compounds? Proceedings of Sixth National Outdoor Action Conference, pp. 401-412.

Schalla, R. and R. W. Landick. 1986. A New Valved and Air-Vented Surge Plunger for Developing Small Diameter Monitor Wells. Ground Water Monitoring Review, Spring, 1986. pp. 77-80.

# PRIORITY POLLUTANT SAMPLING IN THE PIMA COUNTY NPDES STORM WATER PROGRAM[1]

Byron McMillan and David Barraza[2]

ABSTRACT: Pima County submitted Part II of its National Pollution Discharge Elimination System (NPDES) Storm Water Permit Application on May 17, 1993. This paper describes the storm water sampling and monitoring programs developed to meet the application requirements.

Sampling stations identified in Part I of the permit application, representing five different land use types, were sampled during the 1992-93 winter storm season. A total of nine samples were collected representing two different storms more than thirty days apart. An identical sampling and measurement regime was implemented at each site that included runoff measurement, field parameter analysis, grab and flow-weighted composite sampling, and sample preparation for total and dissolved pollutant analysis. Samples were analyzed for organic and inorganic species, nitrogen forms, total chlorine, coliform, oxygen demand, and phenolics. The presence of priority pollutants within the Pima County Municipal Separate Storm Sewer System (MS4) permit area was confirmed by sampling results and pollutant loads were calculated. Results indicated significantly higher total suspended loads than dissolved loads for several pollutants.

Sampling will continue during the next year at representative land use outfalls including a non urban site which will represent an uncontaminated background sample. Two samples each from two different storms (at least thirty days apart) will be obtained at each of the sites during the summer (monsoon) and winter storm seasons. Two quality control (field blank or field duplicate) samples will also be collected for a total of thirty samples. In addition to wet weather sampling, dry weather sediment sampling will be implemented down-gradient of each of the sampling stations to investigate residual and insoluble pollutant levels in the soil. The sampling program will be carried out for at least five years, the term of the permit.

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# INTRODUCTION

Pima County has collected characterization data and proposes a monitoring program to accomplish three ends: (1) to provide the information necessary to meet Part 2 permit application requirements; (2) to develop data compatible with water quality data collected in the southern Arizona region by other agencies, including the City of Tucson, the Arizona Department of Water Quality, and the U.S. Geological Survey; and (3) to contribute to the continuing national effort to assess the potential impacts of storm water runoff to the nation's waters.

## Estimates Of Event-Mean And Annual Pollutant Loads

### Description Of Sampling Stations

Pima County sampled storm events at five locations or sampling stations. These stations are described in detail in the Characterization Plan submitted for the Part 1 permit application, along with the criteria used in their selection. Each drainage is dominated by a single type of land use, specifically: low, medium, or high density residential; commercial, or industrial land use. It should be emphasized, however, that no data are available to indicate whether pollutant discharge patterns for these drainages are statistically typical for their dominant type of land use for the Permit Area as a whole. Plan views of the five drainages were presented in the Characterization Plan submitted for the Part 1 Permit Application.

Descriptive data on the drainages discharging at all five stations were field checked and revised for accuracy during development of this Part 2 application; impervious surface areas were directly measured.

### Description Of Storm Events

Pima County sampled two storm events each at four of the five sampling stations and one storm event at the fifth station during the period June 1, 1992 - April 1, 1993, for a total of nine sampling events. Unanticipated delays in initiating sampling resulted in the County not collecting samples during the Summer, 1992, storm season. Further delays during Fall, 1992, resulted in the County not reaching full readiness to collect samples until late January, 1993. All storms sampled for preparation of this Part 2 application occurred in February and March, 1993.

Table 1 summarizes the methods used to gauge outfall flow at each of the five sampling stations.

Table 1 Hydrograph Gauging Methods, Outfall Sampling Stations

| Station | Gauging Method | Gauging Method Comments |
|---|---|---|
| 1 | Bucket & Stopwatch | 20.5 / (0.0205 $m^3$) bucket standard for timing |
| 2 | Stage:Discharge Rating | Trapezoidal-section open channel, poured concrete, top width = 7.19 *m*, bottom width = 3.35 *m*, side slope (horiz/vert ratio) = 1.1, *n* = 0.015, bottom slope = 0.002 |
| 3 | Stage:Discharge Rating | Circular-section concrete pipe, diameter = 0.914 *m*, *n* = 0.014, slope = 0.0306 |
| 4 | Stage:Discharge Rating | Circular-section concrete pipe, diameter = 1.676 *m*, *n* = 0.014, slope = 0.0166 |
| 5 | Stage:Discharge Rating | Triangular-section open channel, asphalt pavement, top width = 20.0 *m*, bottom width = 0.0 *m*, side slope (horiz/vert ratio) = 12.97, *n* = 0.013, bottom slope = 0.031 |

Characterization Data By Sampling Station And Storm Event

Pima County collected and analyzed samples for all water quality parameters required under 40 CFR 122.26(d)(2)(iii)(A)(3). Additionally, Pima County collected and analyzed samples for a wide range of additional water quality parameters, to allow more detailed comparisons of the analytical results with data commonly collected for surface and ground water in the region. In particular, Pima County recorded field measurements of dissolved oxygen concentration and electrical potential for all grab samples; added several elements and ions to the list of inorganic analytes; and analyzed the composite samples for both total and dissolved concentrations for all inorganic analytes for which such separate analyses were possible. The analyses for dissolved inorganic constituents were carried out on fractions of the inorganic analyte composite sample filtered through a 0.45 $\mu m$ filter. Finally, as a further experiment, Pima County analyzed two composite samples for total vs. dissolved semi-volatile organic compounds and pesticides (EPA Methods 625 and 608), specifically samples 93-3-0326 and 93-4-0326. The analyses for dissolved organic constituents were carried out on fractions of the organic analyte composite sample also filtered through a 0.45 $\mu m$ filter.

The analyses for both total and dissolved concentrations were carried out to determine what fraction of each constituent was being transported in dissolved form vs. as suspended particulate matter or adsorbed to suspended particulate matter. All receiving waters for the County MS4 are ephemeral streams. Suspended pollutant loads thus become part of the stream bed material whenever the streams become dry, and can then be remobilized either as dust or as suspended matter during subsequent storm events. Pima County recognizes that the ecological and human health risks posed by different pollutants will vary depending on the phase and physical mechanisms of their transport. The County therefore has recognized the need to distinguish between dissolved and suspended pollutant loads for purposes of developing its storm water management program.

Pollutant Detection's

The following is a list of pollutants detected for all water quality parameters required to be monitored under 40 CFR 122.26(d)(2)(iii)(A)(3); Oil and Grease, Fecal Coliform, Fecal Streptococcus, Total Phenols, Antimony, Arsenic, Cadmium, Chromium, Copper, Lead, Zinc, Bis(2-ethylhexyl) phthalate, Chrysene, 2-chlorophenol, Di-n-butyl phthalate, Fluoranthene, Methyl Chloride, Phenanthrene, Pyrene, Toluene, Total Suspended Solids, Total Dissolved Solids, Chemical Oxygen Demand, Biological Oxygen Demand, Total Kjeldahl Nitrogen, and Total Nitrate + Nitrite Nitrogen. The detection of toluene is suspected to be the result of laboratory contamination. The list of detected parameters is similar to the list of compounds identified in at least 10% of all samples during the Nationwide Urban Runoff Program or "NURP" (Results of the Nationwide Urban Runoff Program, Volume I, Final Report, EPA 1983), with the most notable exception that no pesticides were detected in the Pima County samples. The City of Tucson obtained detection results very similar to the Pima County results, including similarly failing to detect priority pollutant pesticides (City of Tucson Part 2 Storm Water NPDES Permit Application for EPA Region IX, November 1992).
The sampling station for commercial land use (Station 4) had the greatest number of detected parameters and the greatest number of detection events among all sampling stations. Concentrations of several parameters were consistently higher in the commercial land use station samples than in the samples from any other station, including concentrations for coliform and streptococcus bacteria, TDS, all nitrogen forms, and copper (see Table 2, below). Fecal streptococcus concentrations at the commercial station were especially notable, exceeding 16,000 *NTU*/100 *ml* in several grab samples. Second highest concentrations for most parameters were observed in the high density residential land use station samples (Station 3).

Table 2 Event-Mean Concentrations and Standard Deviations

| | | Measured Storm Event Concentrations, mg/l | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Parameter | Land Use | PC | PC | CT | CT | CT | Mean | Std.Dev. |
| BOD5 | IND | 15 | | 23 | | | 19.000 | 5.657 |
| | COM | 37 | 38 | 7 | 15 | 11 | 21.600 | 14.792 |
| | LDR | 4 | 21 | 17 | 23 | 10 | 15.000 | 7.906 |
| | MDR | 10 | 39 | 9 | 0 | 17 | 15.000 | 14.714 |
| | HDR | 20 | 40 | | | | 30.000 | 14.142 |
| COD | IND | 130 | | 387 | | | 258.500 | 181.726 |
| | COM | 423 | 233 | 90 | 162 | 213 | 224.200 | 124.100 |
| | LDR | 72 | 130 | 287 | 189 | 105 | 156.600 | 84.530 |
| | MDR | 124 | 154 | 236 | 284 | 110 | 181.600 | 75.252 |
| | HDR | 374 | 150 | | | | 262.000 | 158.392 |
| TSS | IND | 266 | | 1073.3 | | | 669.650 | 570.847 |
| | COM | 90 | 160 | 65 | 70 | 160 | 109.000 | 47.487 |
| | LDR | 180 | 342 | 188 | 123.3 | 310 | 228.660 | 92.984 |
| | MDR | 58 | 166 | 110 | 316 | 320 | 194.000 | 119.474 |
| | HDR | 100 | 122 | | | | 111.000 | 15.556 |
| TDS | IND | 120 | | 140 | | | 130.000 | 14.142 |
| | COM | 334 | 208 | 82 | 110 | 112 | 169.200 | 103.736 |
| | LDR | 55 | 120 | 154 | 50 | 46 | 85.000 | 49.071 |
| | MDR | 94 | 226 | 130 | 56 | 80 | 117.200 | 66.462 |
| | HDR | 201 | 144 | | | | 172.500 | 40.305 |
| TKN | IND | 1.2 | | 2.5 | | | 1.850 | 0.919 |
| | COM | 2.9 | 5.3 | 1.6 | 1.4 | 5.6 | 3.360 | 1.996 |
| | LDR | 0 | 4.1 | 0.11 | 2.1 | 0.8 | 1.422 | 1.715 |
| | MDR | 1.6 | 8.1 | 2 | 0.6 | 0.5 | 2.560 | 3.163 |
| | HDR | 2.9 | 4.1 | | | | 3.500 | 0.849 |
| NO3/NO2 | IND | 1.9 | | 1.7 | | | 1.800 | 0.141 |
| | COM | 2.5 | 1.6 | 0 | 0 | 1.7 | 1.160 | 1.115 |
| | LDR | 0.6 | 1 | 2 | 0 | 0 | 0.720 | 0.832 |
| | MDR | 1.8 | 2.3 | 1.7 | 0 | 1.3 | 1.420 | 0.870 |
| | HDR | 2.1 | 1.6 | | | | 1.850 | 0.354 |
| P (total) | IND | 0 | | 1.35 | | | 0.675 | 0.955 |
| | COM | 0 | 0 | 0.08 | 0.46 | 0.34 | 0.176 | 0.211 |
| | LDR | 0 | 0 | 0.3 | 0.45 | 0.78 | 0.306 | 0.329 |
| | MDR | 0 | 0 | 0.5 | 0.34 | 0.87 | 0.342 | 0.367 |
| | HDR | 0 | 0 | | | | 0.000 | 0.000 |
| P (diss.) | IND | 0 | | 0 | | | 0.000 | 0.000 |
| | COM | 0 | 0 | 0 | 0 | 0 | 0.000 | 0.000 |
| | LDR | 0 | 0 | 0 | 0 | 0 | 0.000 | 0.000 |
| | MDR | 0 | 0 | 0 | 0 | 0 | 0.000 | 0.000 |
| | HDR | 0 | 0 | | | | 0.000 | 0.000 |
| Pb (total) | IND | 0.066 | | 0.13 | | | 0.098 | 0.045 |
| | COM | 0.035 | 0.03 | 0 | 0 | 0.044 | 0.022 | 0.021 |
| | LDR | 0.017 | 0.019 | 0.1 | 0 | 0.041 | 0.035 | 0.039 |
| | MDR | 0.035 | 0.042 | 0 | 0.018 | 0.016 | 0.022 | 0.017 |
| | HDR | 0.063 | 0.047 | | | | 0.055 | 0.011 |
| Cu (total) | IND | 0.053 | | 0.18 | | | 0.117 | 0.090 |
| | COM | 0.088 | 0.071 | 0 | 0 | 0.026 | 0.037 | 0.041 |
| | LDR | 0 | 0.035 | 0.09 | 0.012 | 0.022 | 0.032 | 0.035 |

Table 2 cont.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | MDR | 0 | 0.071 | 0.06 | 0.021 | 0.06 | 0.042 | 0.030 |
| | HDR | 0.039 | 0.061 | | | | 0.050 | 0.016 |
| Zn (total) | IND | 0.2 | | 0.35 | | | 0.275 | 0.106 |
| | COM | 0.26 | 0.745 | 0.08 | 0.11 | 0.231 | 0.285 | 0.268 |
| | LDR | 0 | 0.083 | 0.29 | 0.047 | 0.094 | 0.103 | 0.111 |
| | MDR | 0 | 0.147 | 0 | 0.184 | 0.15 | 0.096 | 0.089 |
| | HDR | 0.752 | 0.746 | | | | 0.749 | 0.004 |
| Cd (total) | IND | 0.0014 | | 0 | | | 0.001 | 0.001 |
| | COM | 0.0012 | 0.0017 | 0 | 0 | 0 | 0.001 | 0.001 |
| | LDR | 0 | 0.0006 | 0 | 0 | 0 | 0.000 | 0.000 |
| | MDR | 0.0006 | 0.001 | 0 | 0 | 0 | 0.000 | 0.000 |
| | HDR | 0.0008 | 0.0013 | | | | 0.001 | 0.000 |

NOTES:

IND: Industrial
COM: Commercial
LDR: Low Density Residential
MDR: Medium Density Residential
HDR: High Density Residential
Blank: no data
PC: Pima County
CT: City of Tucson

If reported value is ">" some value, then minimum value is shown;
if reported value is a "non-detect" or "<" the MDL or PQL, then assigned value = 0;
otherwise, reported value is given.

## Event-Mean Concentrations

Table 2 summarizes the data used to calculate event-mean concentrations for the twelve analytes for which the regulations specifically require such calculations. Data from the City of Tucson (City of Tucson Part 2 Storm Water NPDES Permit Application for EPA Region IX, November 1992) were used to supplement the Pima County data wherever feasible, since the Pima County data set includes information on a maximum of two storm events for each category of land use. The City of Tucson used slightly different land use categories in setting up its sampling design. The categorizations of the two municipalities were matched as follows: High Density Residential (County) = no equivalent (City); Medium Density Residential (County) = Multi-Family Residential (City); Low Density Residential (County) = Single Family Residential (City); Commercial (County) = Commercial (City); and Industrial (County) = Industrial (City). Between the County and City, data on a minimum of two storm events and a maximum of five events were available for analysis for each category of land use. Standard deviation values reported in Table 2 are sample standard deviations. The results shown in Table 2 indicate that event-mean concentrations are higher than the mean values found in the NURP for BOD, COD, TSS, and Nitrate+Nitrite; and lower than the NURP mean values for all other parameters (Results of the Nationwide Urban Runoff Program, Volume I, Final Report, EPA 1983).

## Estimated Annual Pollutant Loads

Annual pollutant load estimates for each category of land use are shown in Table 3. The estimates were calculated using the equation,

$$L_{i,j} = P_j C_f R_j C_{i,j} A_j \times 4.4853\text{E-}5$$

where $L_{i,j}$ = the annual pollutant load for pollutant $i$ in land use category $j$, in *tons/yr*; $P_j$ = the annual precipitation in land use category $j$, in *cm/yr*; $C_f$ = a correction factor for fraction of storms producing runoff, given the value of 0.9 here; $R_j$ = the weighted average runoff coefficient for land use category $j$; $C_{i,j}$ = the event mean concentration of pollutant $i$ in land use category $j$, in *mg/l*; $A_j$ = the area of land use category $j$, in *acres*; and 4.4853E-5 is a factor to correct for measurement units. In the absence of more detailed records, annual precipitation was assumed to be equal among all five land use categories at 30 *cm/yr*.

The area of each land use category within the permit area was calculated using 1986 Pima County Planning and Development Services data contained in GIS coverage (see Pima County Part 1 Permit Application, Discharge Characterization Plan, Table 1). Runoff coefficient values were calculated based on the estimated

runoff behavior of each sampling station. Average runoff coefficients have been tabulated for the main categories of land use in Pima County, by the Pima County Department of Transportation & Flood Control District. However, these tabulations apply to specific facilities (e.g., to an industrial facility or a commercial development) rather than to the entire drainage area that might encompass such a facility. It was thus more appropriate to use the runoff coefficients calculated for each storm water sampling station, on the assumption that the percent impervious area in the drainage area for each sampling station was representative of the percent impervious area found in all areas of similar land use within the Permit Area.

An area-weighted event-mean concentration value also was calculated for the entire permit area, for each of the twelve parameters of concern, along with an area-weighted pooled estimate of the standard deviation for each parameter (Table 3). The area-weighted event-mean concentration for each parameter across the entire permit area, $C_{tot,i}$, was calculated using the equation,

$$C_{tot,i} = (\Sigma C_{i,j} A_j)/(\Sigma A_j)$$

where all variables are defined as in the equation for $L_{i,j}$, above. The estimates for $C_{tot,i}$ were then used to calculate area-weighted annual pollutant loads for each parameter across the entire permit area (Table 3).

The area-weighted pooled estimate of the standard deviation for each parameter, $S_{pooled,i}$, was calculated using the equation,

$$S_{pooled,i} = [(\Sigma S^2_{i,j} A_j)/(\Sigma A_j)]^{1/2}$$

where $S^2_{i,j}$ = the standard deviation of the event-mean concentration for parameter $i$ in land use category $j$.

The standard deviations for event-mean concentrations for each category of land use were used to calculate 90% confidence intervals for each annual pollutant load estimate, for each category of land use. These calculations used the common Student's $t$ (two-tailed) equation and values of $\nu$ (degrees of freedom) = $n-1$ where $n$ is the number of storm events contributing data to the calculation of the event-mean standard deviation. The 90% confidence intervals for $C_{tot,i}$ were calculated using $S_{pooled,i}$, but with $\nu = n-5$ to reflect the fact that the estimate of $S_{pooled,i}$ is based on five prior estimates of the standard deviations for each category of land use. The 90% confidence intervals for the estimates of annual pollutant loads also are shown in Table 3.

## Table 3 Event-Mean Concentrations and Annual Pollutant Load Estimates

### A. Summary of Event-Mean Concentration Results (mg/l)

| | Land Use Class | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | High Density Res. | | Med. Density Res. | | Low Density Res. | | Commercial | | Industrial | | Area-Weighted Total | |
| | Mean | Std Dev. | Mean | Std.Dev. | Mean | Std.Dev. | Mean | Std.Dev. | Mean | Std.Dev. | Mean | Std.Dev. |
| BOD5 | 30.00 | 14.14 | 15.00 | 14.71 | 15.00 | 7.91 | 21.60 | 14.79 | 19.00 | 5.66 | 15.38 | 4.64 |
| COD | 262.00 | 158.39 | 181.60 | 75.25 | 156.60 | 84.53 | 224.20 | 124.10 | 258.50 | 181.73 | 164.76 | 91.48 |
| TSS | 111.00 | 15.56 | 194.00 | 119.47 | 228.66 | 92.98 | 109.00 | 47.49 | 669.65 | 570.85 | 241.37 | 148.90 |
| TDS | 172.50 | 40.31 | 117.20 | 66.46 | 85.00 | 49.07 | 169.20 | 103.74 | 130.00 | 14.14 | 91.55 | 51.19 |
| TKN | 3.500 | 0.849 | 2.560 | 3.163 | 1.422 | 1.715 | 3.360 | 1.996 | 1.850 | 0.919 | 1.580 | 1.852 |
| NO3/NO2 | 1.850 | 0.354 | 1.420 | 0.870 | 0.720 | 0.832 | 1.160 | 1.115 | 1.800 | 0.141 | 0.837 | 0.822 |
| P (total) | 0.000 | 0.000 | 0.342 | 0.367 | 0.306 | 0.329 | 0.176 | 0.211 | 0.675 | 0.955 | 0.000 | 0.000 |
| P (diss.) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Pb (total) | 0.055 | 0.011 | 0.022 | 0.017 | 0.035 | 0.039 | 0.022 | 0.021 | 0.098 | 0.045 | 0.037 | 0.038 |
| Cu (total) | 0.050 | 0.016 | 0.042 | 0.030 | 0.032 | 0.035 | 0.037 | 0.041 | 0.117 | 0.090 | 0.036 | 0.039 |
| Zn (total) | 0.749 | 0.004 | 0.096 | 0.089 | 0.103 | 0.111 | 0.285 | 0.268 | 0.275 | 0.106 | 0.117 | 0.113 |
| Cd (total) | 0.00105 | 0.00035 | 0.00032 | 0.00046 | 0.00012 | 0.00027 | 0.00058 | 0.00081 | 0.00070 | 0.00099 | 0.00017 | 0.00036 |

### B. Annual Pollutant Load Calculation Results (tons/yr)

| | Land Use Class | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | High Density Res. | | Med. Density Res. | | Low Density Res. | | Commercial | | Industrial | | Area-Weighted Total | |
| | Mean | +/- 90% CI | Mean | +/- 90% CI | Mean | +/- 90% CI | Mean | +/- 90% CI | Mean | +/- 90% CI | Mean | +/- 90% CI |
| Area (ac) | 416 | | 5124 | | 53797 | | 1107 | | 2632 | | 63076 | |
| Runoff Coef. | 0.63 | | 0.39 | | 0.41 | | 0.63 | | 0.31 | | 0.41 | |
| BOD5 | 9.522 | 20.040 | 36.301 | 158.982 | 400.672 | 942.816 | 18.243 | 55.777 | 18.774 | 24.956 | 483.512 | 58.789 |
| COD | 83.16 | 224.45 | 439.49 | 813.08 | 4183.01 | 10080.85 | 189.36 | 467.95 | 255.43 | 801.70 | 5150.44 | 1158.69 |
| TSS | 35.23 | 22.04 | 469.50 | 1290.90 | 6107.84 | 11089.05 | 92.06 | 179.06 | 661.68 | 2518.33 | 7366.31 | 1886.09 |
| TDS | 54.75 | 57.11 | 283.63 | 718.11 | 2270.47 | 5852.15 | 142.90 | 391.17 | 128.45 | 62.39 | 2880.21 | 648.41 |
| TKN | 1.111 | 1.202 | 6.195 | 34.173 | 37.984 | 204.499 | 2.838 | 7.526 | 1.828 | 4.055 | 49.956 | 23.460 |
| NO3/NO2 | 0.587 | 0.501 | 3.437 | 9.401 | 19.232 | 99.207 | 0.980 | 4.204 | 1.779 | 0.624 | 26.014 | 10.408 |
| P (total) | 0.000 | 0.000 | 0.828 | 3.961 | 8.174 | 39.225 | 0.149 | 0.797 | 0.667 | 4.211 | 9.817 | 0.000 |
| P (diss.) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Pb (total) | 0.017 | 0.016 | 0.054 | 0.180 | 0.946 | 4.644 | 0.018 | 0.077 | 0.097 | 0.200 | 1.132 | 0.476 |
| Cu (total) | 0.016 | 0.022 | 0.103 | 0.328 | 0.849 | 4.173 | 0.031 | 0.153 | 0.115 | 0.396 | 1.114 | 0.488 |
| Zn (total) | 0.238 | 0.006 | 0.233 | 0.962 | 2.746 | 13.226 | 0.241 | 1.011 | 0.272 | 0.468 | 3.729 | 1.437 |
| Cd (total) | 0.0003 | 0.0005 | 0.0008 | 0.0050 | 0.0032 | 0.0320 | 0.0005 | 0.0031 | 0.0007 | 0.0044 | 0.0055 | 0.0046 |

## Total vs. Dissolved Pollutant Concentrations

The data on total vs. dissolved concentrations indicate that several priority pollutants are transported in the Pima County storm water primarily either as suspended particles or adsorbed to suspended particles. Table 4 summarizes the data from the nine sampled storm events, for all EPA-designated target pollutants for which the measured total concentration was more than 1.5 times greater than the measured dissolved concentration. The "1.5 times" criterion was used arbitrarily to weed out cases where the difference between total and dissolved concentrations were possibly not large enough to indicate a real difference. The results in Table 4 indicate that several metals are being transported primarily as suspended particles or adsorbed to suspended particles. Arsenic and lead show high ratios of total to dissolved concentrations in the largest number of samples (nine each), followed by cadmium (eight samples), copper (seven samples), chromium (six samples), and zinc (three samples). Lead shows ratio values consistently much larger than for any other metal. Further, reported values for total Kjeldahl nitrogen (TKN) are more than 1.5 times higher for the unfiltered sample than for the filtered sample, for four storm samples. Unfortunately, the method used to measure nitrate and nitrite nitrogen concentrations can be used only with filtered samples; consequently, comparable ratio values are not available for nitrate + nitrite nitrogen concentrations. The TKN ratios suggest that a significant fraction of the nitrogen in some samples is also being transported in a suspended or adsorbed state.

Finally, two storm samples were analyzed for both total and dissolved semi-volatile organic compounds. The results indicate that four compounds were being significantly transported in a suspended or adsorbed state. The results for total versus dissolved semi-volatile organic compounds may be viewed with a little caution, however. It is possible that some dissolved organic molecules adsorbed to the filter membrane instead of passing through, resulting in a heightened discrepancy between total and dissolved concentrations. Future filtering of samples for organic analysis will use filtering media with known organic adsorption properties.

The analysis of total vs. dissolved concentrations suggests that at least some contaminants are being transported in a suspended or adsorbed state. Consequently, these pollutants may be re deposited as settled particles or adsorbed to settled particles as runoff water dries or infiltrates into streambed sediments. Pollutant concentrations in streambed sediments need to be measured, to determine if the re deposited pollutants pose a continuing risk to human or ecosystem health.

Table 4 Ratios of Total to Dissolved Concentrations
for Parameters Showing Significant Differences Between Total and Dissolved Concentrations

| | Sample No. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Parameter | 93-1-0218 | 93-1-0326 | 93-2-0218 | 93-2-0326 | 93-3-0208 | 93-3-0326 | 93-4-0208 | 93-4-0326 | 93-5-0218 |
| As | 6.50 | 6.50 | 3.00 | 3.50 | 2.00 | 2.50 | 2.00 | 1.67 | 5.00 |
| Cd | | 1.50 | 1.50 | 1.67 | 1.60 | 1.63 | 2.00 | 2.00 | 4.25 |
| Cr | | 11.30 | | 3.42 | 5.38 | 5.36 | | 3.92 | |
| Cu | | 2.33 | | 1.69 | 1.77 | 2.25 | 2.93 | 1.58 | 3.53 |
| Pb | 17.00 | 19.00 | 35.00 | 21.00 | 63.00 | 23.50 | 7.00 | 5.00 | 66.00 |
| Zn | | | 3.13 | | | | | 3.04 | 3.77 |
| TKN | | | 1.60 | 1.84 | 2.90 | | 1.53 | | |
| Bis(2-ethylhexyl)pthalate | | | | | | 10.80 | | | |
| Chrysene | | | | | | | | 6.50 | |
| Fluoranthene | | | | | | 3.18 | | 14.91 | |
| Phenanthrene | | | | | | | | 3.80 | |

NOTES:
Ratios are based on observed total concentration vs. observed dissolved concentration wherever possible. If the dissolved concentration is reported as a non-detect, the MDL or PQL value for the method is used as the dissolved concentration.

# SELECTION OF PRIORITY POLLUTANT SAMPLING SITES IN THE PIMA COUNTY NPDES STORM WATER PROGRAM[1]

Richard Grimaldi[2]

ABSTRACT: Pima County submitted Part I of its National Pollutant Discharge Elimination System (NPDES) Storm Water Permit Application on May 18, 1992. This paper describes the County's approach to selecting storm water sampling sites, to meet application requirements.

Under the NPDES regulations, Pima County was required to develop a monitoring program for storm water discharges from the County owned storm sewer system. The monitoring program had to identify sampling locations, methods, and procedures for storm water sampling.

As is typical in the arid southwest, the Pima County owned storm sewer system is predominantly roadway drainage with few storm sewer pipes. This type of system was not envisioned by EPA in its regulations which made selection of sampling sites difficult.

Based upon the regulations, Pima County developed criteria to analyze and assess information on land use, industrial facilities, water quality, and drainage systems. A Geographic Information System (GIS) was used for this part of the analysis for the ability to manipulate and select data spatially. From this assessment, focus areas were developed which were field inspected to locate potential storm water sampling sites. Based upon regulatory, hydrologic, hydraulic, and safety criteria these potential sites were then examined and ranked as excellent, good, poor, or unacceptable. Five sites, representing five different land uses, were selected as locations for sampling. These sites were found to be the best suited for data collection under the federal storm water program guidelines.

Pima County successfully conducted monitoring at these sites during the 1992-93 winter storm season.

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[1]Paper presented at the Sixth Annual Symposium of the Arizona Hydrological Society, Casa Grande, Arizona, September 23-24,1993.

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## INTRODUCTION

On November 16, 1990, the Environmental Protection Agency (EPA) finalized regulations implementing the National Pollutant Discharge Elimination System (NPDES) program for storm water discharges. Specifically jurisdictions which have a municipal separate storm sewer system (MS4) serving a population of 100,000 or more are required to obtain an NPDES permit. Pima County was identified in the November 1990 regulations as having to obtain a permit for its storm water discharges.

These regulations are the result of over 18 years of rule development by the EPA to control the discharge of pollutants from "point sources" into "navigable waters". From 1978 to 1983, the EPA provided funding for the Nationwide Urban Runoff Program (NURP). The NURP consisted of studies to determine the impacts of industrial storm water discharges and discharges from municipal separate storm sewer systems (MS4). Data collected through the NURP indicated that discharges from the MS4 impacted natural receiving waters with significant concentrations of metals, volatile organic, and pesticides.

In complying with these new regulations, Pima County faced several difficult issues. The EPA had not envisioned the type of storm drainage system that is found in Pima County. Comprised of roadway drainage with few storm sewer pipes, Pima County's system has potentially thousands of outfalls which are difficult to identify and sample. Another factor not considered by the EPA was the diversity in urban land use characteristics. Pima County is comprised of primarily low density residential land use. While the population estimates for the urban area of Pima County meet the federal requirements for inclusion in the NPDES program, the regulations are directed at urban areas with higher land use densities and well developed storm drainage systems. Safety of personnel during storm water sampling was also a major issue in complying with the regulations. Sudden, intense monsoons posed a threat to sampling personnel.

As part of the NPDES permit application, Pima County was required to collect a wide variety of information on land use, industrial facilities, the County MS4, surface water drainage patterns, watersheds, and surface water quality data. To effectively analyze this data, Pima County staff utilized a Geographic Information System (GIS). The GIS allowed staff the ability to analyze information in various combinations (i.e. land use and drainage) and scales (i.e. regional and area specific). By using GIS, specific information could also be selected from a database and analyzed spatially (i.e. hazardous waste facilities could be selected from the industrial database and then plotted graphically). Lastly, with the GIS individual points on a map could be developed into focus areas by placing a buffer around each point (i.e industrial facilities) and joining the intersecting buffers to form

areas (i.e. industrial areas). These areas could then be ranked by density (the number of facilities located within an area) or by the types of points located within the areas (the number of hazardous waste facilities, manufacturing facilities, or building contractors).

This approach allowed staff to quickly assess the data collected resulting in the development of focus areas which could be field inspected to find suitable sampling sites. Based upon regulatory, hydrologic, hydraulic, and safety criteria these potential sampling sites were then classified into four categories; excellent, good, poor, and unacceptable. The best ranked sites were then recommended to EPA as Pima County's storm water sampling locations as per the federal regulations.

## METHODOLOGY

To begin the analysis of information collected by Pima County, preliminary assessment criteria were developed based upon the federal regulations. Five criteria were determined to be essential in locating areas for storm water sampling. These criteria are:

1. Location of known outfalls to waters of the U.S.
2. Heavy industrial areas
3. Residential (low, medium, and high density) areas
4. Commercial areas
5. Areas with surface water quality impairments

Information on the location of known outfalls to waters of the U.S. was developed by finding the intersection of storm sewers with natural or improved ] that were mapped into the county GIS. This information became one of the primary criteria for sampling site selection since storm sewers have several characteristics which are important in storm water sampling. Storm sewers have a defined drainage area, stable hydraulic sections, and are definitively a "point source" discharge.

Location of heavy industrial areas could have been found based upon industrial land use information that was available on the GIS. This land use information was derived from an analysis of aerial photographs by the Pima County Planning Department. While based upon aerial photographs, this information was not all that useful since there was no data as to the nature of the activities in each area designated as industrial. An industrial database developed for the NPDES project provided the detailed information to begin looking for sampling sites except this information was not in a map form. By using the GIS, the database was converted into a map indicating the location of the

facility by an address matching computer program. This approached developed the industrial map that was needed but did not take the time to locate each of the approximately 300 points by hand.

In reviewing the different categories of industrial facilities in the database, hazardous waste generators, facilities identified as manufacturing plants, and building contractors were chosen as the industries of concern. The type of materials used as well as waste generated from these industries could have a great potential to contain pollutants.

The GIS mapped the individual facilities for each of the three groups selected. To further define specific focus areas, a 1/4 mile buffer was place around each facility. Where buffers from different facilities intersected one another, they were joined or "unionized" to from one area or "polygon". By creating focus areas from the individual facilities mapped, field efforts could be concentrated on those areas that had the greatest number of facilities. These focus areas could then be prioritized by the density of facilities located within each area (which the GIS could calculate) or by the type of facilities located within each area based upon the database information.

After examining the focus areas created with by the 1/4 mile buffer, a second set of focus areas were developed by using a smaller buffer (200 meters). This smaller buffer provided greater resolution by developing smaller areas of greater density. The areas generated by this method were designated as focus areas.

Residential (low, medium, and high density) areas were located based upon land use information that was available on the GIS system. This land use information was derived from an analysis of aerial photographs by the Pima County Planning Department. Using the GIS, land use information was summarized for the unincorporated portions of Pima County within the NPDES permit area (Table 1). Of the residential classifications, low density residential areas were the most abundant and comprised approximately 33% of the land use in the County. A very small percentage of the land use in the permit area was found to be medium (3.6%) or high density (less than 1%) residential areas. The land use information was then analyzed graphically to the determine spatial distribution for each land use category.

Commercial areas comprise less than one percent of the land use in the County and are distributed in small parcels throughout the permit area (based upon analysis of land use information using the GIS). Areas that were drained by storm sewers were designated as preferred sampling sites due to the controlled drainage. These sites were noted when field inspections were made of the storm sewer systems.

Location of areas with surface water quality impairments were difficult to determine since little data exist on surface water quality in the permit area. Based upon a review of state documents on areas with

Table 1

Summary of Land Use
in the
Unincorporated Portion of the NPDES Permit Area

| Land Use Category | Area (Acres) | Percent ( % ) |
|---|---|---|
| High Density Residential | 353 | 0.21 |
| Medium Density Residential | 6,056 | 3.61 |
| Low Density Residential | 54,519 | 32.54 |
| Commercial | 1,193 | 0.71 |
| Industrial | 2,798 | 1.67 |
| Open Space | 97,201 | 58.02 |
| Institutional, Mining, Transportation, Mixed | 5,424 | 3.24 |
| Totals | 167,544 | 100.00 |

surface water quality impairments, the majority of known water quality impacts are attributed to the regional wastewater treatment plants located along the Santa Cruz River. Other data was too sparse to draw any conclusions since information required to calculate the appropriate surface water quality standard was not available.

After the GIS analysis, several focus areas were identified for field inspection to locate possible storm water sampling sites. Standard procedures were developed for inspecting each area. These procedures consisted of:

1. Review of drainage system (from County GIS) for the area

2. Review of aerial photography for the area

3. General reconnaissance of area noting land use, drainage, and all weather accessibility of the area

4. Potential sampling sites were examined, measured (if pipe), and photo-documented

5. A standard field inspection sheet was filled out for each potential sampling location

A total of 12 focus areas were field inspected with approximately 50 potential sampling sites being documented. A wide variety of drainage structures were observed. In some instances a specific area was identified by several criteria (i.e. a known storm sewer pipe located in a commercial area).

After the focus areas were field inspected, a list of potential sampling sites was developed and assessed based upon regulatory acceptability, hydrologic/hydraulic characteristics, and safety criteria. While a site first had to meet specific regulatory criteria, other criteria which reflected technical considerations as well as safety aspects were also important. The criteria consisted of:

1) Regulatory outfall or part of conveyance system.

2) Pima County owned or operated storm water conveyance structure

3) Representative of a particular land use/area of concern

4) Hydraulically stable section for flow sampling

5) Sampling site access

6) Proximity to precipitation station

7) All weather access and access route

8) Safety of personnel during sampling

In general, older areas have uncontrolled overland flow as the primary drainage system. Adequate sampling locations were difficult to find within this type of drainage system. In contrast the newer areas or recent road improvements had storm sewer systems or well developed street drainage.

Low density areas were found to have little, if any, drainage structures due to the ability of many homesites to have runoff collect in adjacent natural washes. Many of the medium density areas were found to have privately owned streets which would exclude them from being considered as part of the County owned system.

Based upon the assessment of the site specific information for each location, a ranking of potential sites was developed. Sites were categorized into four groups: excellent, good, fair, or poor.

Sites classified as excellent met all the regulatory requirements, had a stable hydraulic section, represented a specific land use or area of concern, and provided easy and safe site access. These sites will be the highest priority to sample.

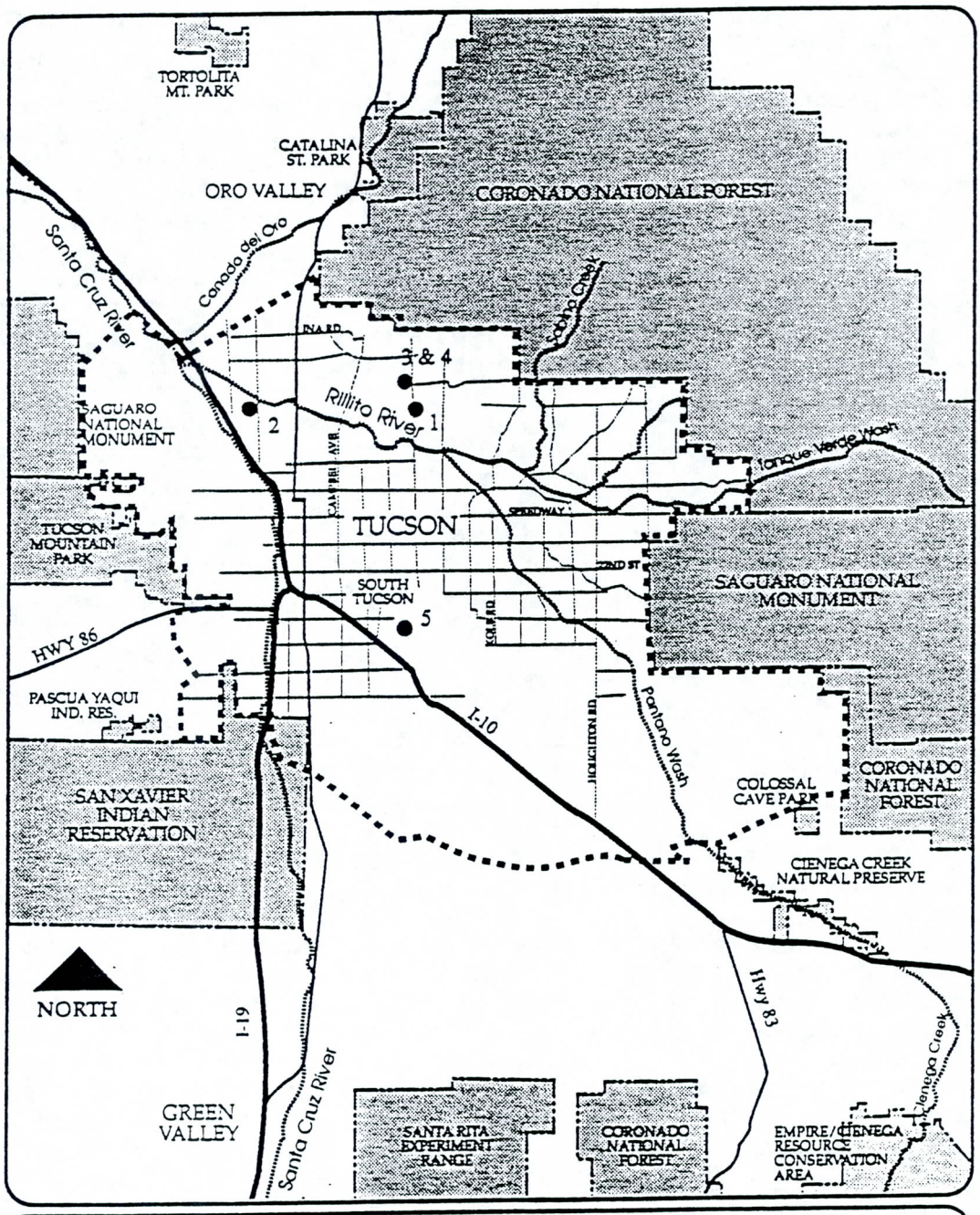
Sites classified as good met all regulatory requirements but did have one of the following characteristics: stable hydraulic section, represent a specific land use or area of concern, or provided easy and safe site access.

Sites classified as poor met all regulatory requirements but did not have two of the following characteristics: stable hydraulic section, represent a specific land use or area of concern, or provided easy and safe site access.

Sites classified as unacceptable were determined to not meet the regulatory requirements. These sites were found to be owned or operated privately or by another jurisdiction.

Only five sites (Figure 1) were proposed as storm water sampling locations. Theses sites were found to be the best suited for data collection under the federal storm water program. A majority of the sites examined where found to be inadequate based upon lack of controlled hydraulic sections or they were owned and operated by other jurisdictions/entities.

The first site, Camino Esplendora, drains a low density residential development in the foothills of the Catalina Mountains. Drainage from nearby lots run down a Pima County owned and operated curbed street to an opening with a spill way. The curb opening and spill way discharge to a natural wash (unnamed) and can be considered a point source discharge




## Monitoring Site Locations

● NPDES Monitoring Site

1. Low Density Residential
2. Medium Density Residential
3. High Density Residential
4. Commercial
5. Industrial

FIGURE 1

to water of the U.S. All weather site access can be gained from Swan Road and Calle Barril. Safety at the site is considered good due to the low volume of traffic predicted at this location. Manual grab sampling will be required at this site.

The second site, Sullinger Avenue, drains a medium density residential development by the Ruthrauff Road area via a storm sewer system. The storm sewer discharges to an improved channel which conveys water to the Rillito River. While the improved channel may or may not be waters of the U.S, the storm sewer outfall can be classified as a point source discharge. This system is owned and operated by Pima County. Automatic sampling could be completed for this site with the equipment installed down a manhole along Sullinger Avenue. All weather access to this site can be gained from Ruthrauff Road. Safety at the site is considered good due to the low volume of traffic predicted at the site.

The third and fourth sites, referred to as the Sunrise Storm Sewer, consist of a major storm sewer system draining two commercial developments and a high density residential area (apartment complex). The storm sewer discharges to a natural wash (Valley View Wash). This storm sewer system is owned and operated by Pima County. Two automatic sampling locations could be located in the system to collect runoff from the commercial areas and high density residential area. Samplers can be installed down manholes for collection of runoff from the commercial areas while another sampler can be located in a large catch basin for sampling of the residential area. The quality of the runoff will be determined prior to the mixing of these waters in the main trunk of the storm sewer. All weather access can be gained along Swan Road. Site safety is considered good due to the off street location of manholes. One sampling team is projected to operate both sites.

The fifth site, Columbia Street and Country Club Road, drains a high density industrial area by the Ajo detention basin which was determined to be of high priority due to the types of industrial facilities (producing hazardous waste), condition of the area (determined to be poor) and presence of an illicit discharge. The proposed location is only rated as good due to the lack of well defined drainage system. However, a sample can possibly be taken along a v-shaped depression running adjacent to Country Club Road. The v-shaped depression drains an alleyway and discharges across Country Club Road to vacant desert. The v-shaped ditch is believed to be part of the County owned conveyance system. This location would be manually sampled. All weather access can be gained from Ajo Way. Site safety is considered fair.

## EPA APPROVAL OF THE PROPOSED SITES

The methodology developed to select sampling sites for the NPDES program was extremely important in justifying the location of the sites proposed to EPA for sampling. In February 1991, the County submitted the proposed sites to EPA. EPA approved these sites based on the rationale presented in this paper and the sites were successfully sampled during the winter of 1992-1993.

# Part III

# WASTEWATER RECLAMATION THROUGH SUBSURFACE RECHARGE: AN EMERGING WATER MANAGEMENT TECHNOLOGY ISSUE

# RECHARGE TECHNOLOGY AND HYDROGEOLOGY AT THE WATER CAMPUS PROJECT, SCOTTSDALE, ARIZONA[1]

Floyd L. Marsh and Gary G. Small[2]

ABSTRACT: The City of Scottsdale has undertaken a project to design and construct an innovative state-of-the-art water reclamation facility known as the Water Campus. The project, located in north-central Scottsdale, is scheduled to become operational in 1996. The facility will be designed to initially treat 6 million gallons per day (mgd) of municipal wastewater with the capability for expanded capacity to 44 mgd. The project will include aquifer storage facilities designed to recharge product water in specially designed dry wells. Recovery of the recharged water will be through existing and new production wells connected directly into the City's potable water system. A pilot phase of the project will evaluate the design and efficiency of dry wells to recharge water into the dry Upper Alluvial Unit of the Paradise Valley Aquifer. The 16 initial dry wells, grouped in clusters of four, will be approximately 48 inches in diameter and 150 feet in depth. Eight monitor wells, comprised of two monitor wells for each dry-well cluster, approximately 600 feet deep will determine the background water quality and allow detection of water quality changes due to recharge. Construction and pilot testing of the two dry wells in the initial cluster began in June 1993.

## INTRODUCTION

As a central element of water management and reclamation, the City of Scottsdale has made a strong, long-term commitment to groundwater recharge and subsurface storage as an integral component of its water resources master planning. At ultimate buildout, Scottsdale will have an estimated annual water demand of approximately 140,000 acre feet per

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[1]Paper presented at the Sixth Annual Symposium of the Arizona Hydrological Society, Casa Grande, Arizona, September 23-24, 1993.
[2]Floyd Marsh is Water Resources Director, City of Scottsdale, 9388 E. San Salvador Dr., Scottsdale, AZ 85258 and Gary Small is Principal, Hydro-Analysis, Inc., 600 E. Baseline Rd., Tempe, AZ 85285.

year. Reclaimed effluent and the supply from other than currently available Central Arizona Project (CAP) and Salt and Verde surface water sources comprise approximately one-half of the required supply to meet future demands. Reclaimed effluent alone represents slightly more than one-third of the City's future water supply. That quantity will need to be reclaimed and used either for direct irrigation of turf and non-residential landscape or converted to potable quality water with advanced treatment, recharged and then recovered and delivered to the municipal system for domestic use.

Not only does effluent comprise a significant future source in relation to other supply components, but there are great variations in when the reclaimed effluent supply is available and the demand for its direct use exists. In the supply-demand relationship, the greatest effluent demand is during summer months; whereas, the greatest supply is during the winter months creating a seasonal supply-demand imbalance. Therein lies the need for an innovative recharge technology as a supply management tool. Overall, with buildout of the City service area, reclaimed municipal effluent will become a significant component of the City's future water budget and, therefore, an integral water source.

## RECHARGE AND RECLAMATION MASTER PLANNING

The City of Scottsdale's recharge-recovery program is evolving in a multi-dimensional direction. That is, it includes multiple water sources, comprising both raw and treated CAP water and advanced treated municipal wastewater, at multiple locations with multiple objectives. Functionally, the program is developing as a dual-faceted approach including provisions for both operational peaking capacity and future reserve subsurface storage capacity for recovery and use during drought periods or other unforseen emergencies. Recharge-recovery locations include proposed projects both inside and exterior to City boundaries. The City is evaluating two primary recharge-recovery locations within the City boundaries for use as annual storage and system peaking facilities. Whereas, the City is considering the Granite Reef Underground Storage Project (GRUSP) site, located along the Salt River floodplain east of Phoenix, as reserve capacity for subsurface storage to meet emergency needs over the long term.

In the late 1980's, the City of Scottsdale developed and subsequently updated a three-element integrated water resources master plan including wastewater collection-water reclamation and recharge-subsurface storage elements. A centralized Water Reclamation Campus (WRC) concept evolved from these master planning update activities. Figure 1 schematically depicts the integration of major existing and proposed wastewater collection, treatment and reclamation facilities, together with aquifer storage facilities, into the master-planned idea of a water reclamation campus.

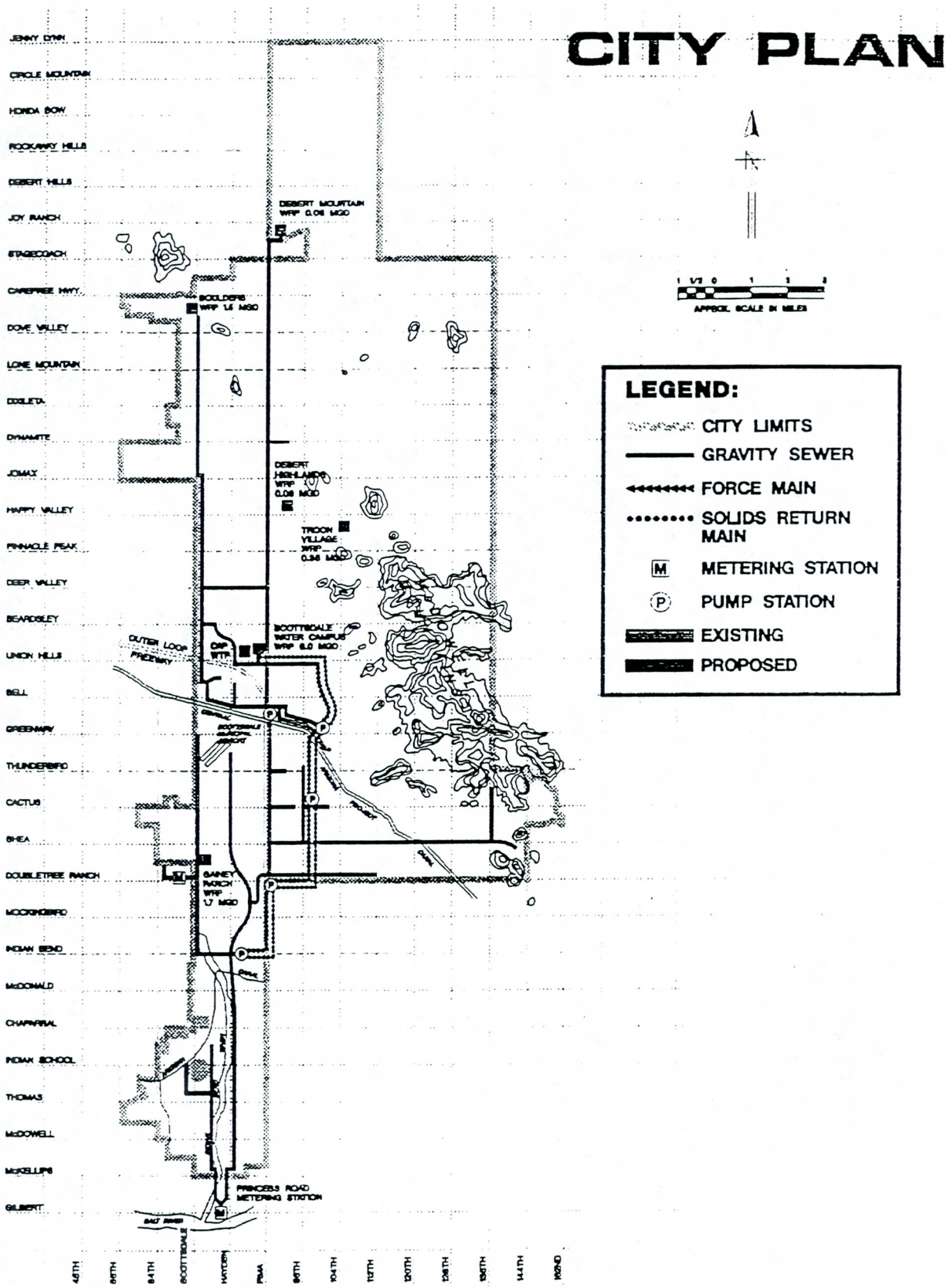



**FIGURE 1 - FACILITIES MASTER PLAN**

## PROJECT DESCRIPTION

The Water Reclamation Campus (WRC) project consists of three primary facilities: a water reclamation plant (WRP); an advanced water treatment plant (AWTP); and, an aquifer storage facility (ASF). This project configuration is conceptualized in Figure 2. Through this project concept, the City expects to enhance its overall water resource management capability by reclaiming wastewater generated in central and north Scottsdale for use in irrigation and groundwater recharge and recovery. The project facilities will be centrally located near the intersection of Union Hills and Pima Roads east of and immediately adjacent to the existing CAP Water Treatment Plant. (See Figure 1).

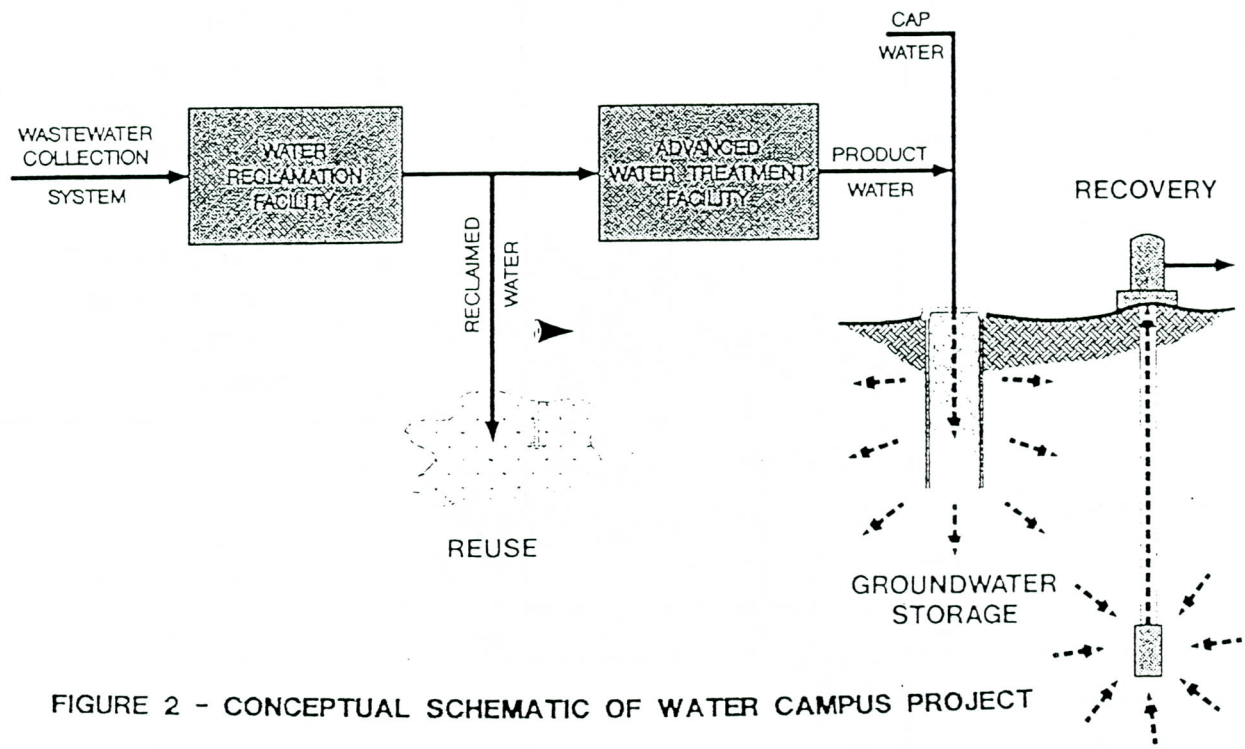



FIGURE 2 - CONCEPTUAL SCHEMATIC OF WATER CAMPUS PROJECT

The facilities to be evaluated, designed and constructed under this project will initially provide treatment and reclamation of approximately 4.5 to 6.0 million gallons per day (mgd) of domestic wastewater with master planning for expansion in 6-mgd stages to an ultimate 44-mgd facility. The facilities to be piloted and designed include a water reclamation plant (WRP) to produce treated water for open-access irrigation, an advanced water treatment plant (AWTP) to provide potable quality product water for recharge to the underlying groundwater system, utilizing aquifer recharge and recovery through an aquifer storage facility (ASF), and associated wastewater collection system improvements (ASCI) to convey raw wastewater from both the areas north and south of the facility to the WRC site.

Following reclamation of the wastewater resources for direct irrigation purposes, any surplus reclaimed effluent, either seasonal or over the long term, will be further treated to potable quality through advanced water treatment and recharged to aquifer storage for ultimate recovery and delivery to the municipal water system. Figures 3 and 4 are schematics which show the concept of recharge and recovery and a one-cluster block diagram representation of the dry-well layout.

## DRY WELL TECHNOLOGY

### General Hydrogeology and Site Investigations

The Paradise Valley Aquifer underlying the project site is composed of three stratigraphic units. The Upper Alluvial Unit (UAU) is found at the surface throughout the basin and consists of unconsolidated sands and gravels with variations in thickness as great as 600 feet. The Middle Fine Grained Unit (MFGU) lies directly below the UAU and consists of clays, silts, and evaporite deposits. The MFGU varies in thickness from none in the northern part of the valley to as much as 800 feet in the southern part. The Lower Conglomerate Unit (LCU) lying directly below the MFGU, consists of semi-consolidated sands and gravels and some stringers of basalt varying in thickness up to 900 feet. The general lithology of the UAU at the project site is alluvium comprised of a complex mixture of interbedded silts, sands, gravels and clays. This lithology is consistent with other high-energy environments associated with mountain-front deposition. Decomposed metamorphic materials are mixed with the other sediments in the alluvium.

To date, the drilling operation associated with this project consists of four soil borings to a depth of 350 feet, one monitoring well 540 feet deep, and two recharge wells at 150 feet. The five deeper borings completely penetrated the UAU. Samples of drill cuttings and geophysical logs verify the complex interbedding that occurred over geologic time. The monitor well and the soil borings were placed no more than 800 feet apart in a triangular format in order to provide better analytical data on the lithology. The correlation of individual layers among the boreholes is very poor. The geophysical logs and the TV logs for the two recharge bore holes, drilled 50 feet apart, showed better but not complete correlation, again verifying the complexity of the lithology at the site.

Depth of groundwater in the Scottsdale area ranges from less than 200 feet in the south to 900 feet in the north. In the project area, groundwater depth is approximately 500 feet, with the regional water table occurring in the lower conglomerate unit underlying two alluvial units. Production wells are between 1,500 to 1,600 feet in depth in this location.

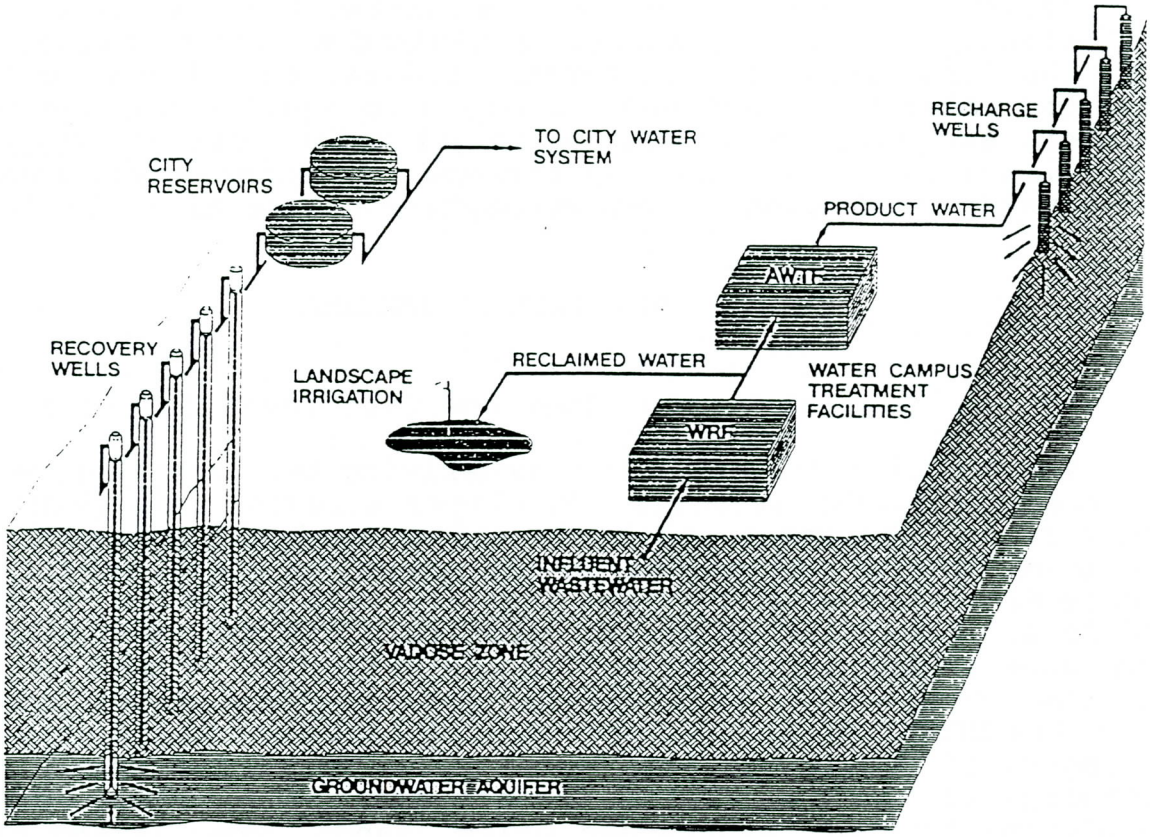
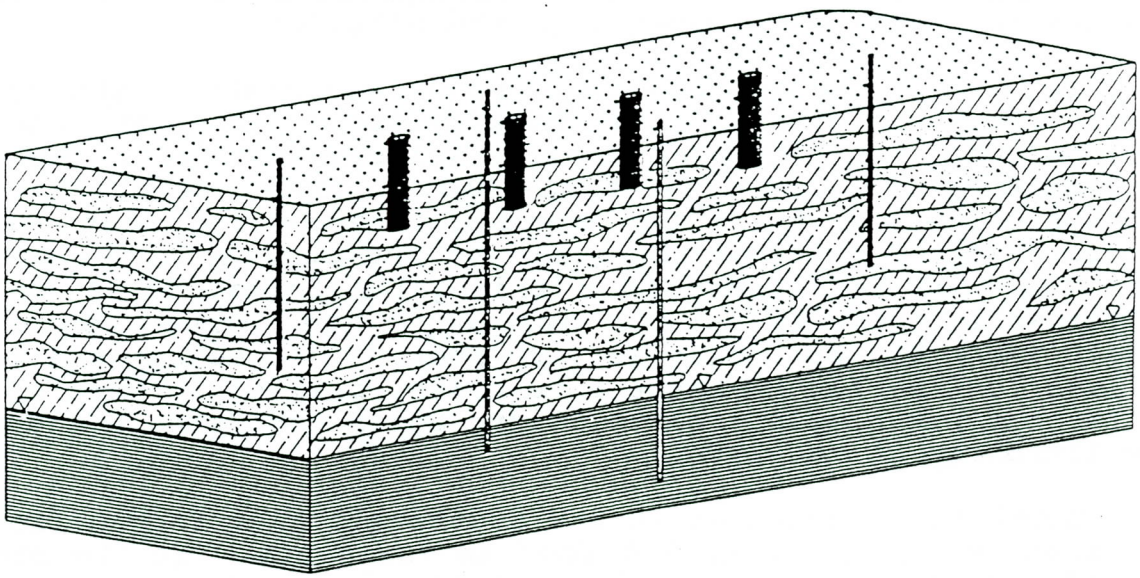



FIGURE 3 - BLOCK DIAGRAM OF RECHARGE AND RECOVERY CONCEPT



| | | | |
|---|---|---|---|
| DEEP MONITOR WELLS | (6" x 600') | FINE GRAIN MATERIAL | |
| DEEP SOIL BORINGS | (6" x 350') | COARSE GRAIN MATERIAL | |
| DRYWELLS | (4' x 150') | WATER TABLE | |

FIGURE 4 – CONCEPTUAL DRYWELL CLUSTER

## Dry Well Design and Operation

The basic dry well technology, modified for site-specific hydrogeologic conditions, was selected as the initial recharge strategy of choice for cost and land availability reasons. Dry wells constructed and fully equipped to depths of 150 feet and modified to take advantage of site-specific stratigraphic conditions are estimated to range in cost from $14,000 to $16,000 per well; whereas, deep injection wells of an equivalent capacity are estimated to cost ten to fifteen times as much. Therefore, more wells can be constructed initially with the same funding and individual dry wells can be replaced more economically should it become necessary due to clogging or diminished infiltration rates. With regard to land use, dry wells and associated piping and operational facilities can easily be placed in narrow linear corridors which already frequently exist as road right-of-way, medians or utility easements. Such installation can also be made at or below grade. This minimal land use requirement is in contrast to such requirements for larger more complex well installations and surface infiltration basins.

A configuration of numerous dry wells 48 inches in diameter by 150 feet deep is proposed for recharge at the WRC site. These wells will be located east of the existing Scottsdale CAP Water Treatment Plant on or adjacent to existing right-of-way corridors next to Pima Road north of the CAP aqueduct. Initially, treated CAP water will be recharged through these wells into the upper alluvial and lower units of the aquifer, beginning with the upper unit as the preferred zone of recharge because of its high hydraulic conductivity and relatively shallow depth for recovery pumping. Existing municipal production wells, which pump from the lower conglomerate unit but are also perforated in the overlying upper and middle alluvial units, are effectively located for capture of recharged water before it migrates outside the City boundary approximately two miles to the southwest. These production wells will be supplemented as necessary with future recovery wells for purposes of extraction from subsurface storage. (See Figure 3).

A pilot phase of the project will evaluate the design and efficient use of dry wells for recharge beginning with an initial cluster of four dry wells and one monitor well and a minimum of four such clusters for a total of 16 dry wells in the initial phase of the overall facility. The basic design will incorporate the use of a filter fabric or clean, hydraulically-screened mortar sand lining the outer wall of the well to keep the upper clays and fines from migrating downward and plugging the higher infiltration zones. Four general dry well design options, as depicted in Figure 5, are being considered. Modifications to these basic designs are currently being further evaluated, based on analysis of geologic samples from four 350-foot deep soil borings and geophysical logs of one 540-foot deep monitoring well, to improve effectiveness and flexibility of the design for site-specific hydrogeologic conditions.

Each dry well will be designed to allow a maximum recharge rate of approximately 500 gallons per minute (gpm). The specific recharge rate

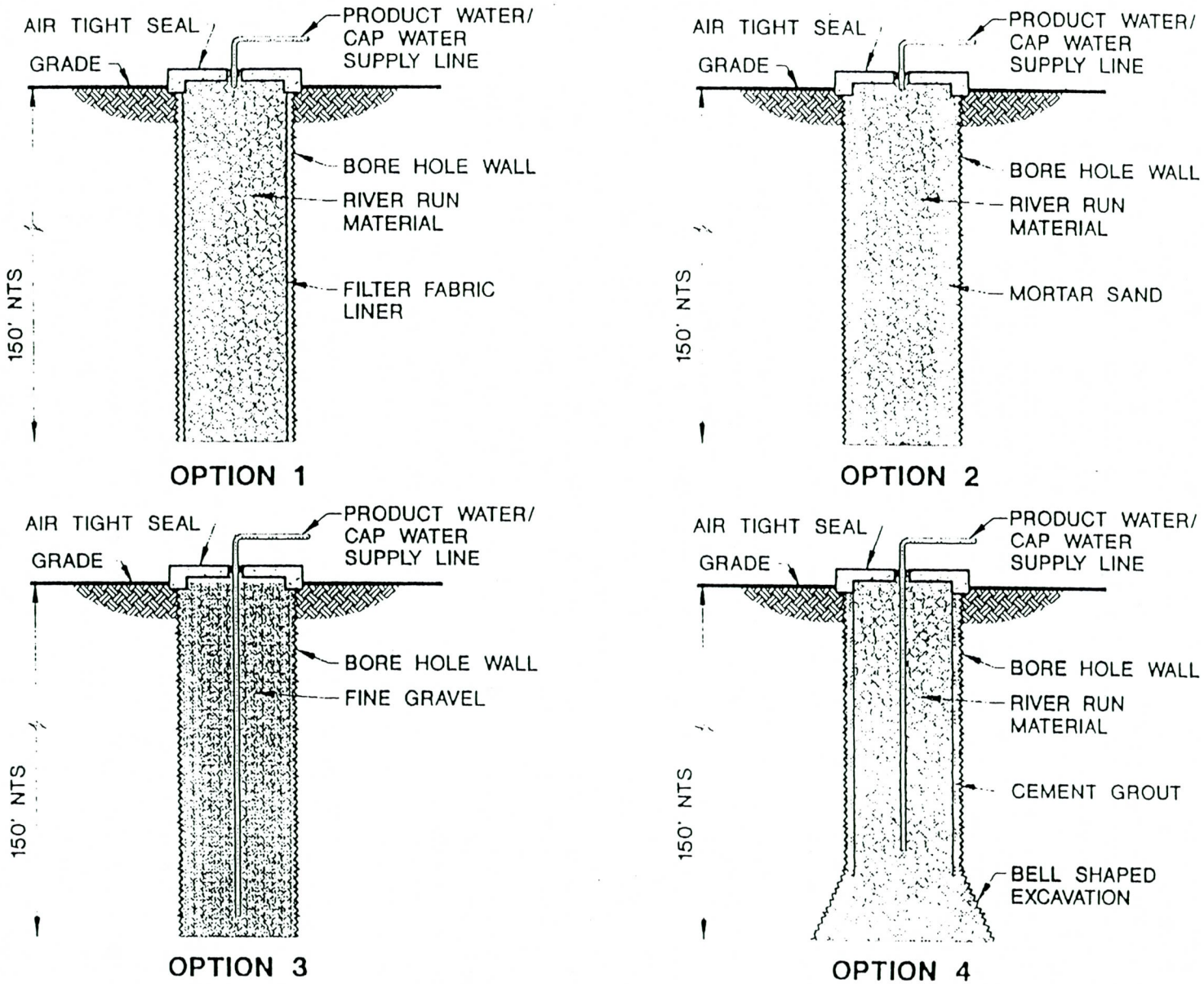



FIGURE 5 - ALTERNATIVE DRY WELL DESIGNS

for each well will be determined during a 45-60 day testing period. Injection testing will be started on one well at a time until all four wells of the initial cluster are in the testing mode. The data obtained from this test will be used to evaluate the effectiveness of the first cluster of dry wells and make appropriate design or operational modifications to subsequent dry well clusters. Each dry well will have its own six-inch diameter well feed header, six-inch gate valve and four-inch totalizing flow meter outside of the well head vault. The wells will be housed in a four-foot square vault buried 3 1/2 feet deep to provide protection for the eductor piping, solenoid-operated diaphragm valves and associated electrical equipment.

As presented by the schematic in Figure 6, the typical dry well will be equipped with a bundle of three small diameter PVC eductor lines (one 1-inch, one 1 1/2-inch and one 2-inch) extending to the bottom of the well. This design and the following startup protocol, together with a PVC cap on the bottom of the well, is being proposed to minimize air entrainment as the recharge water is introduced to the dry well. The one-inch eductor line will be used to start the pilot injection test at each well. This line will be equipped with an open/close solenoid-operated valve that will allow an approximate flow rate of 50 gpm. Once this valve is opened, it will remain open until the test is terminated. The two-inch eductor line will be equipped with a 1 1/2-inch modulating flow valve that will allow a range of flows between 50-260 gpm. The 1 1/2-inch eductor line will be equipped with an open/close solenoid-operated valve that will produce an approximate flow rate of 245 gpm. These three eductor lines, which will be opened automatically in succession via telemetry control to achieve a pre-programmed water-level rise in the well, will produce an approximate combined flow rate of 500-550 gpm based on the decline in flow rate due to the increase of head pressure in the well as the water level rises. Each dry well will also be equipped with a high water level alarm and a water level transducer. The transducer will measure the head of water within the well. The high water level alarm will be used to close the eductor line valves should the water level rise to a specific elevation within the well.

Throughout pilot testing and full operation, real-time data will be automatically and remotely monitored and collected on prescribed time intervals for evaluation of each of the four dry well clusters. An on-site radio telemetry unit (RTU) will be used to provide remote monitoring and control of each dry-well cluster. Likewise, ultimate operation and control of the entire aquifer storage facility will be fully automated by this remote control system on an expanded level. From dry well technology to the automated remote control system for real-time data collection and operation, the aquifer storage facility of the City of Scottsdale's Water Reclamation Campus is being designed and constructed as a state-of-the-art operation.

Two pilot dry wells have been designed and constructed to date in the initial cluster. The first well piloted, similar to the design in Figure 6, was installed to a depth of 152 feet and constructed with a

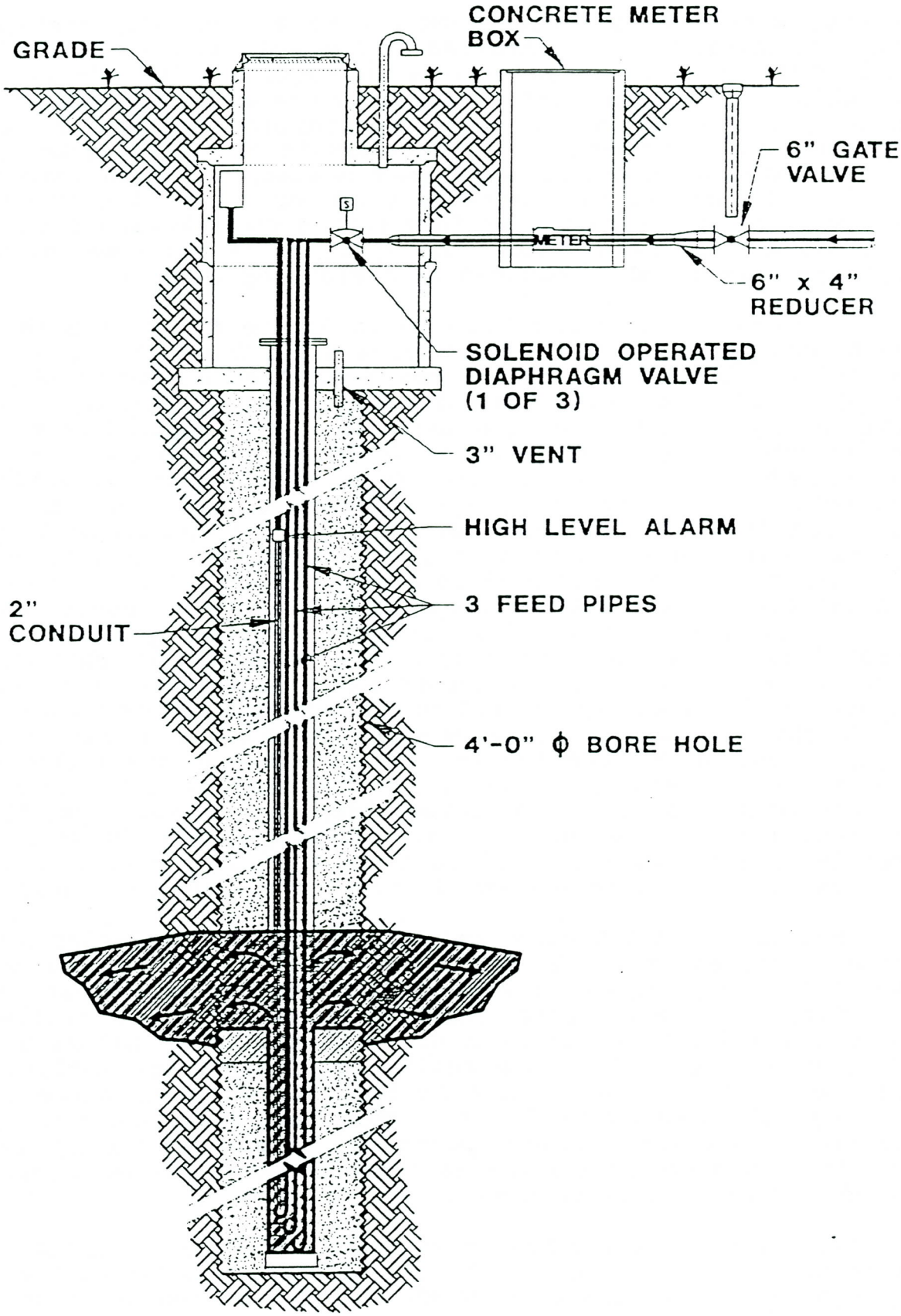



FIGURE 6 - DETAILED RECHARGE WELL OPERATION SCHEMATIC

16-inch 30 slot center PVC casing perforated over a 60 foot interval extending from 80 to 140 feet below ground surface. During a 59-day piloting period using treated CAP water, a recharge rate of 680 gallons per minute was ultimately achieved and sustained until operation of the well was shut down to pilot test a second well. Water level in the well rose to a maximum height of 93 feet from the bottom of the well and a total of 25,100,000 million gallons (77 acre feet) of water was recharged during the test period. Within four hours after water to the well was shut off, the volume of water in the well had drained to the bottom of the well. Pilot testing of a second well, simpler in design and merely backfilled with pea gravel to a depth of 150 feet and constructed with a 120 slot 6-inch PVC center casing, is in progress to evaluate efficiency of different designs. A third and fourth design is being developed for future piloting and evaluation.

## SUMMARY

Scottsdale's long-term commitment to groundwater recharge, subsurface storage and recovery involves a multi-dimensional program and development of a coordinated aquifer management system. Development and application of an effective dry-well technology at the City's future Water Campus is a central feature of this master planning. Construction and pilot testing of two dry well designs in the initial cluster began in June 1993.

## REFERENCES


Boyle Engineering Corporation, June 1987. Water Resources Management Plan-Utilization of Groundwater Reservoir Under City of Scottsdale. Consultant report prepared for the City of Scottsdale.

Dueker, Leonard L. and Floyd L. Marsh, May 1987. Recharge in Scottsdale, Arizona: An Overview, Third Biennial Symposium on Artificial Recharge of Groundwater in Arizona, proceedings published by the Salt River Project, Tempe, Arizona.

Dueker, Leonard L., M. E. Ford, Jr., and R. B. Jeffries, August 1988. Planning, Ground Water Recharge in Scottsdale, Arizona. Artificial Recharge of Ground Water Symposium, presented by F. L. Marsh and published in Proceedings of American Society of Civil Engineers, Anaheim, California.

Dueker, Leonard L., F. L. Marsh, and G. G. Small, May 1993. Recharge Technology at the Water Campus Project, Scottsdale, Arizona, Sixth Biennial Symposium on Artificial Recharge of Groundwater, sponsored and proceedings published by the Salt River Project, U.S. Department of Agriculture Water Conservation Laboratory and University of Arizona Water Resources Research Center.

# SOIL AQUIFER TREATMENT IN COMPLEX GEOLOGIC TERRAINS
# A CASE STUDY - SEDONA, ARIZONA[1]

David S. Prinzhorn and Herman Bouwer[2]

**ABSTRACT:** Central Arizona has experienced substantial geologic and tectonic change over the past few million years. The geologic events that molded the area have had a profound effect on how man interfaces with his surroundings. Shallow depths to bedrock and discharges of septic system effluent form perched water zones of questionable water quality.

In 1989 the residents of the City of Sedona voted to adjust the way they were impacting the land. The voters, cognizant of the fact that groundwater is a way of life in central Arizona, approved a municipal wastewater project to collect and treat the city's wastewater and use it for groundwater recharge.

While the problem of collecting, pumping, and treating the wastewater was solved using conventional engineering methods, groundwater recharge and Soil Aquifer Treatment (SAT) technology was problematic.

With the advent of new laws in Arizona protecting groundwater aquifers, Sedona had to comply and prove that its recharge system would not contaminate underlying aquifers.

The subsurface geology at the effluent recharge site was complex and presented a unique challenge to engineers and hydrogeologists. Substantial local tectonic and volcanic activity had taken place as recently as a few thousand years ago. With very little existing regional or site data available, it was determined that a more comprehensive hydrogeologic analysis was required.

During a study period of over two years, work was performed which included infiltration and hydraulic conductivity measurement of the soil mantle and upper bedrock, a pilot test basin constructed and data collected to satisfy ADEQ so that a conditional Aquifer Protection Permit could be granted.

The new effluent recharge system consists of fifteen SAT spreading basins that will be managed to enhance nitrification and denitrification in the vadose zone.

This paper and presentation have been prepared to illustrate how complex geologic terrains, which in the past may never have been considered for SAT, can be utilized after careful hydrogeologic investigations and studies to make sure that there are no "Fatal Flaws".

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[1]Paper presented at the Sixth Annual Symposium of the Arizona Hydrological Society, Casa Grande, Arizona, September 23-24, 1993.

[2]David S. Prinzhorn is a Project Engineer and Hydrogeologist, Engineering-Science, Inc., Phoenix, AZ, Herman Bouwer is Chief Engineer, USDA-ARS Water Conservation Lab, Phoenix, AZ.

## SOIL AQUIFER TREATMENT PRINCIPALS

In the desert southwest of the United States, and other developing areas of the world, man is slowly depleting his supply of naturally existing groundwater. Natural replenishment rates to dry climate aquifers are historically low, thus leaving little room for excessive groundwater exploitation.

In recent years, significant attention has been directed towards restoration of groundwater supplies through artificial recharge most notably through the use of treated wastewater effluent. In arid areas, wastewater is an important resource which can be used for irrigation, power plant cooling, recreational lakes, landscaping, and other municipal purposes when adequately treated.

One form of artificial recharge involves the use of rapid-infiltration basins to apply sewage effluent and other wastewater to relatively permeable soils allowing it to percolate into the underlying vadose zone and geologic units. Increasingly known as Soil Aquifer Treatment or "SAT", this form of groundwater recharge actually acts as an advanced form of wastewater treatment by providing additional "polishing" of primary or secondary effluent using the soil mantle as a renovating filtration system.

In most systems, the wastewater is applied to the soil with infiltration basins. On sloping land, contour terraces or furrows can be used. Where topographies are very irregular, sprinkler systems can be used, but these require additional energy for pumping and also create aerosol problems. Application or "hydraulic loading" rates for rapid-infiltration systems are typically of the order of 20 to 150 meters per year. Since evapotranspiration rates are of the order of 0.5 to 2.5 meters per year, about 90 to almost 100 percent of the applied wastewater will move down to the groundwater.

Rapid-infiltration soil-aquifer treatment systems are capable of removing essentially all biodegradable organics, suspended solids, and bacteria and viruses from the wastewater. They can also remove almost all of the phosphorus and significantly reduce concentrations of nitrogen and heavy metals.

If properly designed, SAT systems can produce a clear, essentially odorless renovated water that can be used for unrestricted irrigation, primary contact recreation, and other purposes. Potable use requires additional treatment, including activated carbon filtration to remove refractory or trace organics, disinfection, and possibly reverse osmosis (Bouwer, 1985).

Historically, there have been several factors which have affected the overall success of past SAT projects including: adverse climatic conditions like extreme cold or excessive rainfall; incompatible subsurface conditions such as expanding clay layers; shallow depths to bedrock; thin soil mantles which become easily waterlogged; and an overall lack of available land area to adequately dispose of the required wastewater flows.

Recently, new attention is being given to sites throughout the world to use land not completely ideal for SAT applications. As mankind continually expands his occupation to new areas, municipalities and other agencies are forced to acquire whatever land may be available.

Principal issues requiring careful investigation by hydrogeologists faced with these situations include: the overall hydraulic loading capabilities of the surface soils and subsurface vadose zone, how the recharge basins will be designed and managed, what effects the underground flow system will have on the overall success of the system what level of water quality improvement is expected, and if any types of pre-treatment or post-treatment are required.

If hydrogeologists are careful in their analysis of land dedicated for recharge, many of the former obstacles once encountered can be overcome. Additionally, by first developing pilot test projects at questionable sites then performing quantitative research, hydrogeologists can gain new insight about the surface to subsurface relationships and the overall infiltration capabilities of difficult geologic terrains.

## SEDONA PROJECT HISTORY

Early in the 1980's, the City of Sedona, Arizona commenced negotiations for the purchase of a parcel of land within close proximity to it's western boundary for use as a wastewater treatment plant site. At the time of the purchase, little hydrogeologic information existed for the site.

As the Sedona site became more viable, thought was given to using the area as an effluent recharge site as well as a wastewater treatment plant site. With this decision a new series of site hydrogeologic investigations were required. Investigations into the subsurface geology commenced and it was originally believed that no serious obstructions for the recharge of treated effluent existed. The Arizona Department of Environmental Quality (ADEQ) was not entirely convinced and required the City of Sedona to submit additional hydrogeologic information before an Aquifer Protection Permit and Operational Permit would be issued.

Since the Sedona project was the first new wastewater facility in Arizona to require an Aquifer Protection Permit, a rather long and arduous task was in store for project engineers and hydrogeologists.

In order for Sedona to use the site selected several issues had to be evaluated before the project could commence any further. Paramount of these issues was the potential "hydraulic loading" capability of the surface soils and subsurface geologic strata.

It was deemed important to have some idea of the hydraulic loading rates and long-term infiltration capacity of the recharge basins prior to developing the site.

Since little existing information was available at Sedona, a decision was made to perform a series of infiltration tests on the site. Early attempts to fully characterize the sites potential proved inconclusive. To see what final hydraulic loading rates could be expected, Sedona opted to construct a pilot demonstration project to measure the hydraulic conductivity of the site.

## LOCAL GEOLOGIC AND HYDROGEOLOGIC CONDITIONS

### Regional Physiography

The region includes the northern valley of the Verde River bounded by the escarpment of the Mogollon Rim to the north and northeast and by the Black Hills to the southwest. The Mogollon Rim escarpment, which is the boundary between the Colorado Plateau Province and the Central Highlands Province, is a steeply sloping cliff that rises 1,000 to 2,000 feet from the Verde Valley floor to altitudes of 5,500 to 7,500 feet. The rim country is cut by steep walled canyons and south of the rim is a landscape of buttes and mesas.

The late Paleozoic section of this portion of central Arizona contains a broad range of siliciclastic and carbonate sedimentary rocks that were deposited in various continental, shoreline and shallow marine depositional systems.

The margin of the Colorado Plateau Province is a complex physiographic and structural feature with a history of development that probably encompasses all of Tertiary time, as well as an unknown portion of late Mesozoic time (Twenter, 1963).

## Regional Geology

The central Arizona region is comprised of several distinct topographic styles which to some extent reflect the different structural regions across the area.

The uplands of the southern Colorado Plateau (6,500 to 7,500 feet elevation) are generally capped with Tertiary basalt and are underlain by very gently north-easterly dipping Paleozoic strata. Several faults, the largest of which is the Oak Creek fault, disrupt the otherwise simple structural grain.

The southern ramparts of the Colorado Plateau, the Mogollon rim, are dissected into a series of spectacular canyons, buttes, mesas, and spires (4,000 to 6,000 feet elevation) and are composed chiefly of sandstones of the Schnebly Hill formation and Coconino sandstone.

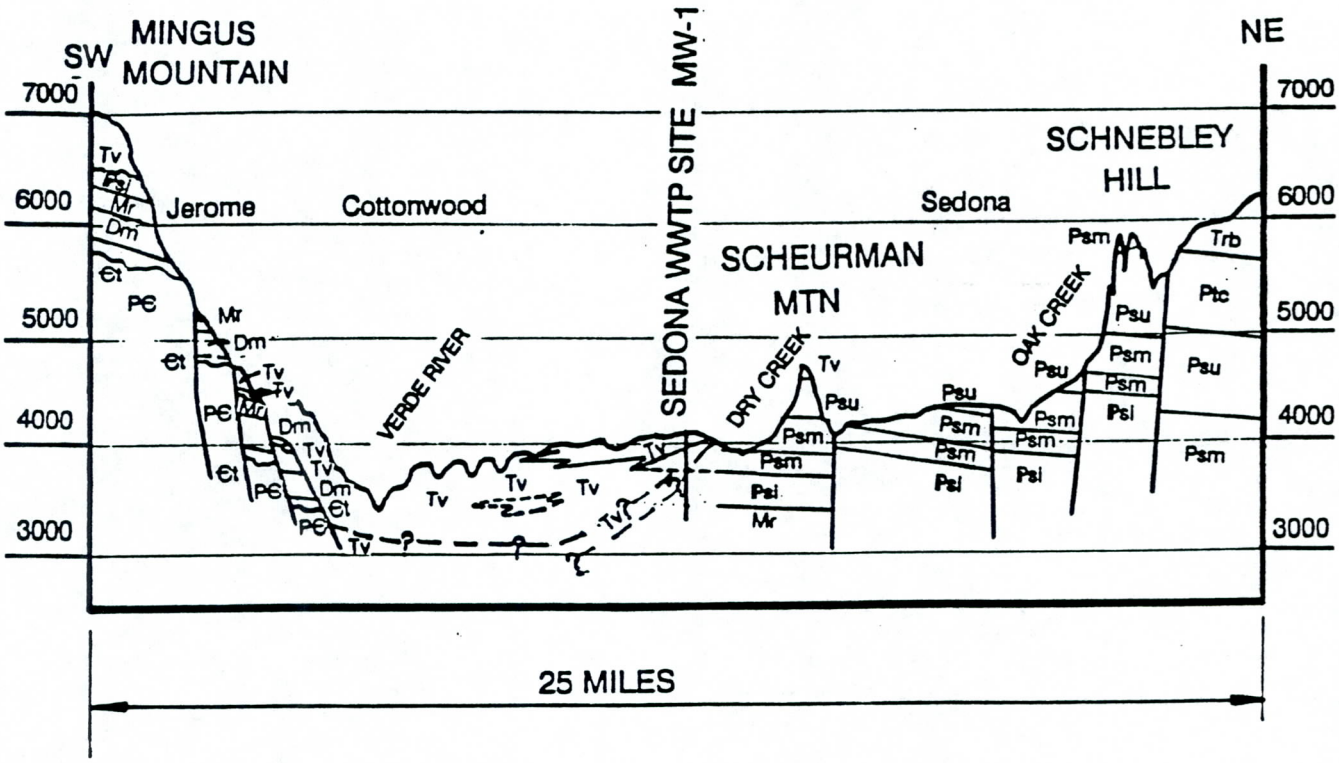
The Verde Valley is a fault-bounded, down-dropped block filled with Cenozoic fluvial-lacustrine deposits most notably the Verde formation and with basalt flows intercalated with sands and gravels known as the Hickey formation. This low region (3,500 to 4,500 feet elevation) consists of broad plains and valleys and low hills and mesas. Several tectonic faults have been mapped in the valley (Levings, 1980 and Moore, 1958).

## Site Geology

The Sedona Wastewater Facility lies in a shallow interridge alluvial basin adjacent to rocky slopes containing members of the Tertiary House Mountain volcanics formation.

The site is located in an area that separates the Pennsylvanian Supai group to the north from the Verde River alluvial basin to the south. Surface soils at the site generally consist of a thin layer of loose to medium dense sandy silts or silty sands underlain by stiff to very stiff sandy clays, dense claylike sand layers and then by volcanic bedrock at relatively shallow depth. The clays are a result of weathering of the volcanic rocks in the area.

Hard to very hard volcanic bedrock belonging to the House Mountain formation is found at depths of about fifteen feet. The House Mountain volcanics layer averages 50 to 60 feet in thickness across the site and was formed during violent local volcanic activity during the Tertiary age. House Mountain lies approximately five miles southeast of the site. During the course of its eruptions, massive basalt flows poured down the slopes of House Mountain and out onto the adjacent sandstone redbed formations, concealing them in this area. Local cinder cone activity also contributed to formation of the House Mountain member. During this same era of violent upheaval, the Mogollon Highlands and associated rim gravels of the area were created.




## SYMBOLS

| | | |
|---|---|---|
| Tv | - | Verde Formation |
| Tvh | - | Volcanics: House Mtn |
| Trb | - | Ramp Basalt |
| Ptc | - | Toroweap Formation and Coconino Sandstone |
| Psu | - | Supai Formation: Upper |
| Psm | - | Supai Formation: Middle |
| Psl | - | Supai Formation: Lower |
| Mr | - | Redwall Limestone |
| Dm | - | Martin Formation |
| Et | - | Tapeats Sandstone |
| PЄ | - | Precambrian |

Adapted From: Blakey & Middleton, Dept. of Geology, NAU 1988

# GEOLOGIC CROSS SECTION

SCHEMATIC

## Regional Hydrogeology

Groundwater in the Verde Valley and the Sedona areas is contained primarily in a regional aquifer which crosses many geologic formation boundaries. Formations which currently provide productive yields and collectively host the regional aquifer system include the Verde River Alluvium, the Verde Formation, Coconino Sandstone, Supai Formation, Naco Formation, Redwall Limestone, Martin Formation, and the Tapeats Sandstone. Spring, stream, and water well data indicates these rock units are hydraulically connected with groundwater flow and the potentiometric surface is controlled by the regional gradient, faults, lineaments, and solution channels.

In the Verde Valley most groundwater production is from the alluvium, Verde Formation, underlying basalts, Supai formation and the Redwall limestone. On the east side of the valley the predominant producer is the Supai formation and Redwall limestone underlying surficial Verde formation deposits and volcanics. In Sedona most wells produce from the middle and lower members of the Supai formation and Redwall limestone.

Water is primarily unconfined, with some confined conditions in the Verde, Supai, and Redwall formations. Near Page Springs the regional potentiometric surface is above ground level and some wells flow under artesian conditions.

The Supai formation is the most developed unit of the regional aquifer in the vicinity with most wells completed in fractured sandstone of the middle and lower members at depths of between 200 and 900 feet below land surface (Levings, 1980 and Langer, 1984).

## Site Hydrogeology

Sedona conducted many different types of vadose zone hydraulic conductivity measurement before deciding to construct a full scale pilot test project. Information derived from these measurements has been used as the basis for establishing the hydrogeologic characteristics of the site.

Infiltration rates play an important role in the ability of the plant to process and recharge treated wastewater effluent.

Some of the specialized vadose zone investigations applied to this project include: the construction of seven geotechnical borings augmented with borehole percolation tests; a series of fourteen 3-meter infiltrometer ring tests incorporating tensiometers; falling head permeability tests at six locations; site wide soil sampling and soil classification; air-entry permeameter tests at eight locations; and the installation of five eight-inch diameter piezometers to a depth of twenty feet coupled with slug testing.

Hydraulic conductivity (both vertical and horizontal components) were estimated by calculating the hydraulic loading rates for the three primary geologic units beneath the site, the surficial alluvium, the House Mountain volcanics, and the Supai sandstone. The lowest conducting material (disregarding secondary fracture conductivity), the House Mountain volcanics, limited the overall average hydraulic conductivity.

Results of the testing performed on the surface alluvial soils indicated vertical hydraulic conductivity values in the range of about 6 feet per day. The House Mountain formation which underlies the surface alluvium was the inhibiting conductive unit at this site and provided vertical hydraulic conductivity values in the range of one to one and a half feet per day. Vertical hydraulic conductivity in the Supai formation, as measured from pump step-drawdown tests, indicated a range of about 30 feet per day (Prinzhorn, 1990).

## Regional Aquifer Characteristics

Regional aquifer characteristics were difficult to quantify because well yields and pumping test data were strongly influenced by lithologic and facies changes across the formations and higher secondary hydraulic conductivity as a result of faults, fractures, and solution channels in the volcanics, sandstone, and limestone.

Well efficiencies are as variable as the physical characteristics and construction methods of the water wells. Regional well yields are typically less than 50 gallons per minute though some can produce as much as 1000 gallons per minute.

Aquifer test data indicates a range of transmissivities from 20 to 16,000 feet squared per day. Specific capacity ranges from 0.1 to 11 gallons per minute per foot indicate a heterogeneity of the regional aquifer. Storage coefficients for the regional aquifer are estimated to range from 0.005 to 0.01 (Levings, 1980).

## Site Aquifer Characteristics

A careful analysis of the local aquifer conditions in the site vicinity was performed by calculating the hydraulic transmissivity, unit porosity, groundwater velocity, and hydraulic conductivity of the aquifer. Additionally, a deep monitor well was constructed and a seven day pump test performed. Groundwater recharge mound calculations using both the Glover's and Hantush methods were performed to obtain information which may indicate a potential for groundwater waterlogging of the soils once recharge commenced.

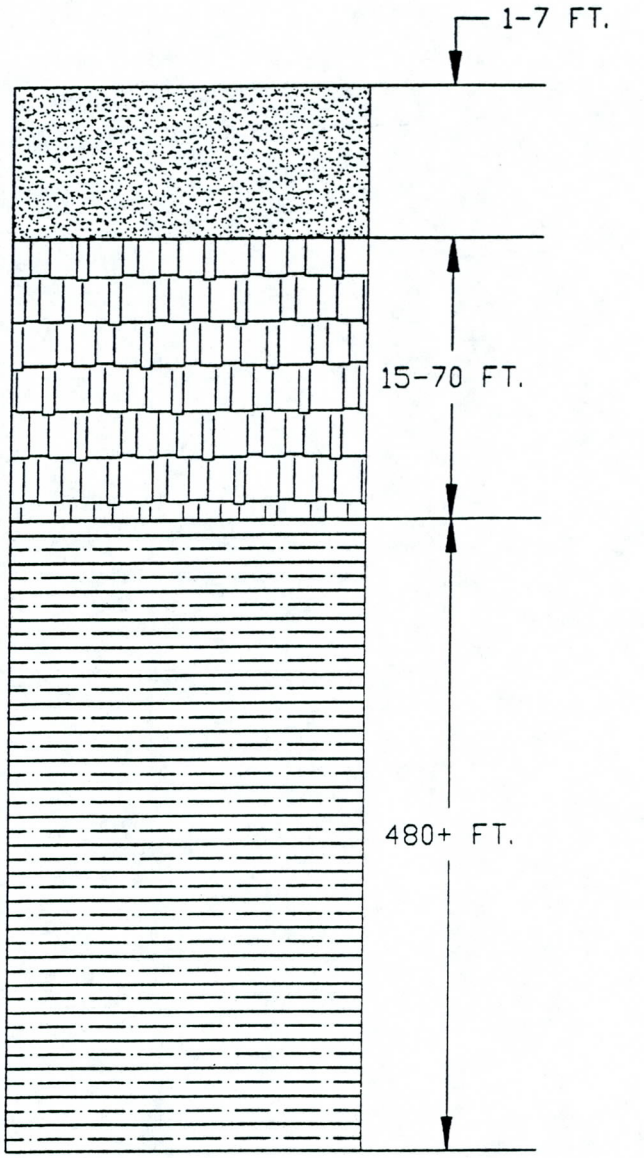
UNIT INFORMATION

UNIT THICKNESS

ALLUVIAL SURFACE SOILS
TEST METHOD: AIR ENTRY PERM.
Kv=5.92'/DAY±
Kh=.1010'/DAY±

HOUSE MOUNTAIN VOLCANICS
TEST METHOD: SLUG TEST
Kv=1.44'/DAY±
Kh=.1351'/DAY±

SUPAI FORMATION SANDSTONE
TEST METHOD: 7 DAY PUMP TEST
Kv=28.95'/DAY±
Kh=1.57'/DAY±




SEDONA WWTP SITE SUBSURFACE ANALYSIS RESULTS

## PILOT INFILTRATION BASIN TESTING

In order to obtain a better understanding of how the site would respond to groundwater recharge, Sedona made a decision to construct a full scale pilot infiltration basin project. The project was developed to not only satisfy regulatory questions, but to also assess that adequate land area had been purchased. If the results proved that the land area available was not adequate to completely dispose of the wastewater flows expected, then Sedona would be required to establish other reuse options.

The pilot project consisted of construction of a 6/10th acre basin with a depth of three feet supplied with water from an on-site monitor well constructed approximately 600 feet downgradient of the basin.

The basin was constructed using methods similar to what would be expected in the construction of the final project. Great care was taken to avoid overcompaction of the basin floor soils. Overcompaction of basin floor soils has created past problems for other SAT projects.

A concrete overflow spillway was constructed at an elevation of one foot above the basin floor. A small water depth was chosen in order to promote fast turnover of the wastewater in the basins during flooding and minimize growth of suspended algae that can clog the bottom soil directly by forming a filter cake on the surface and indirectly by causing precipitation of calcium carbonate due to pH increases as the algae remove carbon dioxide from the water during photosynthesis.

An on-site weather station was constructed to monitor local climatic conditions and an in-line water flow meter was attached to the inlet pipe to meter the quantity of water delivered to the basin each day.

Once the project commenced, daily weather readings were obtained for the site including: wind speed and direction, ambient air temperature highs and lows for the day, daily evaporation rates using a Class A evaporation pan, measurement of daily precipitation amounts, and recording of the actual water delivery as read from the water meter.

The overall pilot project was run for a total of 202 days in order to obtain a fairly good profile of how the basins would respond on a annual basis.

After careful analysis of the data obtained during the pilot project, it was determined that the expected hydraulic loading rate for the Sedona site could be expected to be about 0.21 feet per day or about 68,000 gallons per acre per day.

## CONCLUSION

Soil-aquifer treatment, or SAT, as obtained by using partially treated municipal wastewater for groundwater recharge and recovery, can play an important role in the treatment and storage of wastewater for reuse. Under favorable hydrogeologic conditions, SAT systems can produce water that can be used for irrigation purposes or, through additional treatment, be used for potable reuse.

As municipalities and others face difficulty in obtaining suitable land for wastewater treatment and recharge facilities, SAT siting also becomes increasingly more difficult. Hydrogeologists must carefully evaluate and perform additional testing on sites which may have unknown subsurface conditions or complex geologic structure.

The situation in Sedona proved to be unique because the subsurface geology of the area presented engineers and hydrogeologists with one of the most difficult sites ever encountered for a soil-aquifer treatment system.

Time-consuming and costly evaluations were performed and so far favorable results have been encountered but only time will tell how much the final SAT system will truly infiltrate. If preliminary indications from the pilot project remain correct, then Sedona has chosen an adequate site for a successful groundwater recharge project.

## REFERENCES


Bouwer, H., 1985. Renovation of Wastewater with Rapid-Infiltration Land Treatment Systems. In: Artificial Recharge of Groundwater,1985 Takashi Asano (Editor), Published by Butterworth, London, pp. 249-282.

Langer, W.H., 1984. Maps showing groundwater levels, springs, and depth to water, Basin and Range Province, Arizona. USGS WRI Report 83-4114-B.

Levings, G.W., 1980. Water Resources in the Sedona Area, Yavapai and Coconino Counties, Arizona. Arizona Water Commission, Bulletin 11.

Moore, R.T., 1958. Geologic Map of Yavapai County, Arizona. Arizona Bureau of Mines.

Prinzhorn, D.S., 1990. City of Sedona Phase I Wastewater Facilities Hydrogeological Study. Engineering-Science, Inc., Phoenix, Arizona.

Twenter, F.R., 1963. Geology and Groundwater in Verde Valley - The Mogollon Rim Region, Arizona. USGS Bulletin 1177.

# Part IV

# SURFACE WATER: RAINFALL-RUNOFF ANALYSIS AND INSTREAM SEDIMENT ACCUMULATION

# HEC-1 MODEL ASSESSMENT FOR SELECTED WATERSHEDS IN MARICOPA COUNTY, ARIZONA[1]

**Maximo R. De Vera[2]**

**ABSTRACT:** The US Army Corps of Engineers HEC-1 model has been applied to many watersheds in Maricopa County to estimate the peak flood of various return periods using a design storm. Basic input data files for 26 selected watersheds as formulated by various Consultants and Flood Control District staff have been re-run without modification using Version 4.0 of the model dated September 1990. Only the 100yr-24hr storm which is generally used for floodplain management studies has been used in the analysis. Multiple regression analysis using 23 watersheds shows a mean R-square of 0.83 for the linear model relating generated peak discharge to watershed characteristics. Correlation coefficent between unit peak discharge and various HEC-1 parameters have been determined. Results also show that the unit peak discharge which ranges from 30 to 1729 cfs/sq. mile are not significantly different from results of frequency analysis by USGS for gaged watersheds in the county, even at 1% significance level. In addition, some statistical characteristics of model parameters have been summarized for water resources planners and decision makers.

## INTRODUCTION

The planning and design of many water resources projects depend upon the results of hydrological studies. One of the most important tasks is the estimation of a design peak flow for a given return period as decided through guidelines and criteria set by a water resources planning and development agency or by the various cities and jurisdictions . In Maricopa County, usage of the HEC-1 model has a long history, as in many parts of the US and in the world. It is probably the most widely used hydrologic model in the United States.

In Maricopa County, a multi-agency task force representing various agencies and juristidctions was formed in 1985 under the auspices of the Flood Control District (FCD) to develop uniform policies and standards for drainage projects. Eventually, a Drainage Design Manual for Maricopa County was prepared consisting of 2 volumes, the first volume covers hydrology, which deal mostly on procedures dealing with the HEC-1 model. During the last 10 years, most of the hydrological studies done by the Flood Control District use the HEC-1 model to estimate peak floods. Few studies made use of SWMM of the Environmental Protection Agency and TR20 or TR55 of the

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USDA Soil Conservation Service.

This report is an analysis of input data and HEC-1 model results for 26 selected watershed in Maricopa County using the 100yr-24hr storm as input. Multiple regression analysis wa performed to determine how much of the variability in estimated peak discharges have been accounted for by various parameters used in the HEC-1 model. No rigid criteria was used i selecting the watersheds except that relative location was considered such that all conditions in th county are represented and that the original model input data is available. As a check on the applicability of results, a comparison with results of flood frequency analysis done by USGS fo gaged rivers in the county was performed.

## REVIEW OF RELATED REPORTS

An attempt to develop methods for estimating the magnitude and frequency of floods in Arizona was done by Roeske (1978). Regression equations that relate flood maagnitude to some watershed characteristics were developed using 221 gauging stations having 10 or more years c record. Some 29 statons are located in Maricopa County. Only drainage area, mean elevation anu mean annual precipitation were found significant in the regression analyses.

Garrett and Gellenbeck (1989) summarized the basin characteristics and streamflow statistic in Arizona as of 1989 with results of flood frequency anaysis using the log Pearson Type III method. The 100-yr flood peak estimated from instantaneous peak flow records have been presented in thi report for 29 stations located within Maricopa County.

In southeastern Arizona, the flood frequency characteristics of 18 watersheds have bee determined by Boughton and Renard (1984) with the development of a generalized envelope curv for 100-yr peak Q estimate for watersheds ranging from 0.01 to 4000 sq. miles in size. They found that the Roeske regression equation gives significantly lower 100-yr peak Q than their derive regression equation.

## BRIEF DESCRIPTION OF HEC-1 MODEL

HEC-1 was originally developed in 1967 by the Hydrologic Engineering Center of the US Army Corps of Engineers. Several subsequent revisions have been made to meet changing demands and technology. DeVantier and Fieldman(1993) noted that HEC-1 is a lumped rainfall-runo parameter model in which each sub-basin is taken as a hydrologic response unit and that it can also operate as a distributed model through use of small sub-basins and/or kinematic wave routing options. Basically, the model simulates the surface runoff response of a watershed to rainfall inpu through a system of interconnected hydrologic and hydraulic components (USACOE-HEC,1990). It allows a wide variety of options in specifying rainfall and its distribution, rainfall losses, baseflow, rainfall-runoff transformation and routing.

Use of the HEC-1 model at the Flood Control District has been made easier with the preparation of Drainage Design Manual for Maricopa County, Volume 1, Hydrology which include two HEC-1 input loader programs, MCUHP1 for Clark Unit Hydrograph and MCUHP2 for S-Grap options. Most of the modeling performed prior to publication of the manual in 1990 made use of SCS Type II rainfall distribution, and later rainfall distribution patterns deemed more appropriate t

Maricopa County conditions were developed and included in the input loader programs. The loader program generates a rainfall pattern depending on the size of the drainage area. As the pattern number increases from 1 to 5, the rainfall intensity decreases. Depth-area adjustments were made based on recommendations from NOAA Technical memorandum NWS Hydro-40 (Zehr, R.M. and V. A Myers, 1984).

The transformation of rainfall excess into sub-basin outflow in so far as modeling in Maricopa County is concerned used either the Clark Unit Hydrograph or the S-graph options. Kinematic wave routing through sub-basins overland flow regimes is done for some watersheds. Flood wave movement through the river reaches and reservoirs or detention basins have been simulated using such methods as Muskingum, Muskingum-Cunge and Modified Puls methods.

## SELECTED WATERSHED

Table 1 shows the selected watersheds and some of the characteristics. The location of the watersheds are shown in Figure 1. The drainage area covers a wide range from 5.13 to 476.16 square miles approximating the drainage area of most gaged watersheds in the county. It can be noted that in sub-dividing the watersheds into sub-basins no specific criteria was imposed on Consultants. Identification of sub-basin concentrations points is mostly based on available USGS topographic map of 1:24,000 scale (7.5 minutes series). For the selected watersheds, the number of sub-basins ranges from 3 to 211. The length, highest and lowest elevation were taken from the watershed or hydrologic network map. The length of watershed ranges from 4.1 to 37.1 miles.

## HEC-1 MODEL PARAMETERS

The HEC-1 data file for the various watersheds have been re-run without any modification using Version 4 dated September 1990. Except for one watershed where the RK record was slightly modified, no serious run errors were encountered. A data retrieval computer program in Fortran 77 was developed to summarize input parameters and compare them with model parameters extracted from the HEC-1 output file. Table 2 shows the mean values of sub-basin area, areally reduced rainfall, loss parameters, and some routing parameters. These were used to calculate the peak discharge at the concentration point of each delineated sub-basin. The rainfall depth indicated by either the PB or JD record has been extracted from the input file. Where a JD record is specified only the rainfall depth for the smallest drainage area is considered. The basic rainfall data was taken from the NOAA Atlas. The areally reduced 100 yr-24 hr rainfall depth varies from 3.28 inches for Wagner Wash to 4.8 inches for Rodger Creek.

Rainfall loss parameters that have been used in Maricopa County fall into 3 categories: (1) initial-uniform loss rates using LU record, (2) SCS curve number using LS record and (3) Green and Ampt loss rate parameters using LG record. To facilitate watershed modeling, a Lotus 1-2-3 spreadsheet was developed for computation of the Green and Ampt parameters based upon soil type. With the GIS system land use and soils area delineation have been facilitated. In addition, slope adjustment factor is also included to account for effect of steep slopes. Green and Ampt parameters were used in 12 out of the 26 watersheds. No other loss rates have been used.

The unit graph or other kinematic data used includes the UI for S-graph, UA for Clark or Snyder methods, UC for Clark Unit Hydrograph and UD record for SCS Dimensionless Unit Graph.

## Table 1 - Selected Watersheds and Some Characteristics

| WATERSHED | DA(m-sq) | No.SB | L(miles) | H.Elev | L.Elev | Recip.Bf | REFERENCE REPORT |
|---|---|---|---|---|---|---|---|
| 1. Apache Wash | 32.46 | 30 | 12.9 | 3100 | 1320 | 5.13 | J.R. Jones, Jul 1990 |
| 2. Bender Wash | 77.9 | 23 | 22.8 | 3800 | 1126 | 6.67 | FCD-WSMB, Apr 1991 |
| 3. Buchanan Wash | 11.28 | 13 | 6.2 | 2269 | 1435 | 3.41 | Huitt-Zollars, Inc, Mar 1990 |
| 4. Cave Creek (lower) | 34.71 | 36 | 24.1 | 2045 | 1236 | 16.73 | Burgess & Nipple Jan 1990 |
| 5. Cline Creek | 16.01 | 13 | 7.3 | 4690 | 2000 | 3.33 | Baker Engineers, Dec 1989 |
| 6. Deadman Wash | 32.57 | 51 | 10.7 | 3176 | 1430 | 3.52 | SEA, Inc.,Sept 1990 |
| 7. Eagletial | 134.15 | 55 | 17.1 | 2400 | 1300 | 2.18 | FCD-JRG/TWL, Mar 1993 |
| 8. Hidden Valley | 28.48 | 90 | 12.1 | 2698 | 976 | 5.14 | Cella Barr Assoc, Sep 1991 |
| 9. Jackrabbit Wash | 476.16 | 114 | 35.6 | 3382 | 1050 | 2.66 | Burgess & Nipple May 1991 |
| 10. Moon Valley Wash | 7.25 | 15 | 4.1 | 2039 | 1300 | 2.32 | Kaminski Hubbard Dec 1991 |
| 11. Morgan City Wash | 23 | 13 | 11.6 | 3550 | 1300 | 5.85 | Baker Engineers, Dec 1989 |
| 12 Queen Creek | 244.34 | 117 | 16.9 | 3104 | 1320 | 1.17 | Wood & Associates, Jan 1991 |
| 13. Rodger Creek | 5.13 | 3 | 6.1 | 2840 | 1910 | 7.25 | Baker Engineers, Dec 1989 |
| 14. San Domingo Wash | 20.28 | 16 | 10.9 | 4237 | 1860 | 5.86 | FCD-SS Jun 1989 |
| 15. Sand Tank Wash | 157.77 | 46 | 21.4 | 3720 | 807 | 2.90 | FCD-WSMB, Apr 1991 |
| 16 Scatter Wash | 15.58 | 29 | 7.1 | 2100 | 1350 | 3.24 | Kaminski Hubbard, May 1992 |
| 17. Scottsdale Alluvial Fan | 32.54 | 29 | 13.1 | 4000 | 3100 | 5.27 | FCD-AA/AMM, May 1991 |
| 18. Skunk Creek | 23.78 | 38 | 11.2 | 2100 | 1180 | 5.28 | Coo & Van Loo, Nov 1990 |
| 19. Tiger Wash | 159.08 | 9 | 22.7 | 5681 | 1380 | 3.24 | FCD-Waters, Jul 1991 |
| 20 Tonto Verde W.#10 | 6.66 | 5 | 10.2 | 3055 | 1550 | 15.62 | Wiley & Associates, Jul 1992 |
| 21. Upper Cave Creek | 109.23 | 63 | 16.7 | 5293 | 2000 | 2.55 | CH2M Hill, Mar 1990 |
| 22. Upper Centennial Wasl | 451.53 | 40 | 34.5 | 4800 | 2040 | 2.64 | URS Consultants, Apr 1990 |
| 23. Wagner Wash | 42.07 | 83 | 13.5 | 1765 | 1240 | 4.33 | FCD-WSMB, Jan 1991 |
| 24. Waterman Wash | 401.57 | 18 | 37.1 | 3800 | 860 | 3.43 | Cella Barr Assoc., Sept 1988 |
| 25. White Tank #3 Wash | 21.32 | 10 | 6.7 | 4083 | 1200 | 2.11 | FCD-Rice/Plasencia, Oct 1989 |
| 26. Wittman | 322.99 | 211 | 29.1 | 4250 | 1340 | 2.62 | WLB Group modified by FCD |
| Total | 2887.84 | 1170 | | | | | |

Notes: H.ELEV - highest elevation in feet
L.ELEV - lowest elevation

Recip.Bf = Reciprocal of Basin Factor defined by DA/L squar

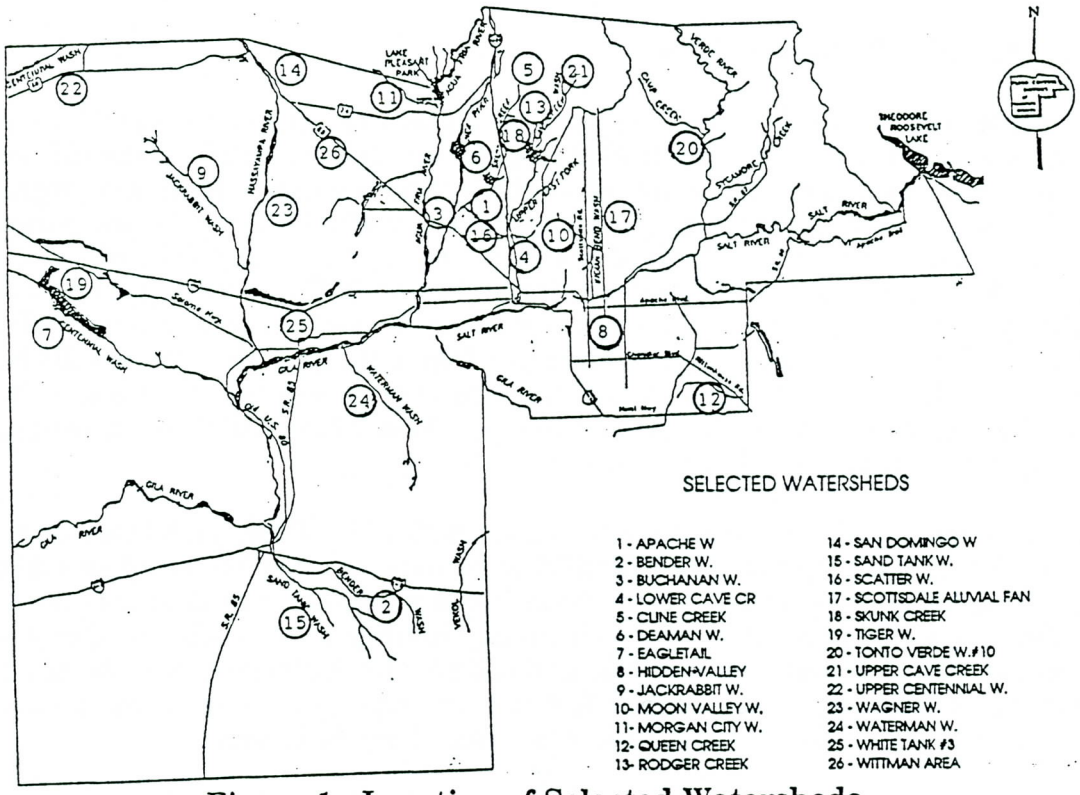


**Figure 1 - Location of Selected Watersheds**

**Table 2 - Mean Sub-basin Size, Rainfall, Loss Parameters, Lag Time or Unit Hydrograph Time to Peak and Unit Peak Q**

| Watershed | Mean SB Area | Rd.Rfl | Pattern | Option | Dtheta | Xksat | Rtimp | Inilos | Cnslos | Curnbr | SCSLag | Uh2pk | Unit PQ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Apache Wash | 1.082 | 4.61 | SCS Type II | PB | | | 0.81 | 0.36 | | 84.8 | 0.39 | | 1729 |
| 2. Bender Wash | 3.387 | 4.53 | ditto | JD | 0.28 | 0.16 | 4.19 | | | | | 1.87 | 127 |
| 3. Buchanan Wash | 0.868 | 4.13 | ditto | PB | | | | 0.34 | | 85.5 | | | 233 |
| 4. Cave Creek (lower) | 0.964 | 3.96 | ditto | PB | | | 31.8 | 0.35 | 0.19 | | 0.43 | | 583 |
| 5. Cline Creek | 1.232 | 4.08 | ditto | JD | | | 4.08 | 0.78 | 0.18 | | 0.55 | | 1028 |
| 6. Deadman Wash | 0.639 | 4.33 | ditto | PB | | | 0.84 | | | 83.9 | | | 868 |
| 7. Eagletail | 2.439 | 3.44 | ditto | PB | 0.28 | 0.38 | 3.81 | | | | | 6.09 | 28 |
| 8. Hidden Valley | 0.316 | 3.78 | ditto | PB | 0.17 | 0.38 | 12.6 | | | | 0.71 | | 37 |
| 9. Jackrabbit Wash | 4.177 | 4.2 | ditto | JD | 0.34 | 0.45 | 4.53 | | | | | 5.04 | 72 |
| 10. Moon Valley Wash | 0.483 | 3.69 | ditto | PB | 0.3 | 0.28 | 35.7 | | | | 0.44 | | 628 |
| 11. Morgan City Wash | 1.769 | 4.5 | ditto | JD | | | 30.1 | 0.89 | 0.37 | | 0.65 | | 617 |
| 12 Queen Creek | 2.088 | 3.62 | ditto | JD | | | | 0.56 | | 77.9 | 2.01 | | 48 |
| 13. Rodger Creek | 1.718 | 4.8 | ditto | PB | | | | | | | | | 1202 |
| 14. San Domingo Wash | 1.268 | 4.6 | ditto | JD | | | | 0.57 | 0.08 | | 0.38 | | 1259 |
| 15. Sand Tank Wash | 3.429 | 4.53 | ditto | JD | 0.29 | 0.17 | | | | | | 1.82 | 166 |
| 16 Scatter Wash | 0.537 | 3.72 | ditto | PB | 0.29 | 0.68 | 19.46 | | | | 0.39 | | 302 |
| 17. Scottsdale Alluvial F | 1.122 | 4.33 | SCS Type IIA | PB | 0.36 | 0.32 | 5.03 | | | | | 7.39 | 523 |
| 18. Skunk Creek | 0.626 | 3.9 | ditto | JD | 0.31 | 0.27 | 19.58 | | | | 0.88 | | 283 |
| 19. Tiger Wash | 17.675 | 3.45 | SCS Type II | PB | 0.26 | 0.27 | 8.08 | | | | | 5.61 | 205 |
| 20 Tonto Verde W.#10 | 1.332 | 4.35 | FCD-Pattern | PB | 0.34 | 0.15 | | | | | | | 397 |
| 21. Upper Cave Creek | 1.734 | 4.25 | SCS Type II | PB | | | 0 | 0.67 | 0.11 | | 0.51 | | 372 |
| 22. Upper Centennial V | 11.288 | 4.05 | ditto | JD | 0.31 | 0.29 | 0 | | | | 2.12 | | 48 |
| 23. Wagner Wash | 0.507 | 3.28 | FCD-Pattern | JD | | | | 0.79 | 0.23 | | 0.58 | | 374 |
| 24. Waterman Wash | 22.309 | 3.98 | SCS Type II | PB | | | | | | 79.13 | 4.46 | | 80 |
| 25. White Tank #3 Wash | 2.132 | 4.2 | ditto | PB | | | | | | 82.2 | | | 409 |
| 26. Wittman | 1.531 | 4.21 | ditto | JD | | | | | | | | | 30 |

Based on review of the input data for most watersheds, flow diversions have been retrieved back into the watershed, except for a few cases such as White Tank and Jackrabbit watersheds. In general, the effect of flow diversions have been neglected in the computation of watershed unit peak discharge.

## HEC-1 MODEL RESULTS

The results of HEC-1 modeling have been summarized for each selected watershed, an example of which is shown in Appendix A for Skunk Creek Watershed. Also included are the rainfall and its assumed distribution, the computation interval, IT; input tabulation interval, IN; the rainfall loss; some routing parameters and the peak discharge of each delineated sub-basin. Sub-basin names have been included for possible GIS applications of the results. The unit peak discharge and the different measures of central tendencies have been calculated for purposes of comparative analysis.

Statistical analyses of the results have been done using a package called "STATIT" as released by Stateware (1990). This statistical software packge is a modular system for interactive users in UNIX environment. In the multiple regression analysis done for each watershed, the unit peak flow generated using HEC-1 model is expressed as a linear function of the selected parameters. Only 23 watersheds have a sufficient number of sub-basins for the analyses. Table 3 shows the summary of multiple regression analyses results for watersheds with at least R-sq=0.8. The F-ratio, which is a criteria for significance of the regression line, are all greater than F-tabulated given in statistical tables, even 1% significance level. This implies that the regression function is a good predictor of the dependent variable.

Correlation coefficients of the various HEC-1 parameters used to calculate the unit peak

discharge have been determined for each watershed having an adequate number of sub-basins. Table 4 shows the correlation coefficients between unit peak discharge and the selected parameters.

## RELIABILITY OF MODEL GENERATED PEAK FLOW

The reliability of the peak flow estimate is important to any flood control structural design. In general, hydrologic models are calibrated using observed rainfall and instantaneous flood peak discharge data for a given watershed. In many places, this is not possible, hence the use of design storm. The relibility of the model can be improved by comparison with actual flood discharge data.

**Table 3 - Summary of Multiple Regression Analyses Results**

| WATERSHED | A(Intercept) | B1 *X1 | B2 *X2 | B3 *X3 | B4 *X4 | B5 *X5 | R-sq | SEE | F-Ratio |
|---|---|---|---|---|---|---|---|---|---|
| Apache Wash | 45369.38 | 77.76 * DA | -14698 * IA | -421.05 *CRVN | 20.28 * RTIMP | -3603.1 * SCSLAG | 0.839 | 332.21 | 24.92 |
| Bender Wash | 1609.55 | -62.66 *DA | -803.02 * DTHETA | -1759 * XKSAT | -6.01 * RTIMP | -296.64 * UHT2PK | 0.799 | 172.28 | 13.53 |
| Buchanan Wash | -82188.19 | -134.2 * DA | 28660 * IA | 857.58 *CRVNO | | | 0.831 | 250.48 | 14.66 |
| Cave Creek (Lower) | 2747.08 | -161.2 *DA | -282.77 *INILOS | -1082.1 *CNCLOS | -1.03 * RTIMP | -1708.1 *SCSLAG | 0.932 | 126.07 | 82.25 |
| Cline Creek | 2628.69 | -40.32 *DA | -400.73 *INILOS | -401.33 *CNSLOS | 3.05 *RTIMP | -1501.2 *SCSLAG | 0.988 | 32.24 | 114.59 |
| Eagletail | 1434.16 | -7.3 *DA | -614.66 *DTHETA | -867.61 *XKSAT | 2.21 *RTIMP | -54.75 *UHT2PK | 0.809 | 89.97 | 41.38 |
| Hidden Valley | 1764.84 | 140.13 * DA | -705.62 *DTHETA | -449.99 * XKSAT | 7.02 * RTIMP | -1045.3 * TC | 0.893 | 112.029 | 28.47 |
| Jackrabbit Wash | 1529.48 | -6.71 * DA | -15.94 *DTHETA | -548.37 * XKSAT | -121.88 *UHT2PK | 0 | 0.798 | 112.04 | 51.25 |
| Moon Valley Wash | 1718.35 | 336.37 * DA | -20.31 *DTHETA | -481.72 *XKSAT | 3.13 * RTIMP | -135.83 * TC | 0.944 | 82.57 | 30.71 |
| Morgan City Wash | 2350.11 | 46.59 * DA | -145.78 * IA | -693.04 * CNSLOS | -1.37 * RTIMP | -1371.9 * SCSLAG | 0.986 | 36.48 | 97.02 |
| Queen Creek | 608.81 | 14.38 * DA | -402.01 * STRTL | 0.16 * CRVNBR | -85.79 *SCSLAG | 0 | 0.924 | 23.96 | 161.97 |
| San Domingo Wash | 6090.67 | -58.88 * DA | -6498.2 *INILOS | 3061.87 *CNSLOS | -2089.7 * SCSLAG | 0 | 0.988 | 40.56 | 217.37 |
| Sand Tank Wash | 1083.54 | -13.02 * DA | 1097.2 * DTHETA | -838.01 *XKSAT | -232.24 * UHT2PK | 0 | 0.847 | 109.09 | 56.66 |
| Satter Wash | 2145.11 | 137.38 * DA | -1704.1 *DTHETA | 4.06 * XKSAT | 2.01 * RTIMP | -1203 * SCSLAG | 0.853 | 117.39 | 26.77 |
| Scottsdale Aluvial Fan | 2164.87 | -4.21 * DA | -1913.5 * DTHETA | 110.67 * XKSAT | 4.77 * RTIMP | -71.13 * UHT2PK | 0.849 | 168.37 | 33.65 |
| Skunk Creek | 1545.82 | 19.82 * DA | 529.15 *DTHETA | -757.93 * XKSAT | 0.38 * RTIMP | -745.79 * TC | 0.858 | 137.06 | 38.67 |
| Tiger Wash | 820.47 | -5.35 * DA | -911.77 * DTHETA | 199.32 *XKSAT | -9.83 * RTIMP | -23.53 * UHT2PK | 0.965 | 27.92 | 16.59 |
| Upper Cave Creek | 2371.24 | 29.72 * DA | -706.46 * CNSLOS | -1462 * SCSLAG | 0 | 0 | 0.854 | 241.03 | 114.62 |
| Upper Centennial Wash | 1060.96 | 1.93 * DA | -1963.3 * DTHETA | 620.44 * XKSAT | -173.17 * SCSLAG | 0 | 0.867 | 55.88 | 57.22 |
| Wagner Wash | 5856.51 | 575.94 * DA | -1745.7 * INILOS | 1440.93 * CNSLOS | -5216.7 * TC | 0 | 0.723 | 705.27 | 33.35 |
| Waterman Wash | -137.81 | -1.68 * DA | 5.54 * CRVNO | -22.02 * SCSLAG | 0 | 0 | 0.866 | 24.71 | 30.26 |

Note: Deadman Wash, Rodger Creek, Tonto Verde Wash #10, White Tank #3 and Wittman Area are not included. R < 0.5
Unit Peak Discharge = A + B1X1 + B2X2 + B3X3 + B4X4 + B5X5
Multiply R-sq by 100 to get % accounted in variability of unit peak discharge

**Table 4 - Model Parameters Correlation Coefficient With Unit Peak Q**

| WATERSHED | NO.SB | SB-AREA | DTHETA | XKSAT | IA/INILOS | CNSLOS | CRVNBR | RTIMP | LAG/TC | UHT2PK |
|---|---|---|---|---|---|---|---|---|---|---|
| Apache W. | 30 | -0.14 | | | -0.21 | | 0.21 | -0.01 | -0.91 | |
| Bender W. | 23 | -0.69 | -0.31 | -0.34 | | | | 0.31 | | -0.85 |
| Buchanan W. | 13 | -0.27 | | | -0.72 | | 0.75 | | | |
| Lower Cave Cr | 36 | -0.41 | | | 0.12 | -0.54 | -0.37 | | -0.95 | |
| Cline Creek | 13 | 0.09 | | | -0.47 | -0.51 | | -0.02 | -0.93 | |
| Deadman W. | 51 | -0.53 | | | | | 0.09 | 0.01 | | |
| Eagletail | 55 | -0.24 | 0.59 | -0.49 | | | | 0.24 | | -0.85 |
| Hidden Valley | 90 | -0.22 | 0.61 | -0.32 | | | | 0.53 | -0.77 | |
| Jackrabbit W. | 114 | -0.45 | -0.27 | -0.56 | | | | | | -0.79 |
| Moon Valley W. | 15 | 0.37 | -0.09 | -0.43 | | | | -0.03 | -0.94 | |
| Morgan City W. | 13 | -0.25 | | | 0.37 | -0.28 | | 0.06 | -0.96 | |
| Queen Creek | 117 | -0.49 | | | -0.73 | | 0.26 | | -0.79 | |
| San Domingo W. | 16 | -0.21 | | | -0.69 | -0.76 | | | -0.98 | |
| Sand Tank W. | 46 | -0.63 | -0.51 | -0.55 | | | | | | -0.91 |
| Scatter W. | 29 | -0.48 | -0.79 | -0.54 | | | | 0.74 | -0.81 | |
| Scottsdale Al.Fan | 29 | -0.22 | -0.27 | 0.23 | | | | 0.52 | | -0.91 |
| Skunk Creek | 38 | -0.33 | -0.26 | -0.44 | | | | 0.31 | -0.87 | |
| Tiger W. | 9 | -0.56 | -0.76 | -0.68 | | | | 0.27 | -0.74 | |
| Upper Cave Cr | 63 | -0.61 | | | | -0.47 | | | -0.92 | |
| Upper Centennial | 40 | -0.59 | -0.06 | -0.05 | | | | | -0.91 | |
| Wagner W. | 83 | -0.49 | | | 0.01 | 0.13 | | | -0.84 | |
| Waterman W. | 18 | -0.79 | | | | | 0.29 | | -0.91 | |
| Wittman | 211 | -0.58 | | | 0.21 | | | | | |
| TOTAL | | -8.72 | -2.06 | -4.17 | -2.11 | -2.43 | 1.23 | 2.93 | -13.23 | -4.31 |
| Mean | | -0.38 | -0.19 | -0.37 | -0.23 | -0.41 | 0.21 | 0.24 | -0.88 | -0.86 |

Some Consultants of the Flood Control District have attempted to compare model generated peak flows with results of frequency analysis of available peak discharge data. The length and period of record are issues which often make the comparison unrealistic. In a flood insurance study for Waterman Wash by CBA (1988), several comparisons of the 100 yr flood near Buckeye (Gauge No. 09514200) were made as follows: (1) frequency analysis of 12 years data, Q=11800 cfs; (2) available regression equation (Roeske, 1978), Q=16400 cfs; (3) log Pearson Type F.A for 22 yrs record Q=9000 cfs. It can be noted that the 12 years or the 22 years record is not representative of the 100 year period. The cyclic pattern of hydrologic data may come into the picture. In a study of the cyclic behavior of runoff and precipitation in Arizona, Creighton (1990) raised questions on the validity of frequency analysis method being used in Arizona. He emphasized the need for assessment of the primary assumptions of randomness and non-cyclic behavior of historical streamflow data. If the available record used for frequency analysis is in the wet cycle period, the estimated peak flow would be relatively higher than those in the dry cycle period.

The model generated peak flows resulting from assumed long term rainfall have been compared to results of frequency analysis of available streamflow data by USGS using log Pearson Type III method as reported by Garrett and Gelenback (1989). Appendix B shows data for 29 stations in Maricopa County. Fig. 3 shows the station location. Statistical results show a generated unit peak discharge mean of 448 cfs for HEC-1 model and 409 cfs for USGS frequency analysis. Standard deviations are 444 cfs and 446 cfs, respectively. The probability value for equality of population variances is 0.99114. This implies that the model generated unit peak Q's using HEC-1 are not significantly different from results of frequency analyis as reported by USGS even at the 1% significance level.

## CONCLUSIONS AND RECOMMENDATIONS

The results of HEC-1 modeling have been presented for 26 selected watersheds in Maricopa County. These models have been formulated by various Consultants of the Flood Control District and also by the District technical staff. The different variables that affect the peak discharge have been assumed to be independent of each other. Their choice and quantification depend upon the modeler's criteria. Statistical analysis was performed to determine how much of the variability of peak discharge estimates have been accounted for by the chosen independent variables.

The results of multiple regression analyses show that in most watersheds studied, more than 80% of the variability in 100yr-24hr peak discharge have been accounted for by the chosen variables. Only 3 watersheds have R-square less than 0.8 excluding 3 in which number of samples or sub-basins are not sufficient for regression analysis. The mean value of the R-square is 0.83.

Analysis of the correlation matrix shows that lag time, time of concentration or unit hydrograph time to peak have the highest correlation coefficient of 0.88 with the unit peak discharge. This parameter should therefore be determined as accurately as possible in any HEC-1 modeling.

Two sample t-test statistics were used to compare the model generated peak discharges with results of frequency analysis done by USGS for 29 gaging stations in Maricopa County. There is no significant difference in means and variances of the estimates even at the 1% significance level. This implies that the HEC-1 model peak discharges are as good as those derived by frequency analysis,

at least for the 100yr-24 hr floods which are being used for floodplain delineation and design c landfill drainage facilities as required by the Department of Environmental Quality.

With peak discharge estimates for each identified sub-basin in each watershed and with th various HEC-1 model parameters already determined it is possible to facilitate future hydrologic studies using GIS methodologies.

Similar type of analysis could be done to include unit peak discharge of various return periods of 5, 10, 25 and 50 years. This could be useful in the development of iso-runoff lines for Maricopa County as a guide for hydrologic studies. The results can also be useful for flood contrc planners and decisions makers.

## REFERENCES


Baker Engineers. Cline Creek Floodplain Delineation Study. Hydrology Report. Prepared for FCD January 1990.

Boughton, W.C. and K.G. Renard. 1984. Flood Frequency Characteristics of Some Arizona Watersheds. AWRA Water Resources Bulletin. Vol 20(5), pp 761-769.

Burgess & Nipple, Inc. Cave Creek Floodplain Delineation, Cave Buttes Dam to the Arizona Canal Diversion Channel, Final Hydrology Report, Prepared for FCD. Jan. 1990.

_____. Jackrabbit Wash Floodplain Delineation Study Report. Prepared for FCD. February 1990.

Cella Barr Associates. Flood Insurance Study-Waterman Wash Hydrologic Analysis Report. Prepared for FCD. September 1988.

CH2M Hill, Inc. Upper Cave Creek Floodplain Delineation Study Prepared for FCD. March 1990.

Coo & Van Loo, Inc. Skunk Creek Flood Insurance Study, Between Arizona Canal Diversion Channe and Central Arizona Project. Prepared for FCD. November 1991.

Creighton, Jr. D.E. 1990. Cyclic Streamflow Test for Validity of Randomness. J. Proceedings of th International Symposium on Hydraulics/Hydrology of Arid Lands, sponsored by ASCE, July 30-Aug 2, 1990. San Diego, California.

DeVantier, B.A. and A.D. Feldman. 1993. Review of GIS Applications in Hydrologic Modeling. J. of Water Resources Planning and Management. Vol 119(2). Mar/Apr 1993. pp 246-262.

FCD. Hydrologic Analysis of Bender and Sand Tank Washes. Gila Bend, Arizona, Technical Data Handbook, April 1991.

Garrett, J.M. and D.J. Gellenbeck. 1989. Basin Characteristics and Streamflow Statistics for Arizona as of 1989. USGS Water Resources Investigation Report 91-4041, prepared in cooperation

with Arizona Department of Transportation and Flood Control District of Maricopa County. 612p.

Huitt-Zollars, Inc. Buchanan Wash Drainage, Storm Master Plan Report.Prepared for FCD. March 1990.

J.R. Jones & Associates. Apache Wash Area Drainage Master Study. Drainage Report in 2 volumes. Prepared for FCD. July 1990.

Kaminski Hubbard Engineering. Scatter Wash Watershed ACDC-ADMS Hydrology Report. Prepared for FCD May 1993.

Roeske, R.H. 1978. Methods for Estimating the Magnitude and Frequency of Floods in Arizona, Final Report on Research Project - Arizona HPR-1-15(121) USGS, Water Resources Division, Tuczon, Arizona. 82p.

Sabol, G.V. J.M.Rumann, D.Khalili and S. D. Waters. 1992. Drainage Design Manual for Maricopa County. Volume 1 - Hydrology. Flood Control District of Maricopa County, Phoenix, Arizona

SEA, Inc. Deadman's Wash Area Drainage Master Study, Vol. 1. Report Preapred for FCD. September 1990.

Stateware, Inc. 1990. STATIT. 260 SW Madison Avenue. Corvallis, Oregon

URS Consultants, Inc. Upper Centenial Wash Floodplain Delineation Study.for FCD. April 1990.

USACOE-HEC. 1990. HEC-1 Flood Hydrograph Package, User's Manual. US Army Corp of Engineers, Hydrologic Engineering Center, Sept 1990 Version 4, Davis, California.

Wiley & Associates, Inc. Tonto Verde Master Drainage Plan. Prepared for Rio Verde Services, Inc.July 1990.

WLB Group. Wittman Area Drainage Master Study. Part A: Hydrology and Hydraulics. Prepared for FCD. March 1989.

Wood and Associates, Inc. Queen Creek Area Drainage Master Study Report.Prepared for FCD. August 1991.

Zehr. R.M. and V.A. Myers. 1984. Depth-Area Ratios in the Semi-Arid Southwest United States. NOAA Technical Memorandum NSW HYDRO-44, Office of Hydrology, Silver Springs, Maryland. 45p.

**Disclaimer:**

**The views and opinions expressed in this paper are those of the author and does not necessarily reflect those of the Flood Control District of Maricopa County.**

## Appendix A - Sample Data Table Compiled for Each Watershed

SKUNK CREEK WATERSHED (between ACDC and CAP)

100yr-24hr storm — Coo & Van Loo

SCS TYPE II

| SUB-BAS | DA(SQ.MI) | DTHETA | XKSAT | RTIMP | TC | STOR.K | PEAK Q | Unit PQ | Est. UPQ | DIFF |
|---|---|---|---|---|---|---|---|---|---|---|
| 5S | 1.33 | 0.27 | 0.16 | 4.00 | 0.52 | 0.16 | 1906.00 | 1430.93 | 1207.527 | 223.40 |
| 20S | 1.38 | 0.29 | 0.17 | 0.00 | 0.75 | 0.35 | 1408.00 | 1021.03 | 1038.415 | -17.38 |
| 35S | 1.51 | 0.31 | 0.23 | 0.00 | 0.87 | 0.45 | 1275.00 | 842.14 | 916.7028 | -74.56 |
| 40S | 0.55 | 0.26 | 0.12 | 6.00 | 0.52 | 0.25 | 737.00 | 1352.29 | 1217.713 | 134.58 |
| 55S | 0.59 | 0.32 | 0.29 | 0.00 | 0.77 | 0.60 | 416.00 | 707.48 | 932.7442 | -225.26 |
| 60S | 1.20 | 0.27 | 0.15 | 8.00 | 0.93 | 0.49 | 1084.00 | 901.83 | 908.2719 | -6.44 |
| 90S | 1.23 | 0.32 | 0.35 | 1.00 | 1.10 | 0.73 | 666.00 | 542.79 | 654.2016 | -111.41 |
| 95S | 0.97 | 0.27 | 0.15 | 5.00 | 0.85 | 0.46 | 916.00 | 946.28 | 962.1603 | -15.88 |
| 140S | 1.23 | 0.33 | 0.43 | 1.00 | 1.38 | 1.07 | 466.00 | 377.94 | 390.1565 | -12.22 |
| 145S | 0.38 | 0.31 | 0.27 | 0.00 | 0.58 | 0.35 | 380.00 | 992.17 | 1080.248 | -88.08 |
| 175S | 0.30 | 0.29 | 0.19 | 75.00 | 0.68 | 0.77 | 257.00 | 859.53 | 1082.481 | -222.95 |
| 195S | 0.40 | 0.31 | 0.31 | 80.00 | 0.53 | 0.45 | 454.00 | 1137.84 | 1117.858 | 19.99 |
| 235S | 0.06 | 0.31 | 0.02 | 74.00 | 0.23 | 0.17 | 112.00 | 1806.45 | 1552.441 | 254.01 |
| 250S | 1.10 | 0.32 | 0.26 | 26.00 | 1.08 | 0.53 | 878.00 | 796.01 | 744.3485 | 51.66 |
| 255S | 0.62 | 0.32 | 0.23 | 10.00 | 1.50 | 1.23 | 265.00 | 430.89 | 438.1184 | -7.22 |
| 280S | 0.74 | 0.33 | 0.32 | 13.00 | 0.80 | 0.52 | 566.00 | 760.75 | 900.943 | -140.19 |
| 295S | 0.35 | 0.34 | 0.33 | 11.00 | 1.67 | 1.04 | 173.00 | 491.48 | 241.2904 | 250.19 |
| 325S | 0.65 | 0.34 | 0.44 | 9.00 | 1.50 | 1.13 | 261.00 | 401.54 | 289.8508 | 111.69 |
| 340S | 0.09 | 0.35 | 0.66 | 13.00 | 0.33 | 0.25 | 89.00 | 1034.88 | 991.3095 | 43.57 |
| 350S | 0.26 | 0.32 | 0.25 | 23.00 | 0.33 | 0.13 | 401.00 | 1524.71 | 1293.484 | 231.23 |
| 375S | 0.98 | 0.33 | 0.38 | 18.00 | 0.80 | 0.38 | 875.00 | 889.23 | 862.119 | 27.11 |
| 380S | 1.41 | 0.33 | 0.43 | 8.00 | 1.48 | 0.79 | 681.00 | 484.70 | 321.6395 | 163.06 |
| 390S | 0.80 | 0.34 | 0.34 | 23.00 | 0.75 | 0.28 | 872.00 | 1091.36 | 933.2455 | 158.12 |
| 405S | 1.78 | 0.33 | 0.28 | 20.00 | 1.50 | 1.03 | 894.00 | 503.38 | 432.3144 | 71.06 |
| 425S | 1.72 | 0.30 | 0.16 | 39.00 | 1.45 | 1.37 | 807.00 | 468.37 | 550.8316 | -82.46 |
| 440S | 0.85 | 0.30 | 0.06 | 20.00 | 0.67 | 0.42 | 948.00 | 1120.57 | 1183.758 | -63.19 |
| 465S | 1.36 | 0.31 | 0.10 | 57.00 | 0.92 | 0.59 | 1238.00 | 909.63 | 996.5147 | -86.89 |
| 475S | 0.59 | 0.31 | 0.03 | 18.00 | 0.60 | 0.37 | 758.00 | 1284.75 | 1258.16 | 26.59 |
| 490S | 1.12 | 0.29 | 0.09 | 26.00 | 1.20 | 0.89 | 716.00 | 642.15 | 768.0651 | -125.91 |
| 515S | 0.48 | 0.34 | 0.28 | 32.00 | 0.92 | 0.82 | 311.00 | 653.36 | 848.9461 | -195.58 |
| 545S | 0.30 | 0.33 | 0.46 | 15.00 | 0.70 | 0.46 | 240.00 | 810.81 | 861.2904 | -50.48 |
| 560S | 0.19 | 0.35 | 0.28 | 21.00 | 0.45 | 0.33 | 221.00 | 1163.16 | 1194.921 | -31.76 |
| 580S | 0.91 | 0.34 | 0.33 | 25.00 | 0.62 | 0.26 | 1054.00 | 1153.17 | 1040.815 | 112.36 |
| 595S | 0.30 | 0.34 | 0.42 | 13.00 | 1.42 | 1.49 | 107.00 | 354.30 | 359.2912 | -4.99 |
| 600S | 1.03 | 0.25 | 0.38 | 8.00 | 1.03 | 0.58 | 679.00 | 661.15 | 645.3175 | 15.83 |
| 610S | 0.69 | 0.27 | 0.18 | 19.00 | 0.77 | 0.42 | 676.00 | 979.71 | 998.8816 | -19.17 |
| 630S | 0.34 | 0.32 | 0.26 | 19.00 | 0.65 | 0.49 | 299.00 | 889.88 | 1047.183 | -157.30 |
| 650S | 0.13 | 0.35 | 0.49 | 4.00 | 0.53 | 0.40 | 103.00 | 824.00 | 968.3616 | -144.36 |
| TOTAL | 23.78 | | | | | | 6722.00 | 282.67 | | |
| Arth.Mean | 0.79 | 0.31 | 0.27 | 19.58 | 0.88 | | | 875 | | |
| Geom.Mean | 0.61 | 0.31 | 0.23 | 0 | 0.8 | | | 810 | | |
| Harm.Mean | 0.4 | 0.31 | 0.15 | 0 | 0.71 | | | 744 | | |
| Median | 0.72 | 0.32 | 0.28 | 14 | 0.79 | | | 874 | | |

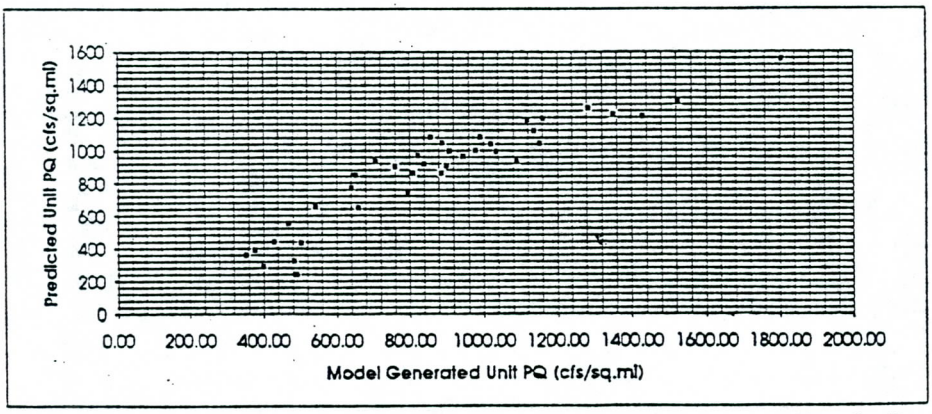


Figure 2 - Plot of Predicted Versus Generated Unit Peak Q

## Appendix B. USGS Gaging Stations in Maricopa County and Estimated Peak Discharges Using Log Pearson Type III Frequency Analysis

| STA.NO | RIVER NAME | LOCATION | DA(sq.mi) | PERIOD | Q10 | Q50 | Q100 | q100 |
|---|---|---|---|---|---|---|---|---|
| 510100 | E. Fork Sycamore | Nr. Sunflower | 5 | 61-86 | 428 | 1660 | 2670 | 534 |
| 510980 | W.Fork Sycamore | Nr. Sunflower | 10 | 62-74,78-89 | 1190 | 4920 | 8030 | 803 |
| 510150 | Sycamore | Nr. Sunflower | 52 | 62-76 | 8160 | 27800 | 42700 | 821 |
| 510170 | Camp Creek | Nr. Sunflower | 3 | 63-79 | 390 | 759 | 950 | 317 |
| 510180 | Rock Creek | Nr. Sunflower | 15 | 63-72 | 2130 | 4530 | 5790 | 386 |
| 510200 | Sycamore Creek | Nr. Fort McDowell | 164 | 60-89 | 12300 | 35500 | 51400 | 313 |
| 512100 | Indian Bend Wash(a) | At Scottsdale | 139 | 43,61-70 | 2950 | 10600 | 16800 | 121 |
| 512300 | Cave Creek | Nr. Cave Creek | 121 | 58-79,81-86 | 6870 | 15200 | 20000 | 165 |
| 512800 | Agua Fria | Nr. Rock Springs | 1110 | 20,70-79 | 39700 | 122000 | 182000 | 164 |
| 513780 | New River | Nr. Rock springs | 67 | 62-89 | 10600 | 25600 | 34600 | 516 |
| 513800 | New River | At New River | 83 | 61-82 | 12600 | 28300 | 37500 | 452 |
| 513820 | Deadman Wash | Nr. New River | 11 | 60-79 | 1550 | 4300 | 6070 | 552 |
| 513835 | New River | At Bell Rd,Peoria | 185 | 63,65-84 | 11700 | 30500 | 41800 | 226 |
| 513860 | Skunk Creek | Nr. Phoenix | 65 | 60-89 | 6910 | 21200 | 31000 | 477 |
| 513890 | New River | At.Grand Ave,Peoria | 317 | 43,60-71 | 20800 | 54900 | 75000 | 237 |
| 513910 | New River | Nr. Glendale | 323 | 43,55,60-79 | 17500 | 37000 | 47100 | 146 |
| 513970 | Agua Fria (b) | At Avondale | 633 | 60-82 | 15000 | 37000 | 49000 | 77 |
| 515500 | Hassayampa | Nr Wickenburg | 417 | 25,27,37-38,46-82 | 13900 | 32270 | 43000 | 103 |
| 514200 | Waterman Wash | Nr Buckeye | 420 | 64-78,80-89 | 3380 | 6240 | 7840 | 19 |
| 515800 | Hartman | Nr. Wickenburg | 6 | 64-79 | 1550 | 4960 | 7450 | 1242 |
| 516600 | Ox Wash | Nr. Morristown | 6 | 60,63-79 | 1240 | 3660 | 5330 | 888 |
| 516500 | Hassayampa | Mr. Morristown | 796 | 39-47,61-81,83-89 | 12200 | 31300 | 43900 | 55 |
| 517400 | Winter Wash | Nr. Tonopah | 48 | 62-79 | 2120 | 3720 | 4560 | 95 |
| 517000 | Hassayampa | Nr. Arlington | 1470 | 61-80,83-84,86-89 | 12900 | 34500 | 49300 | 34 |
| 519780 | Windmill Wash | Nr. Gila bend | 13 | 64-78 | 3120 | 16020 | 27600 | 2123 |
| 519750 | Bender Wash | Nr. Gila Bend | 69 | 63-79 | 3270 | 9040 | 12600 | 183 |
| 519760 | Sauceda Wash (c) | Nr. Gila Bend | 106 | 63-79 | 33310 | 8350 | 11400 | 108 |
| 520100 | Military Wash | Nr. Sentinel | 9 | 63-79 | 946 | 3330 | 5220 | 580 |
| 520200 | Black Gap Wash | Nr. Ajo | 12 | 62-79 | 868 | 1300 | 1490 | 124 |

a- since Oct 1975, DA = 62 sq. miles
b-effective area, 2066 sq. miles minus DA above Lake pleasant
c-plus 20 sq. miles that contributes to another basin

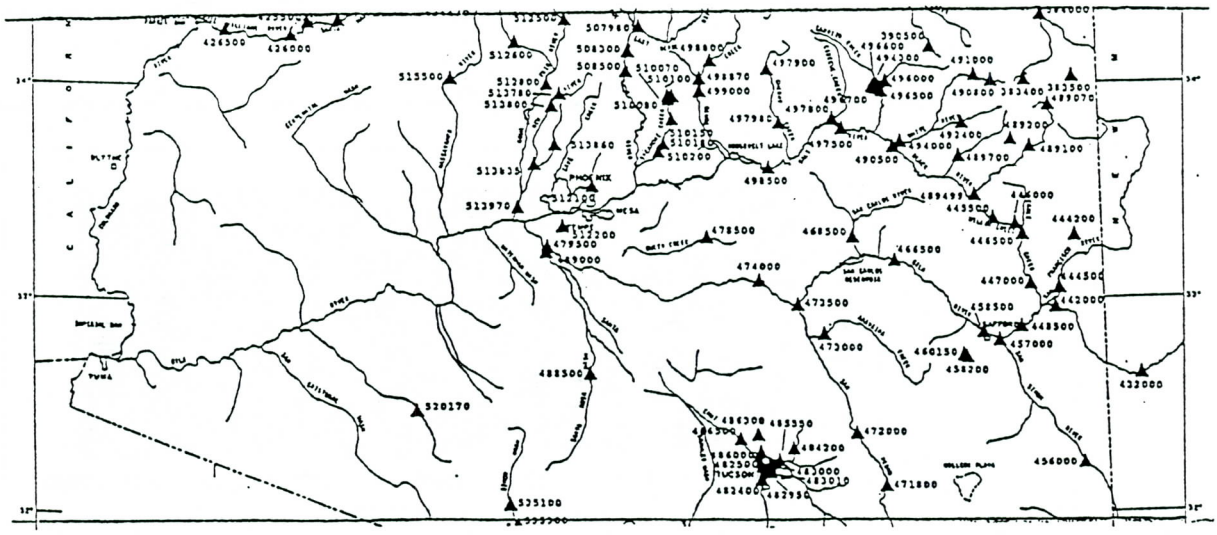

Figure 3 - Location of USGS Gaging Stations in Maricopa County

# APPROPRIATE ANTECEDENT MOISTURE CONDITION FOR 100-YEAR PEAK DISCHARGE ON AGRICULTURAL LANDS[1]

**David B. Boggs, P.E.[2]**

**ABSTRACT:** A HEC-1 rainfall-runoff model was constructed for the 28.5 $mi^2$ Laveen watershed, south of Phoenix, Arizona,to develop 100-yr. peak flow estimates for use in floodplain delineation. The 6-hour 100-year Maricopa County Design Storm was applied to the watershed, which consisted of 67 subbasins. The model utilized the Green-Ampt procedure to account for infiltration losses. On undeveloped desert lands, a "dry" antecedent moisture condition (AMC) was assumed. For residential developments and irrigated turf, a "normal" AMC was assumed. The "saturated" condition was assumed for agricultural lands, which account for over 50% of the total watershed area.

The resulting peak flows along Baseline Road ranged from 3000 cfs to 3200 cfs. These values were judged to be too high based upon the experience of local residents, so it was decided to re-evaluate the assumed antecedent moisture condition. In 1988, Salt River Project (SRP) installed a float-type recording stage recorder upstream of a drop structure in Maricopa Drain, the main tailwater drainage canal leaving the study area. Rainfall data were available from the Flood Control District's recording rain gauges on South Mountain, and at Durango Complex. A National Weather Service non-recording observer gauge located in Laveen provided daily rainfall totals.

Daily rainfall records from 1988 to the present were searched to locate a storm large enough to produce sufficient runoff for calibration of the HEC-1 simulation of peak flows using actual stream gauge data on Maricopa Drain. Stream gauge data for 1993 was unreliable. The only suitable rainfall event with good stream gauge data occurred August 14 and 15, 1990. Over 3.2 inches of rain was recorded in a 24-hour period, and local street flooding was reported for this event. To assess the actual cropping patterns at the time of this rainfall event, ADWR SPOT satellite imagery were examined. False color near-infrared imagry had been previously acquired on July 29, 1990--just two weeks prior to the desired rainfall event. The satellite digital imagery was viewed and printed with the ARC/INFO GIS software.

Of the 67 subbasins, the 37 located in agricultural areas were randomly assigned an AMC that fell into one of four conditions, ranging from near wilting point to near saturation. The HEC-1 simulation was performed with actual rainfall data from the two recording and one non-recording gauge in the area. The results of the simulation closely approximated the observed flows during the early portion of the storms, before all of the watershed contributes to runoff at the gage site. The stream gauge data revealed that the upper portions of the watershed *never* contributed to runoff at the gauge site, but the HEC-1 simulation included the upper watershed, overestimating peak flows by a factor of two.

Conclusions of the study are that saturated conditions are too conservative for large agricultural areas when applying design storms of 100-year return period and that a random distribution of four classes of antecedent moisture conditions more closely estimates actual runoff--at least in the early stages of the 10-year or less frequent event.

## *BACKGROUND*

In 1991, a consultant was engaged by the Flood Control District (FCD) of Maricopa County to develop a hydrologic model of the 28.5 $mi^2$ [73.85 $km^2$] watershed area shown in Figure 1. The area includes the northern slopes of the Phoenix South Mountains, which rise to an elevation of 2690 ft. [820 m] above sea level; the foothills on the north slopes of the South Mountains; and a gently-sloping agricultural area north to the Salt River. The study area is bounded on the west by the Gila River Indian Reservation. The majority of the area lies in an unincorporated area of Maricopa County; however, portions of the developed areas and South Mountain Park are incorporated by the City of Phoenix. The study area is named for the unincorporated community of Laveen, located at 51st Avenue and Dobbins Road.

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[1]Paper presented at the Sixth Annual Symposium of the Arizona Hydrological Society, Casa Grande, AZ, Sept. 23-24, 1993.

[2]Hydrologist, Flood Control District of Maricopa County, 2801 W. Durango, Phoenix, AZ Arizona 85009.

The southern 25% of the study area is barren desert mountains, consisting of steep slopes (0.2 t 0.3 ft/ft), transitioning through moderately-sloping (0.008 to 0.01 ft/ft) foothills into very nearly-level (0.0001 ft/ft) farmland. Many of the farm plots have been laser levelled for improved irrigation efficiency. The low-lying area is predominantly irrigated agricultural land. Irrigation water i supplied by ground water pumping, and by the Salt River Project's Western

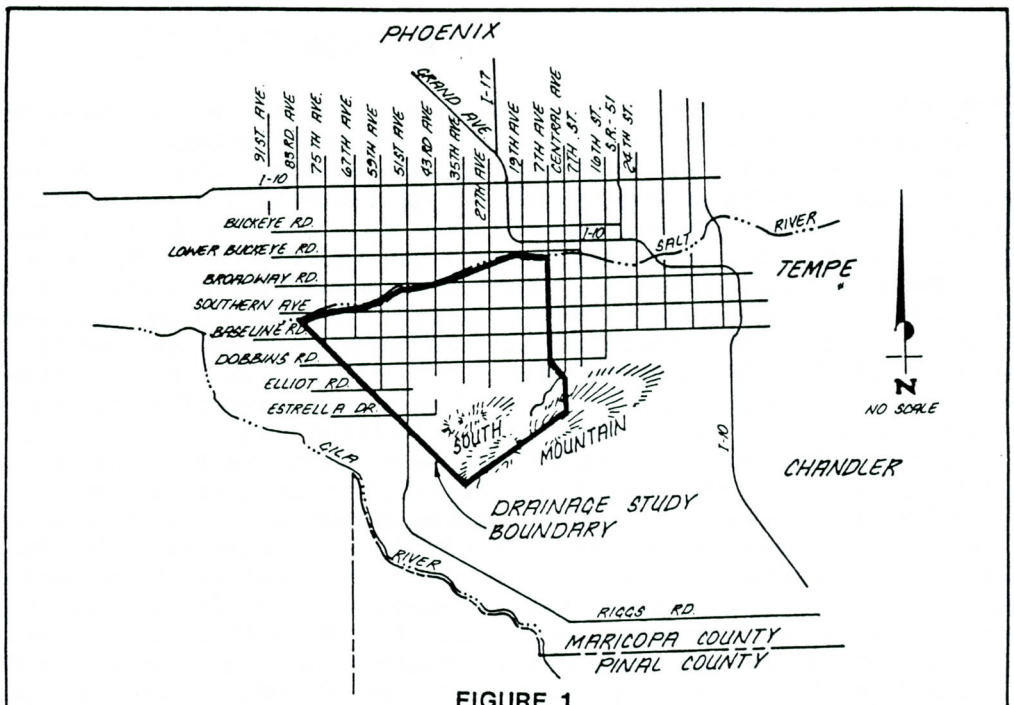


**FIGURE 1**
**VICINITY MAP**

Canal, which has a capacity of 175 cfs (5 $m^3$/sec). Two other smaller SRP lateral irrigation channel bring in an additional 22.5 cfs ( 0.6 $m^3$/sec) for a total surface water inflow of 197.5 cfs (5.6 $m^3$/sec) to the study area. About five percent of the area is developed as low to medium density residential

The major drainage channel of the area is known as the Maricopa Drain. This channel is an irregular trapezoidal earthen ditch, constructed originally as a conveyance channel for irrigatio tailwater. Maricopa Drain has conveyance capacity ranging from less than 400 cfs (11.3 $m^3$/sec) t over 4000 cfs (113 $m^3$/sec.) The drain is maintained in various sections by SRP, Maricopa County Highway Department (MCDOT), and a private irrigation company. There are portions of the drai for which no maintenance exists.

The City of Phoenix maintains a 590 Acre-Foot (728,060 $m^3$) Detention basin which intercept stormwater runoff from a 4.31 square-mile (11.1 $km^2$) portion of the South Mountain watershed This basin completely contains the runoff from the 100-yr design rainfall, thus effectively removing 4.31 square miles (11.1 $km^2$) from the contributory catchment area for rainfall events of 100yr returr period or less.

The SRP Western Canal enters the study area at 7th Ave. and Baseline Road, and travels in a WSW direction, bisecting the study area. The presence of numerous wide canal overchutes prevent significant ponding of runoff behind the canal.

The Laveen Area Drainage Master Study (ADMS) was intended to develop 100-yr base flood elevations for the area. Historically, flooding has occurred in the area of 43rd Ave., just south of Southern Ave. The consultant developed a rainfall/runoff model of the watershed using the U. S. Army Corps of Engineers HEC-1 Flood Hydrograph Package. Resulting peak flows for the 100-yr event were subsequently input to the U. S. Army Corps of Engineers HEC-2 Water Surface Profiles model. Due to the extreme flatness of portions of the study area between 43rd Ave. and 75th Ave., a wide floodplain was identified.

In the process of presenting the study findings to the pubic, concerned citizens of the Laveen area requested that the area be restudied to consider more local site-specific information than had been used in the consultant's study. Since the Maricopa Drain had no maintenance plan, it was not considered in the HEC-2 analysis. The Flood Control District (FCD) subsequently began an in-house re-examination of the consultant's findings to ascertain whether the assumption employed in the study were too conservative.

## *HYDROLOGY METHODOLOGY*

### Unit Hydrograph

The consultant had employed the Clark Unit Hydrograph procedure for the generation of excess rainfall hydrographs in each of the 67 subbasins in the study. This procedure is recommended in the FCD *Drainage Design Manual*, and its use was approved by FCD. The input data for the HEC-1 model for the Clark Unit Hydrograph are the time of concentration and Clark storage coefficient, R. FCD uses an empirical equation for the time of concentration adopted with some procedural modifications from Papadakis and Kazan (1987):

$$T_c = 11.4\ L^{0.5}\ K_b^{0.52}\ S^{-0.31}\ i^{-0.38}. \qquad [1]$$

Where:
$T_c$ = Time of concentration (hours),
L = length of flow path in miles,
$K_b$ = representative watershed resistance coefficient,
S = watershed slope (ft/mile), and
i = average rainfall intensity during $T_c$ (in/hr).

The FCD *Drainage Design Manual* provides both graphical and mathematical procedures for the determination of the value of $K_b$, which ranges from less than 0.02 for large areas of minimal roughness to a value of 0.20 for small, very rough areas.

The value of the Clark storage coefficient, R is established by use of the following empirical relationship:

$$R = 0.37\ T_c^{1.11}\ A^{-0.57}\ L^{0.80} \qquad [2]$$

Where:
R = Clark Storage Coefficient (hours), and
A = drainage area in square miles.

FCD uses a computer program called Maricopa County Unit Hydrograph Procedure (MCUHP) to compute the Clark input parameters automatically from a simple input data set.

## Losses

Rainfall losses were computed using the Green-Ampt procedure. The SCS *Soil Survey of Maricopa County* was used to determine soil groups in the study area. FCD had previously developed a spreadsheet to determine the Green-Ampt infiltration parameters of saturated hydraulic conductivity (XKSAT,) volumetric soil moisture deficit (DTHETA,) and wetting front suction (PSIF) from soil classifications contained in the *Soil Survey of Maricopa County*. The study consultant used a method of averaging the area-weighted logarithms of the Green-Ampt parameter values for each subbasin delineated. Values of saturated hydraulic conductivity were modified based upon the extent of vegetative cover.

Saturated hydraulic conductivity (XKSAT) of a given soil type is modified by vegetation by the relation:

$$XKSAT_{veg} = C_k - XKSAT_{bare} \qquad (3)$$

Where: $XKSAT_{veg}$ = Saturated Hydraulic Conductivity with vegetative cover,
$XKSAT_{bare}$ = Saturated Conductivity of bare ground, and
$C_k$ = Ratio of vegetated to bare XKSAT given by:

$$C_k = (V_c - 10)/90 + 10, \text{ where } V_c = \text{vegetated cover as \%.} \qquad (3a)$$

The saturated hydraulic conductivity of an area with 100% vegetation is thus twice that of bare soil using Equation 3.

Initial abstraction losses are specified in the FCD *Drainage Design Manual* based upon land use or surface cover. The values used by the consultant in the Laveen study are shown in Table 1.

**Table 1: Surface Retention Losses for Various Land Surfaces in Maricopa County**

| Land Use and/or Surface Cover (1) | Surface Retention Loss, IA (Inches) (2) |
|---|---|
| Natural | |
| Desert and Rangeland, flat slope | 0.35 |
| Hillslopes, Sonoran Desert | 0.15 |
| Mountain, with Vegetated Surface | 0.25 |
| Developed (Residential/Commercial) | |
| Lawn and Turf | 0.20 |
| Desert Landscape | 0.10 |
| Pavement | 0.05 |
| Agricultural | |
| Tilled Fields and Irrigated Pasture | 0.50 |

### Antecedent Moisture Condition

For desert mountain hillslopes, a "dry " antecedent moisture condition (AMC) was assumed. For residential areas and turfed areas, a "normal" condition was used, and for agricultural fields, a "saturated" condition was used. The AMC selection is specified as the value of the volumetric soil moisture deficit (DTHETA) in the HEC-1 model. The values of DTHETA used for the "dry" and "normal" AMC are also specified in the FCD *Drainage Design Manual*, as a function of soil type. "Dry" condition values range from 0.15 for clay to 0.40 for silty loams; "normal" condition values range from 0.05 for clays to 0.30 for sand and loamy sand. When the "saturated" condition is assumed for agricultural land, the Green-Ampt procedure reduces to initial loss equal to IA, with uniform loss equal to XKSAT.

### Design Rainfall Event

The study used a 6-hour storm with a return period of 100 years. This storm was determined by the consultant to have a depth of 3.5 inches [8.89 cm] from isopluvial maps contained in the FCD *Drainage Design Manual.* These values were derived from the NOAA Atlas 2, *Precipitation-Frequency Analysis of the Western United States, Vol. III--Arizona.* Figure 2 shows the isopluvial lines for the 100-year 6-hour storm over the study area.

## *RESULTS OF HYDROLOGIC STUDY*

The results of the HEC-1 modeling are shown in Table 2. As shown, 100-year peak flows are predicted at nearly 3000 cfs or greater for most of the study area west of 47th Avenue. Because of doubts about the reliability of the peak flow estimates, it was decided to re-examine the assumptions used in the Laveen Area Drainage Master Study. Several assumptions were re-examined; however, the assumption that was found to have the greatest effect on the final results was the assumption of the "saturated" AMC for agricultural lands.

**Table 2: Peak Flow Results of the Consultant's HEC-1 Modeling**

| Concentration Point Name | Location | Area ($MI^2$) | Qp (cfs) |
|---|---|---|---|
| CPR27C | 27th Ave. and Roeser | 1.54 | 545 |
| CPR35C | 35th Ave. and 36th Drive | 12.1 | 1691 |
| CPS37C | 39th Ave. and Southern | 12.7 | 1770 |
| CAV43C | 43rd Ave. and Burgess Street | 15.7 | 2175 |
| CVR47C | 47th Ave. and Vineyard Street | 20.2 | 3089 |
| CB51C | 51st Ave. and Freemont Street | 21.8 | 2976 |
| CB159C | 59th Ave. and Baseline Road | 22.3 | 2795 |
| CB163C | 63rd Ave. and Baseline Road | 25.0 | 3231 |
| CPCD1C | 67th Ave. and South Mountain Ave. | 25.7 | 3154 |
| CCD2C | 75th Ave. and South Mountain Ave. | 27.2 | 3104 |

### *Re-study of Antecedent Moisture Condition*

The first step to examine the sensitivity of the peak flow results to the AMC assumption was to reduce all agricultural lands AMC from "saturated" to "normal". Since the actual range of agricultural soil moisture would theoretically fall between saturation and wilting point. While "normal" was thought to be too dry to

represent all agriculture, it was chosen to give an initial assessment of the sensitivity of AMC on final pea flow results. Table 3 gives a comparison of the "saturated" condition peak flows with those of the "normal condition. At 47th Ave. and westward, this change reduced peak flow estimates by around forty percent.

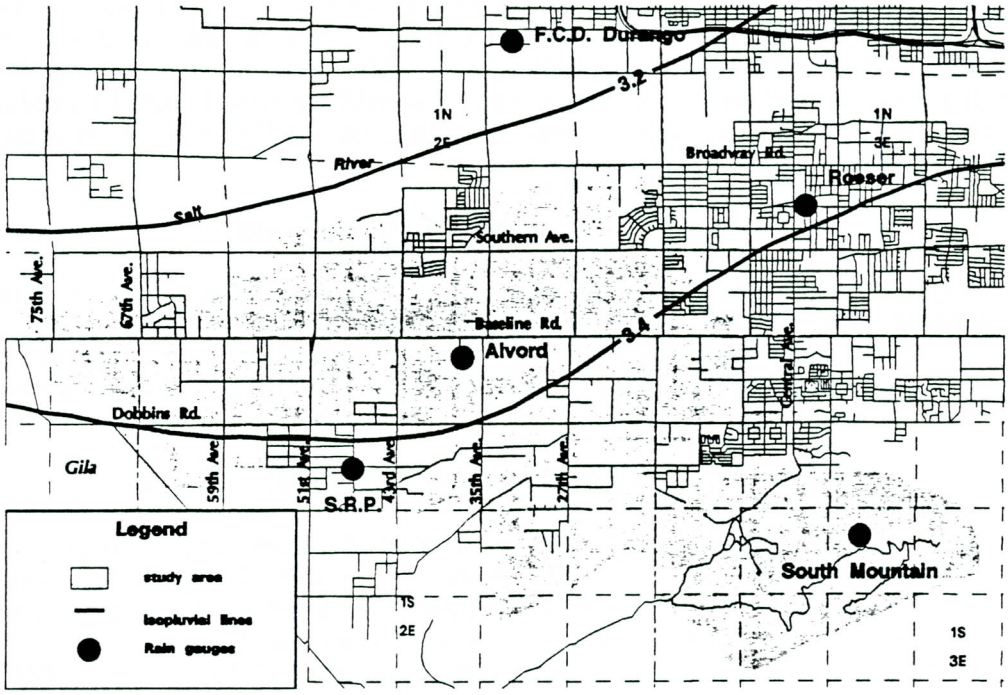


Figure 2: Isopluvials of Depth of 100-Yr. 6-Hr. Rainfall

Table 3: Comparison of Qp Generated by HEC-1 Model with "Saturated" and "Normal" AMC Assumptions

| Concen-tration Pt | Location | Area ($MI^2$) | Qp (cfs) "SATURATED" | Qp (cfs) "NORMAL" | % Differ-ence |
|---|---|---|---|---|---|
| CPR27C | 27th Ave. and Roeser | 1.54 | 545 | 545 | 0 |
| CPR35C | 35th Ave. and 36th Drive | 12.1 | 1691 | 1044 | -38.3 |
| CPS37C | 39th Ave. and Southern | 12.7 | 1770 | 964 | -45.5 |
| CAV43C | 43rd Ave. and Burgess St | 15.7 | 2175 | 1107 | -49.1 |
| CVR47C | 47th Ave. and Vineyard St | 20.2 | 3089 | 1792 | -42.0 |
| CB51C | 51st Ave. and Freemont St | 21.8 | 2976 | 1760 | -40.9 |
| CB159C | 59th Ave. and Baseline Rd | 22.3 | 2795 | 1679 | -40.0 |
| CB163C | 63rd Ave. and Baseline | 25.0 | 3231 | 1875 | -40.6 |
| CCD2C | 75th Ave. and S. Mtn Ave. | 27.2 | 3104 | 1864 | -40.0 |

In the "normal" condition, only the AMCs for the agricultural areas were changed. The values for residential and desert mountain areas were not changed. These results showed that the model peak flow results were extremely sensitive to the input value for DTHETA. It was believed that the composite average AMC for all agricultural lands may be somewhat wetter than "normal," but that "normal" was nearer to an average AMC that "saturated". To test this hypothesis, it was decided to examine the actual runoff from a storm of appreciable magnitude, and to see how well the HEC-1 model could duplicate the observed runoff flows in the "saturated" and "normal" antecedent moisture states.

A further refinement of an assumed uniform "normal" AMC was applied to the watershed model prior to calibration. Of the 67 subbasins in the Laveen HEC-1 model, 32 are predominantly agricultural land use. For each of the agricultural subbasins, DTHETA values were calculated for the "dry" and "normal" AMC based upon soil types. Four categories of AMC were arbitrarily established as follows:

1. "NEAR WILTING POINT"MID-WAY BETWEEN "DRY" AND "NORMAL"
2. "NORMAL""NORMAL"
3. "ABOVE NORMAL"0.66 X "NORMAL"
4. "NEARLY SATURATED"0.33 X "NORMAL".

Each of the 32 agricultural subbasins was randomly assigned to one of the four classes of AMC, resulting in 8 subbasins in each class. The appropriate values were input for DTHETA on the LG card of the HEC-1 input, and the model was re-run.

### *Calibration of HEC-1 Model to Observed Runoff Event*

West of 65th Avenue, Maricopa Drain is maintained by the Salt River Project (SRP.) SRP has installed a section of concrete-lined trapezoidal channel with a 6-foot drop structure in Maricopa Drain west of 75th Avenue on the boundary with the Indian Reservation. The structure creates enough backwater to impound a significant volume for SRP to pump water onto the Indian Reservation to satisfy a senior surface water right holder.

The drop structure forms a broad-crested weir with a bottom width of 26 feet [7.63 m]. The weir is concrete lined 3 feet [0.91 m] from the weir crest. The flow across the weir was approximated by use of the broad-crested weir equation.

The drop structure is equipped with a float-type stage recorder which is connected to a rotating drum-type chart paper with pen plotter. The record of stage from this recorder is directly translatable to discharge over the structure. SRP has also developed a rating table using the same relationship. Records have been kept by SRP since the gauge was installed in January, 1988.

To calibrate the HEC-1 model, it was desired to consider a rainfall event that produced measurable runoff during the period of record--1988 to the present. Daily precipitation data were reviewed from FCD recording rain gauges at Durango and South Mountain stations. Although there were significant rainfall events during January, 1993, the stage recorder was not operating properly during this period. The only usable rainfall event with both good rainfall and runoff gauge data during the period of record occurred on August 14-15, 1990.

As shown in Figure 3, the storm of August 14-15, 1990 consisted of two distinct precipitation events,

separated by approximately 12 hours of no rain. On August 14, rainfall began between 9:00 ar 9:30 AM and continued until 11 AM. At FCD Durango Gauge, 1.6 inches [4.06 cm] of rain accumulated in 90 minutes time. At South Mountain Gauge, about one inch [2.54 cm] fell betwee 9:20 AM and 10:20 AM. The daily total rainfall for August 14 at the National Weather Servi (NWS) Coop non-recording gauge (located at 47th Ave. and Olney) was 1.46 inches [3.71 cm].

At 2:30 AM on August 15, rainfall began at the FCD Durango Gauge; thirty minutes later rainfa began at the South Mountain Gauge. By 6 AM, the South Mountain Gauge had received 2.05 inches [5.2 cm] and Durango had reported 1.20 inches [3.05 cm.] The NWS gauge reported 0.62 inche [1.57 cm.] as a daily total for August 15, 1990. The NWS Coop gauge provides only daily total dept of rainfall. For the 24-hour period, the observed precipitation has a return period of about 10 years for the August 14-15, 1990 event. The time series of rainfall from Durango and South Mountain gages was input to the HEC-1 model using the PG and PI records. For the Laveen NWS Co gauge, only the total depth of precipitation for the entire event was input. For each subbasin in the HEC-1 model, the temporal distribution of rainfall is computed by using the PR/PW combination to weight the influence of the Durango and South Mountain gauges. This weighting is based up relative distance from the subbasin centroid to each of the two gauges. Since the Laveen Coop gaug provides only daily totals, it is not used in computing the temporal distribution for any subbasin.

The total depth of rainfall accumulated on each subbasin is computed by the PW/PT combinatio of records in HEC-1. Distance between a subbasin centroid and each of the three gage stations was used to determine the relative influence of the data from each of the rainfall gauges. Figure 2 show the locations of the rain gauges in the Laveen area that were used for the calibration of the Augu 14-15, 1990 event.

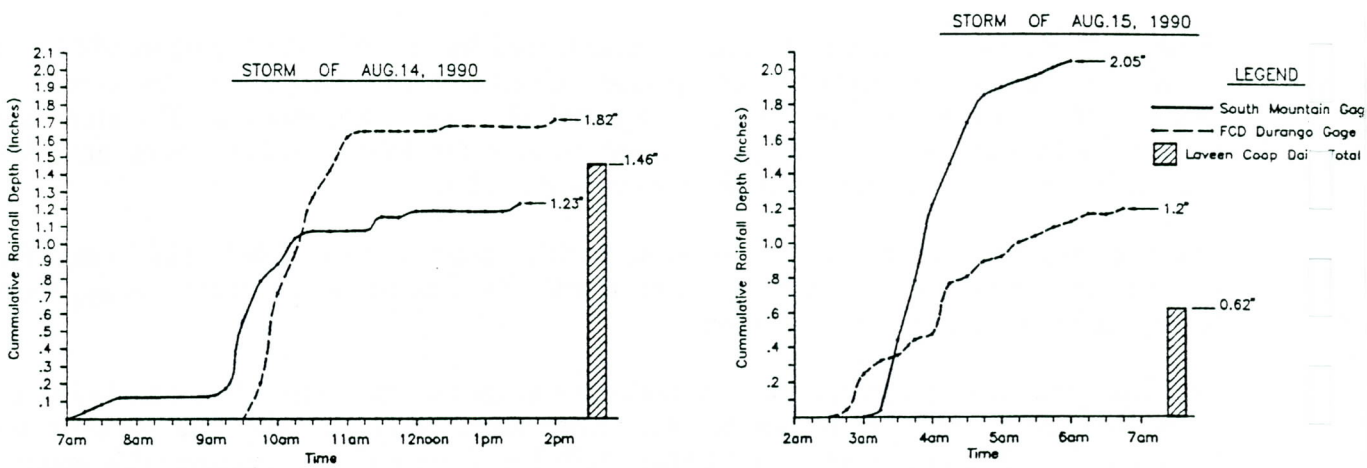


Figure 3: Cummulative Rainfall Recorded at Laveen Gauges for Aug.14–15, 1990

## *COMPARISON OF HEC-1 SIMULATION WITH OBSERVED RUNOFF*

Figure 4 is a plot of the observed flows in Maricopa Drain and the HEC-1 output for the August 1 15, 1990 rainfall event. The observed precipitation from the Durango Complex is plotted on Figure 4 as an inverted histogram, although, as shown in Figure 3, the rainfall depth and tempor

distribution seems to have varied considerably over the project watershed.

The most obvious difference between the simulated and actual peak flows is that the HEC-1 model over-predicts the peak flow. Predicted peak flow was 349 cfs [9.89 $m^3$/sec], compared to the observed peak flow of 138 cfs [3.91 $m^3$/sec]--an over-prediction by a factor of 2.5. The second noticeable discrepancy is the timing of the peak flow. The HEC-1 model predicts the occurrence of the peak flow around 10 PM on the 15th of August, whereas the peak actually occurred around 10 AM--about 12 hours earlier than predicted.

A third discernable difference between the two plots in Figure 4 is that the observed runoff occurred with two distinct peaks, separated by about 16 hours in time--about the same time interval as between the most intense portions of rainfall that produced the runoff, whereas the simulated discharge has only a single peak.

The volume of actual runoff was 281.5 acre-feet [347,492 $m^3$], while the volume of simulated runoff was 426 AF [525,867 $m^3$]. Thus the simulated runoff volume was 1.5 times the actual runoff volume.

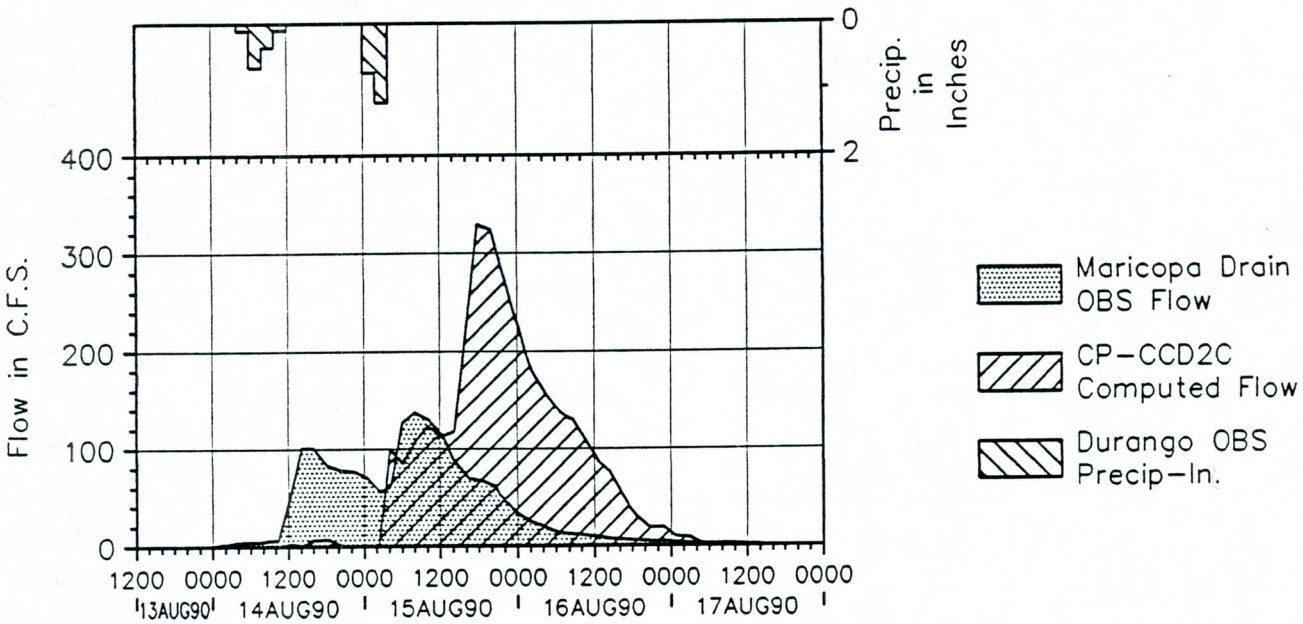


**Figure 4: Simulated and Actual Flows in the Maricopa Drain.**

### *Causes of Discrepancies Between Simulated and Actual Flows*

Since the rainfall occurred as two distinct events, separated by 12 hours (seven of which were during daylight hours) there was a considerable amount of recovery of soil moisture after the cessation of the first rainfall. The HEC-1 model does not compute soil moisture recovery, so as far as the HEC-1 model is concerned, the two rainfall events occurred without any break in time separating them. This is a major reason that the peak flow is over-predicted.

In Figure 4, the simulated flow occurring after noon on August 15th are the result of runoff from

the upper portion of the Laveen watershed. The observed flow tends to indicate that the upper portion of the watershed does not contribute runoff to the gauging point, since the observed hydrograph continues to recede after noon on the 15th. The slight flattening of the recession limb of the observed flow between 14:00 and 18:00, is most likely the meager contribution of the upper watershed. The actual runoff from the upper portion of the watershed is probably being retained in shallow ponding areas, and detained long enough to infiltrate. The HEC-1 model does not adequately describe this phenomenon, otherwise, there would not be a peak flow predicted so late in the event.

The fact that the first rainfall event on the 14th produced a much higher peak flow (100 cfs [2.83 $m^3$/sec]) than the predicted flow (11 cfs [0.31 $m^3$/sec]) may indicate that either the initial abstractions of the model are too high or that the model's antecedent moisture condition is drier than the actual moisture condition on the day of the first rainfall (August 14.) Another explanation of the discrepancy is that the relatively short-lived peak flow of 100 cfs [2.83 $m^3$/sec] was due to the contribution of relatively impervious areas such as streets and bare, compacted embankments surrounding Maricopa Drain.

As shown in Figure 4, during the period between 0400 and 1200 on August 15th, the actual and observed peak flows are in good agreement. Thus the HEC-1 model tends to under-predict the early part of the event, over-predict the end, but to do a good job in the middle of the event.

**Table 4: HEC-1 Results of the Final Model, $Qp_{100}$**

| Concen-tration Pt | Location | Area ($Mi^2$) | Original Qp (cfs) | Final Qp (cfs) | % Difference |
|---|---|---|---|---|---|
| CPR27C | 27th Ave. and Roeser | 1.54 | 545 | 507 | -7.0 |
| CPR35C | 35th Ave. and 36th Drive | 12.1 | 1691 | 1033 | -40.3 |
| CPS37C | 39th Ave. and Southern | 12.7 | 1770 | 970 | -45.2 |
| CAV43C | 43rd Ave. and Burgess St | 15.7 | 2175 | 1049 | -51.8 |
| CVR47C | 47th Ave. and Vineyard St | 20.2 | 3089 | 1436 | -53.3 |
| CB51C | 51st Ave. and Freemont St | 21.8 | 2976 | 1438 | -51.7 |
| CB159C | 59th Ave. and Baseline Rd | 22.3 | 2795 | 1399 | -50.0 |
| CB163C | 63rd Ave. and Baseline | 25.0 | 3231 | 1592 | -50.7 |
| CCD2C | 75th Ave. and S. Mtn Ave. | 27.2 | 3104 | 1563 | -49.6 |

The non-contribution of the upper portion of the watershed during the August 14-15 precipitation event ($T_R \approx 10$ yrs) would most likely not be repeated in the case of the 100-year event. Thus the factor by which the HEC-1 model overpredicts peak flows (2.5 for $T_R = 10$ yrs) probably decreases with increasing return period. Hopefully the factor would be seen to approach 1.0 as the 100-year event is reached. If not, there is still some comfort that the HEC-1 model still provides a degree of conservatism in its estimate.

## *USING OF THE FINAL MODEL TO ESTIMATE THE 100-Yr. RUNOFF*

The results of the HEC-1 model after making all of the abovementioned changes are shown in Table 4. As shown in Table 4, the peak flow estimates for the 100-yr event are about 50 percent less than in the original model prepared by the consultant. Although there were some other modifications to the model, the primary reason for the reduction in peak flow estimates is the assumption of the

antecedent moisture condition in the agricultural areas. It appears that the assumption of "saturated" agricultural lands is too conservative for large areas. While this assumption has merit when considering smaller drainage areas, such as individual fields, it cannot be substantiated for large, irrigated areas greater than 100 to 200 acres.

## *CONCLUSIONS*

In developing a rainfall/runoff model for a large, predominantly agricultural watershed for estimation of the 100-year peak discharge, the assumption that all agricultural land is in the saturated antecedent moisture condition is too conservative. Assuming a "normal" AMC appears to be more reasonable for large watersheds, but a separation of agricultural subbasins into different AMC states ranging from near wilting point to near saturation also appeals to reason.

If a stream gauge is available, an indication of the reasonableness of the assumed AMC can be obtained by inputing actual rainfall data to the model and comparing the actual gauged outflow to the rainfall/runoff model predictions.

The event chosen will almost certainly be much smaller than the 100-year event, so the ability of the model to simulate the actual runoff is only a general indication of its applicability to the 100-year event. A major problem in input of actual rainfall data is the non-uniform areal variation in precipitation, and the general paucity of instrumentation of rain gauges.

### *References Cited*


Cella Barr Associates, 1991, *Laveen Area Drainage Master Study, Phase I, Hydrology Report: Existing Conditions,* prepared for FCD.

Clark, C. O., 1945, "Storage and the Unit Hydrograph," *ASCE Transactions* 110, 1419-1446.

Kennedy, Curt, Salt River Project, 1993, Personal Communications.

Laveen Phoenix Planning Committee, *Laveen Land Use Plan*, undated.

Maricopa County Flood Control District, 1992, *Drainage Design Manual, Volume I: Hydrology.*

Papadakis, C. N., and M. N. Kazan, 1987, "Time of Concentration in Small, Rural Watersheds," Proceedings of the Engineering Hydrology Symposium, ASCE, Williamsburg, VA, pp. 633-638.

U. S. Army Corps of Engineers, 1990, *HEC-1 Flood Hydrograph Package User's Manual*, Hydrologic Engineering Center, Davis, CA.

U. S. Geological Survey, 1991, *Basin Characteristics and Streamflow Statistics in Arizona as of 1989,* WRI Report 91-4041.

U. S. Soil Conservation Service, 1977, *Soil Survey of Maricopa County, Arizona, Central Part.*

Tankersley, Earl L., Salt River Project, 1993, Personal Communications.

Thacker & Associates, Inc., 1993, *Reporter's Transcript of Proceedings, Laveen Planning Committee Meeting, December 14, 1992.*

# FUZZY REGRESSION - BASED RAINFALL RUNOFF ESTIMATION[1]

**Kuo-lin Hsu, Ertunga C. Özelkan, Lucien Duckstein [2]**

**ABSTRACT:** From the continuity principle, the rainfall runoff process of a watershed can be formulated as a difference relation. The parameters are event based and are subject to high uncertainty. To take this uncertainty in consideration *fuzzy linear regression* is applied to assess the parameters. The *fuzzy linear regression* is performed on the watershed model using three runoff events for the particular watershed Walnut Gulch. The first event is used for simulation whereas the others to validate the model. The simulation is done under different possible vagueness scenarios of the observed data. The model gives fairly good results for the small watershed and it has the potential to be applicable for larger watersheds.
Keywords:*fuzzy linear regression*

# 1 INTRODUCTION

The purpose of this paper is to estimate the parameters of watershed model using *fuzzy linear regression* analysis of downstream outflow on rainfall and upstream inflow. The method is based on the continuity equation and the storage-discharge relation. It is usually applied to channel routing. Here the storage is assumed to be a linear function of the inflow and the outflow of the channel. The continuity considers basically that the change of storage in time is a difference of inflow and the outflow to the channel.

The methodology given here is based on the same principle whereas the rainfall is introduced as one of the inputs to the watershed model. That is, the prediction of the downstream discharge uses the two upstream gauge station data plus the average areal rainfall. The linear regression model can be assessed easily after writing the process continuity equation in difference form.

The parameters are watershed based and are strongly influenced by the inaccuracy of data records. There are some other factors such as the infiltration process which are not taken into consideration. Also for the observed watershed the rainfall data were only available from a few nearby rainfall stations which in reality might not be the actual rainfall series for this watershed. One can conclude that the parameters of the system are quite *fuzzy*, that is, imprecisely defined

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because of these explained noise factors. Therefore the *fuzzy linear regression* analysis can be considered as an appropriate tool for the estimation of the parameters.

Some different vagueness scenarios are considered, where the model is tested under the possible 0%,10%, and 20% vagueness of the observed data. Once the parameters of the system are estimated, the model can be used for future flood estimation. For now, a small sub-watershed is considered in this study, but one can connect the other sub-watersheds in the same manner and generate the runoff at the outlet of every sub-watershed.

# 2 METHODOLOGY

## 2.1 Watershed model

The purpose is to estimate the runoff from the whole watershed using an upstream gauge station data and areal rainfall. The model is shown in Fig.( 1) and the conceptual model can be represented as shown in Fig. ( 2). The whole watershed is taken as a system and the continuity is to be satisfied as follows:

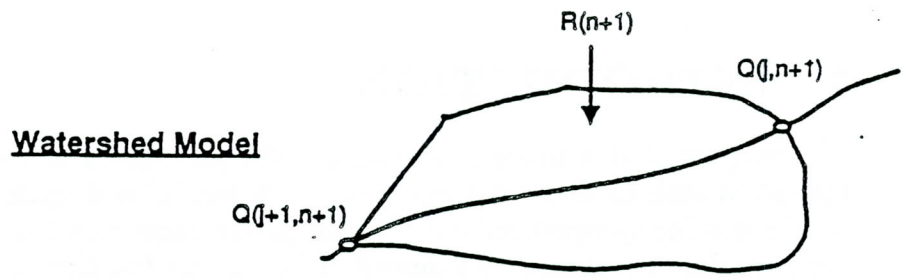


Figure 1: Schematic representation of the watershed model

$$Q_j - Q_{j+1} + R_w = \frac{dS}{dt} \quad (1)$$

where $Q_j$ is the inflow to reach,$Q_{j+1}$ is the outflow from reach and $R_w$ is the average catchment rainfall. Here, the storage $S$ is assumed to be a linear function of $Q_j$, $R_w$, and $Q_{j+1}$.

$$S = f(Q_{j+1}, Q_j, R_w) \quad (2)$$

One can formulate this relation as a backward difference as follows:

$$Q(j+1,n) = C_0 + C_1 Q(j, n-\Delta t) + C_2 Q(j,n) + C_3 Q(j+1, n-\Delta t) + C_4 R_w(n) + C_5 R_w(n-\Delta t) \quad (3)$$

where $C_0$, $C_1$, $C_2$, $C_3$, $C_4$, $C_5$ are coefficients based on physical parameters and $n$ is the time step.

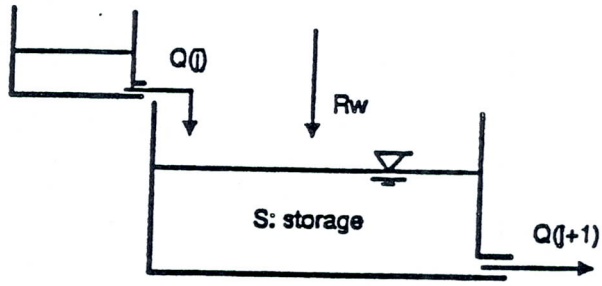


Figure 2: Conceptual representation of the watershed model

## 2.2 Fuzzy linear regression

Some of the basic definitions of *fuzzy numbers* are given in the Appendix. For more detail, the reader is referred to the fundamentals of *fuzzy arithmetic* in Kaufmann and Gupta (1991). The basic fuzzy *linear regression* equations can be formulated as follows (Bardossy,1990;Bardossy et al, 1990):

$$f(x,a) = a(1) + \sum_{k=2}^{K} a(k)(x(k) - \overline{x}) \tag{4}$$

Here $\overline{x} = (\bar{x}(2), \ldots, \bar{x}(k))$ is a selected reference point. Let parameter vector $a$ be *L-R fuzzy number* represented as follows (Dubois and Prade, 1980):

$$a(k) = [A(k), b(k), c(k)][L(k), R(k)] \tag{5}$$

In general, in *fuzzy regression* one tries to minimize the vagueness which may be defined in different ways (Bardossy et al,1990). We have used the following three vagueness criteria of the individual parameters for comparison:
maximum vagueness:

$$V = max_k(b(k), c(k)) \tag{6}$$

average vagueness:

$$V = \frac{1}{2K} \sum_{k=1}^{K} (b(k) + c(k)) \tag{7}$$

prediction vagueness:

$$V = \frac{1}{T} \sum_{t=1}^{T} \int_{-\infty}^{+\infty} sup\{min(\mu_{a_i}(a^*)); y = f(\mathrm{x}_t, a^*)\} dy \tag{8}$$

It can be proved that the conditions for the *fuzzy linear regression* are (Bardossy, 1990)

$$
\begin{aligned}
min_y Y(t,h) \geq\ & A(1) - b(1)L^{-1}(1,h) \\
+ & \sum_{x(k,t)\geq \bar{x}(k)} [(A(k) - b(k)L^{-1}(k,h))(x(k,t) - \bar{x}(k)) \\
+ & \sum_{x(k,t)< \bar{x}(k)} [(A(k) + c(k)R^{-1}(k,h))(x(k,t) - \bar{x}(k)) \qquad (10)
\end{aligned}
$$

$$
\begin{aligned}
max_y Y(t,h) \leq\ & A(1) + c(1)R^{-1}(1,h) \\
+ & \sum_{x(k,t)\geq \bar{x}(k)} [(A(k) + c(k)R^{-1}(k,h))(x(k,t) - \bar{x}(k)) \\
+ & \sum_{x(k,t)< \bar{x}(k)} [(A(k) - b(k)L^{-1}(k,h))(x(k,t) - \bar{x}(k)) \qquad (11)
\end{aligned}
$$

Here h is the level set between 0 and 1, K-1 is the number of independent variables, and $t = 1, \ldots, T$, where $T$ is the total number of observations. The inequality constraints given in Equations ( 9) and ( 10) are linear with respect to the unknown parameters $A(k)$, $b(k)$, $c(k)$ of the linear regression. Considering one of the Equations ( 6) to ( 8) as our objective "optimum" function these constraints can be solved by a linear programming technique to get a parameter set.

# 3 APPLICATION

The simulation watershed Lucky Hills is a subwatershed of Walnut Gulch, located Southeast of Tucson near the San Pedro river (Fig. ( 3) and ( 4)). This experimental watershed of US Department of Agriculture has a catchment area of 44,000 $m^2$. The events used in this study are shown in Table ( 1). The event of 27/July/1973 is selected for the simulation, which is validated with the other two rainfall runoff events shown in Table ( 1). Fig. ( 5)-( 7) show the average rainfall and the measured runoff hydrographs.

The regression is performed for an h-level of 0.5. The summation of upstream gauge station flow is considered as the input flow which was denoted in Equation ( 1) as $Q_j$ and the downstream flow is $Q_{j+1}$.The results of the regression are given in Fig.( 8)-( 16). Fig.( 8) is the simulation event which is chosen as representative event that is validated using the other two events shown in Fig.( 9)-( 10). The procedure is repeated under the scenarios of 10 % and 20 % possible vagueness in the measurement of the flow values. The results for these cases are given in Fig.( 11)-( 16).

As stated before, the *fuzzy regression* turns to be a linear programming problem and the objective function is formulated using Equations ( ( 6) -( 8)). The results of these three different objective functions are evaluated and Equation( 6) is found to yield the best prediction. The regression parameters for these three cases are given in Table( 2).

Table 1: Events used for the regression model

| Event no. | Date | N: Duration (min) | T: # of observations |
|---|---|---|---|
| 1 | 27/July/1973 | 82 | 41 |
| 2 | 01/Aug/1974 | 78 | 39 |
| 3 | 17/July/1975 | 60 | 30 |

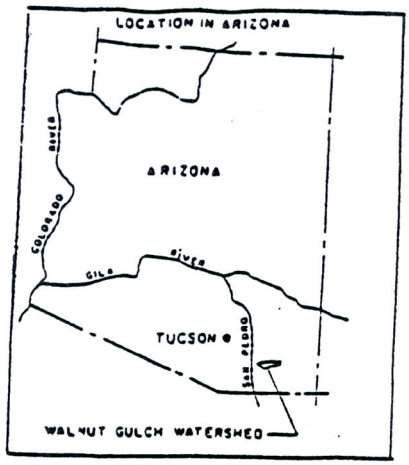


Figure 3: Location of Walnut Gulch Experimental Watershed

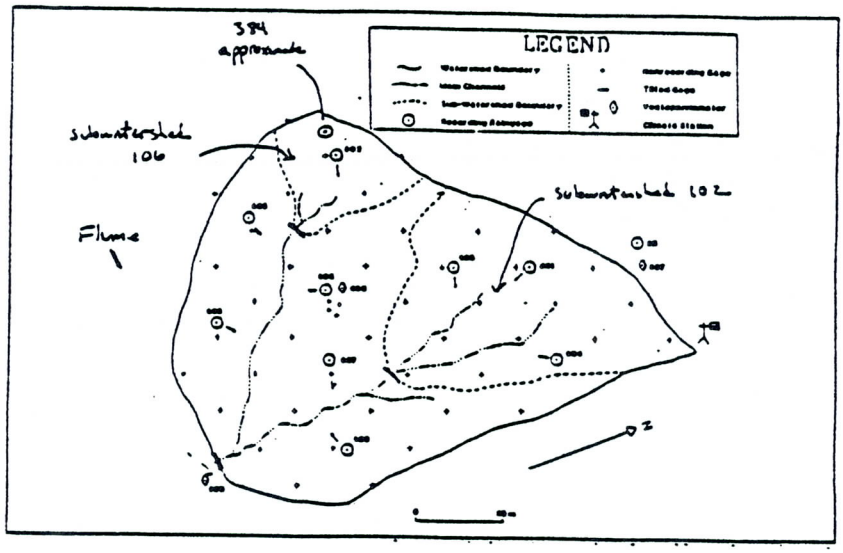


Figure 4: Lucky Hills

# 4 DISCUSSION OF RESULTS

As seen in Fig. ( 8), ( 11), ( 14), for the simulation of event no.1 all observed points are included in the 0.5 h-level band. This result is not surprising because it represents a requirement for *fuzzy linear regression.* Fig. ( 9), ( 12), ( 15) show the validation results for event no.2 which seems to be fairly good. For event no.3 (Fig. ( 10), ( 13), ( 16) the fuzziness is relatively bigger, but most of the observed points are still well predicted. In general, as the vagueness of the data increases the fuzziness gets also larger. However, the flow volume remains almost constant and the results can be considered as fairly good.

# 5 CONCLUDING REMARKS

Mass conservation is taken into consideration to model the runoff generation of a watershed. The storage relation between rainfall and runoff is assumed to be linear (Equation ( 2)). Under this assumption, one can derive a linear differential equation for a specific watershed, which can be approximated by a difference relation with the parameters representing the characteristics of the watershed.

The *Fuzzy linear regression* has been applied to the watershed model. The advantages and the disadvantages in comparison to traditional regression models can be summarized as follows. The estimation of parameters might contain some vagueness because of imprecision in data. There are some drawbacks of the traditional regression models in the case of a small set of data and in the case of high correlation between the independent variables; one can then prefer to use *fuzzy linear regression.* In the case of multicollinearity among the independent variables, the parameters can be very unstable with a tendency to give too large parameter estimates. (Walpole and Myers,1986). For the model given in this paper, this plays a crucial role, because we estimate the coming flow with the flow from one time step before from different gauges.

We think that the application is appropriate, but the drawbacks should be investigated in greater detail. For example the infiltration, evapotranspiration and subsurface flow effects should be taken into consideration and introduced into the model. The formulation of these factors are rather complicated and we believe that a thorough analysis of the *fuzzy-logic* concepts can contribute further.

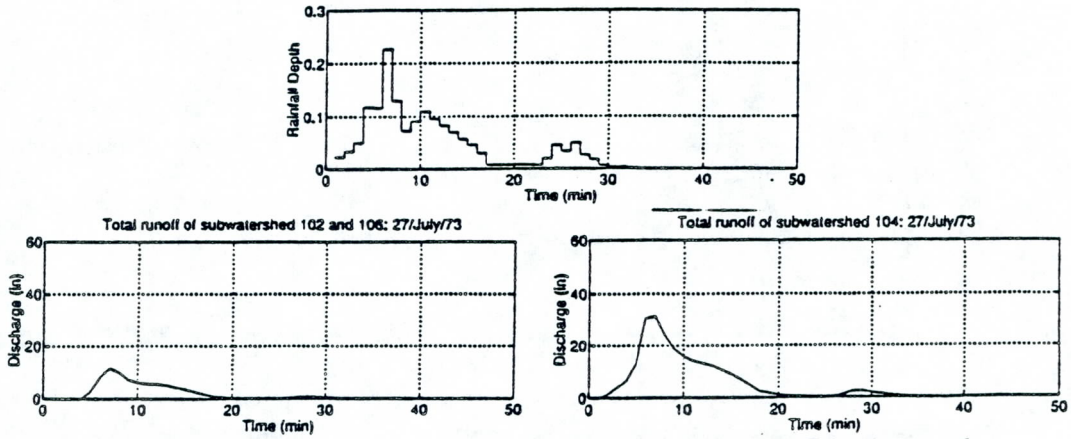


Figure 5: Event of 27/July/73; rainfall and runoff hydrographs

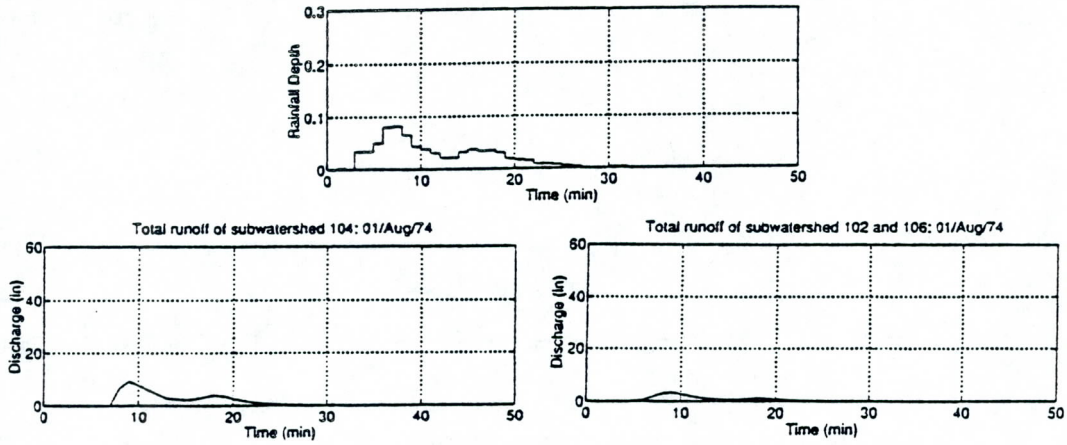


Figure 6: Event of 01/Aug/74; rainfall and runoff hydrographs

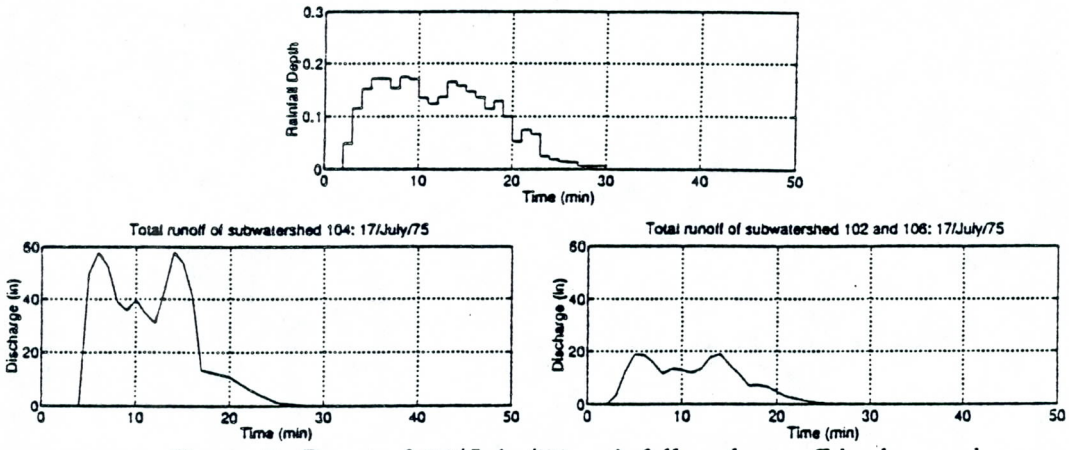


Figure 7: Event of 17/July/75; rainfall and runoff hydrographs

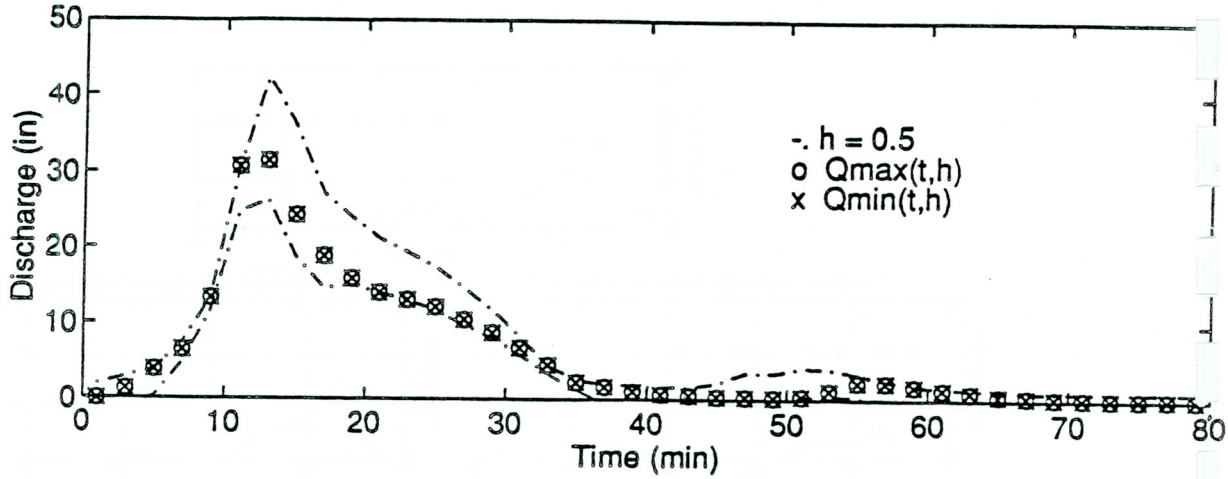


Figure 8: Simulation Event, Lucky Hills-27/July/73; runoff hydrograph; 0 % vagueness.

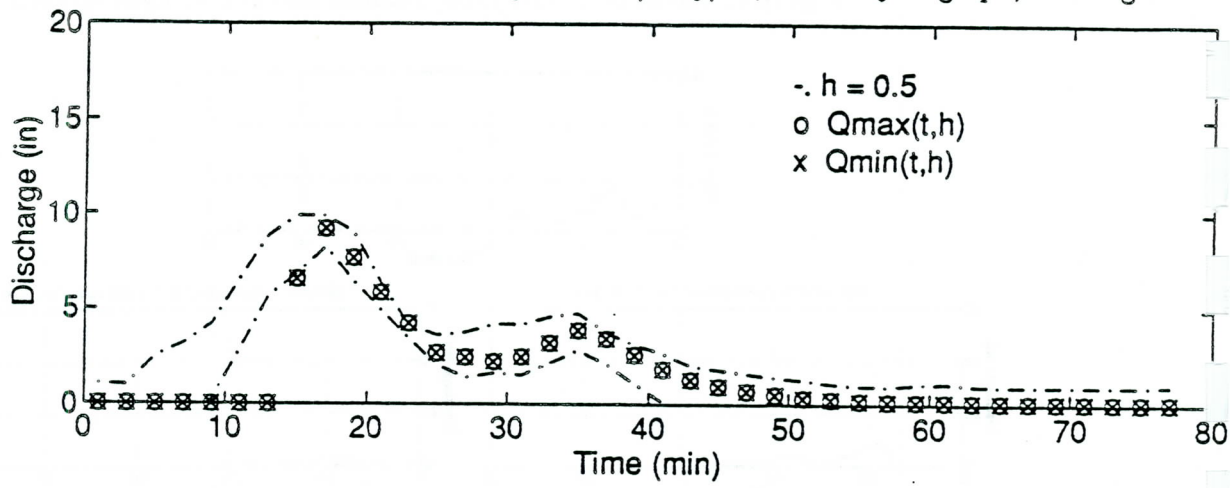


Figure 9: Validation Event, Lucky Hills-01/Aug/74; runoff hydrograph; 0 % vagueness

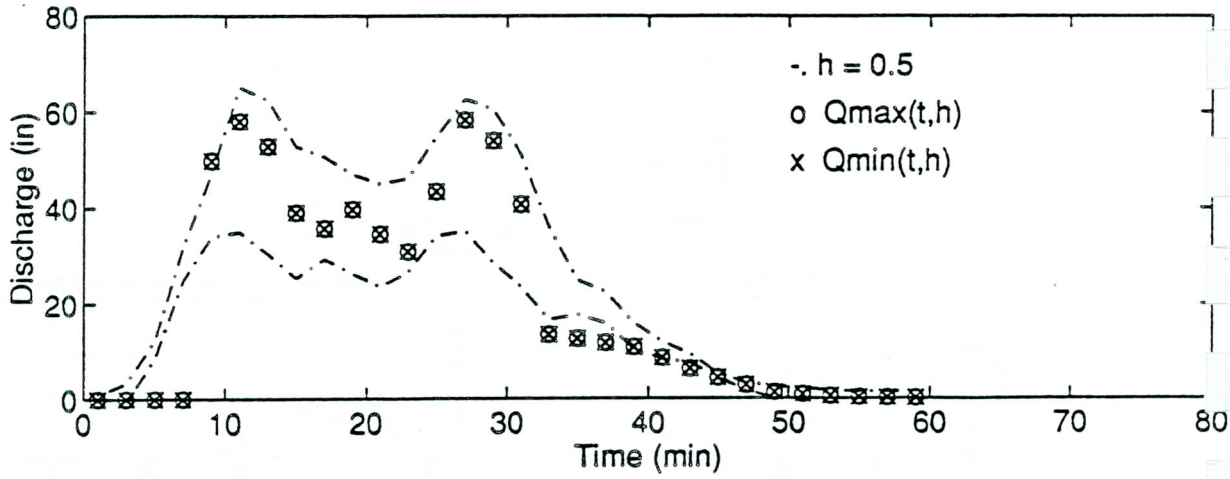


Figure 10: Validation Event, Lucky Hills-17/July/75; runoff hydrograph; 0 % vagueness

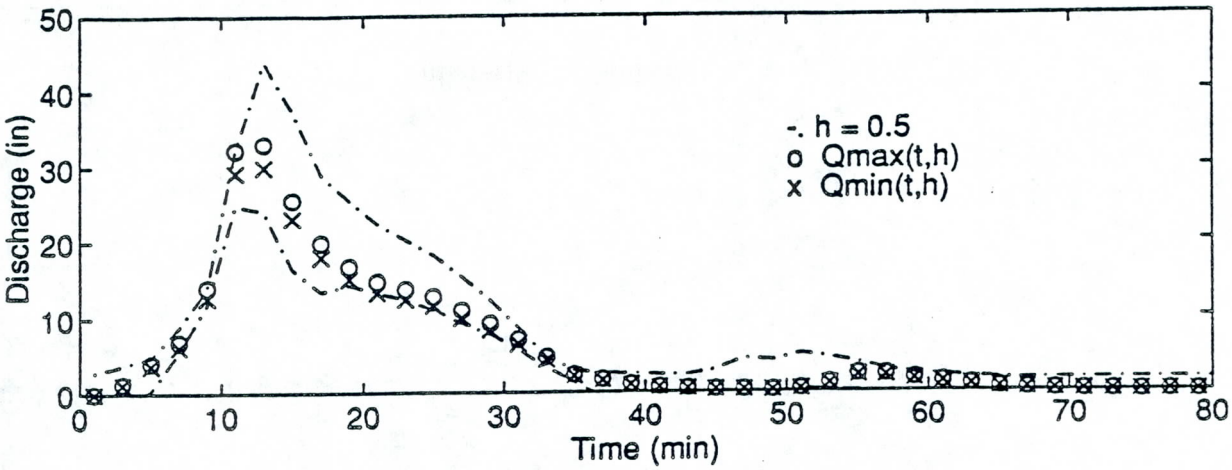


Figure 11: Simulation Event, Lucky Hills-27/July/73; runoff hydrograph; 10 % vagueness:

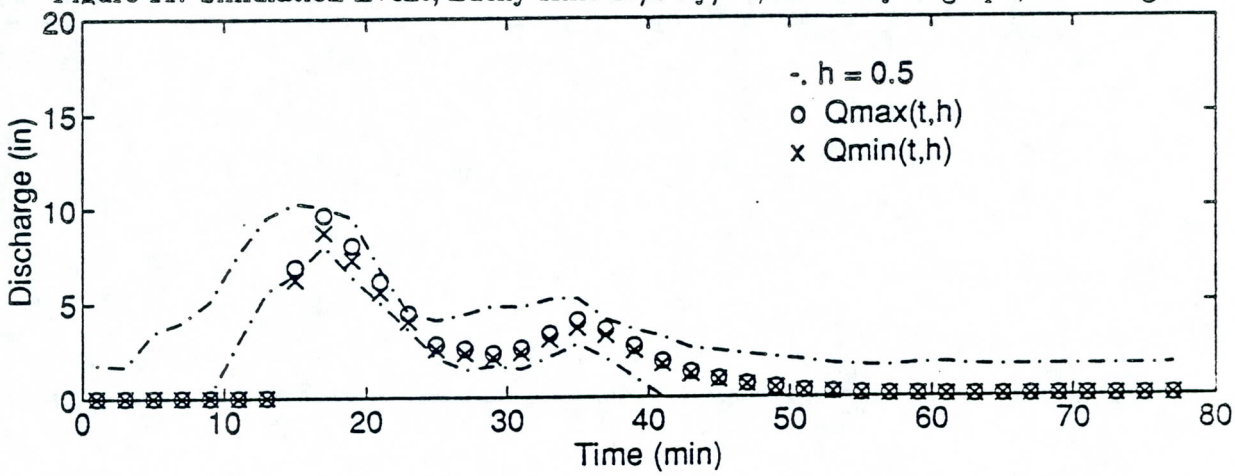


Figure 12: Validation Event, Lucky Hills-01/Aug/74; runoff hydrograph; 10 % vagueness:

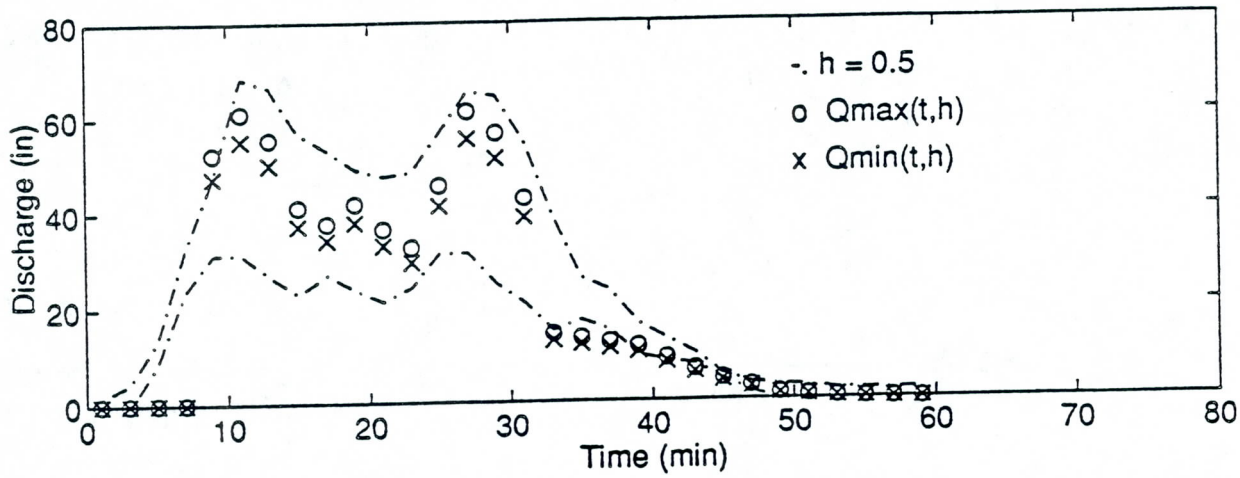


Figure 13: Validation Event, Lucky Hills-17/July/75; runoff hydrograph; 10 % vagueness:

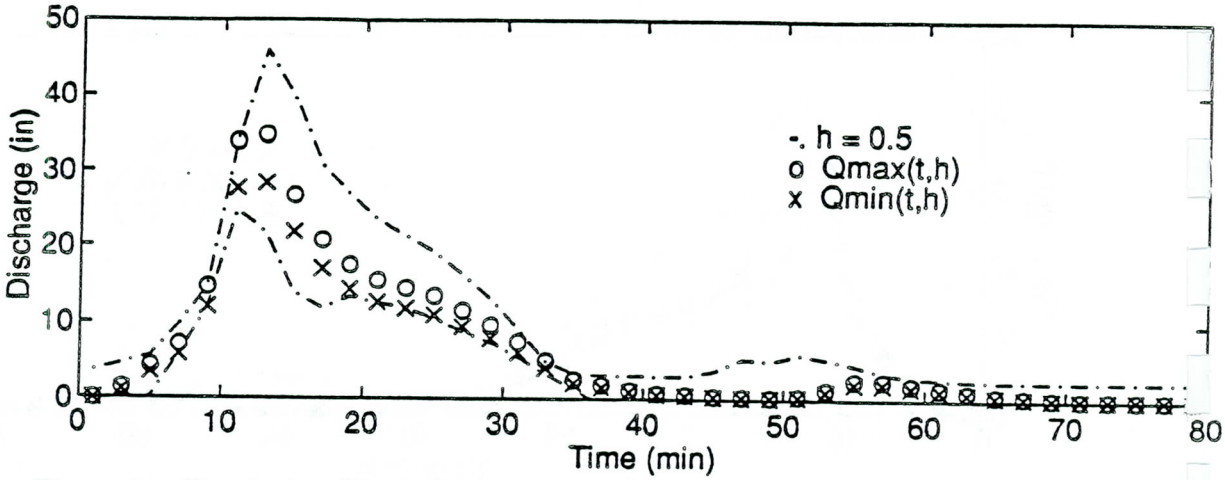


Figure 14: Simulation Event, Lucky Hills-27/July/73; runoff hydrograph; 20 % vaguene s:

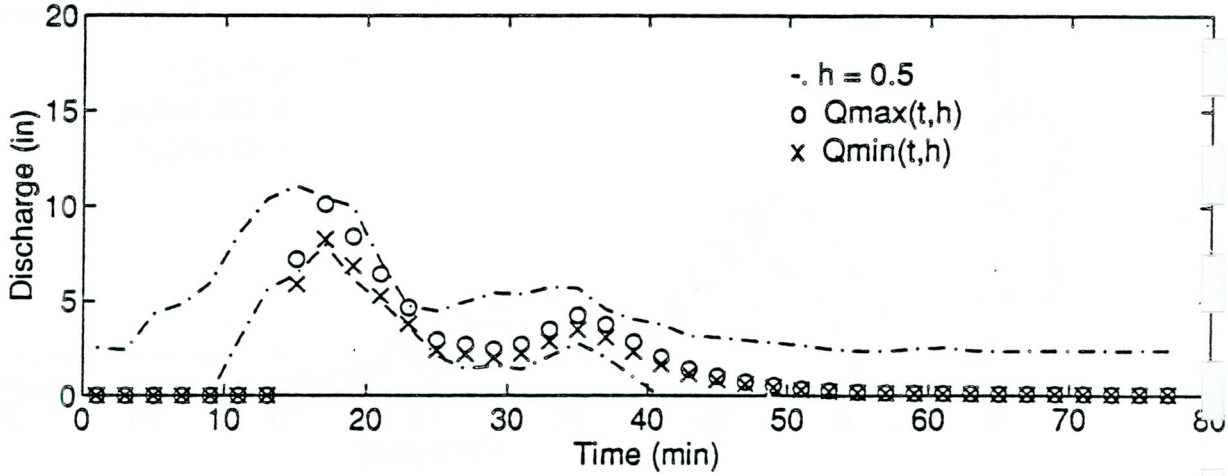


Figure 15: Validation Event, Lucky Hills-01/Aug/74; runoff hydrograph; 20 % vaguene

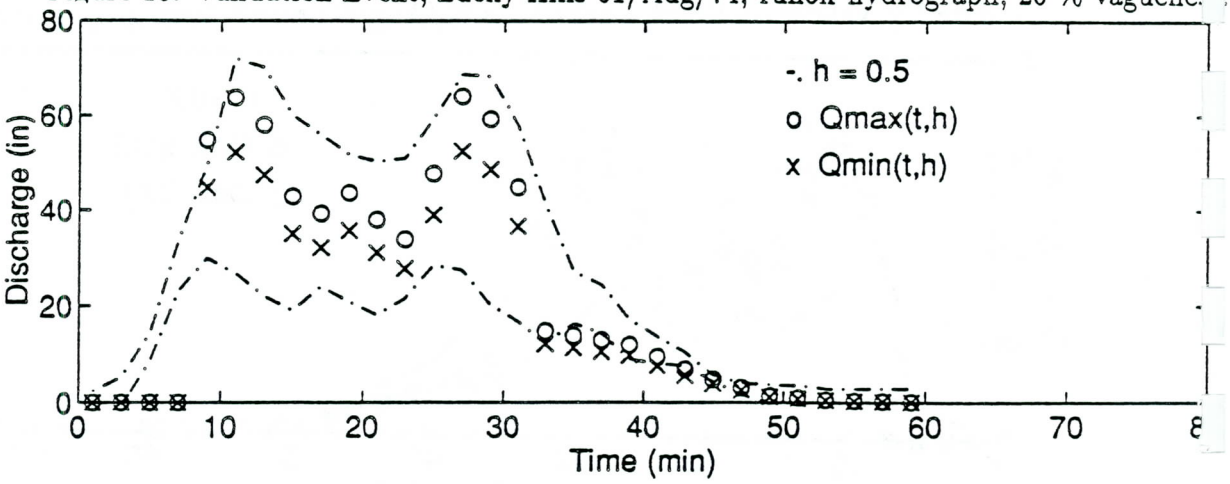


Figure 16: Validation Event, Lucky Hills-17/July/75; runoff hydrograph; 20 % vaguenes

Table 2: Regression Parameters for different objective functions

| | OF1 (Maximum Vagueness) | | | OF2 (Average Vagueness) | | | OF3 (Prediction Vagueness) | | |
|---|---|---|---|---|---|---|---|---|---|
| | A | b | c | A | b | c | A | b | c |
| 0 % Vagueness | | | | | | | | | |
| 1 | 5.81962 | 0.38196 | 0.38196 | 5.98376 | 0.00000 | 0.00000 | 5.03125 | 3.85305 | 3.85305 |
| 2 | 19.82937 | 0.38196 | 0.38196 | 22.86701 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| 3 | 46.39166 | 0.38196 | 0.38196 | 51.19530 | 0.00000 | 0.00000 | 64.79822 | 0.00000 | 0.00000 |
| 4 | 0.00000 | 0.38196 | 0.38196 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| 5 | 1.63020 | 0.38196 | 0.38196 | 1.32582 | 0.00000 | 0.00000 | 1.80042 | 0.00000 | 0.00000 |
| 6 | 0.19678 | 0.38196 | 0.38196 | 0.27835 | 0.79559 | 0.79559 | 0.05336 | 0.00000 | 0.00000 |
| 10 % Vagueness | | | | | | | | | |
| 1 | 6.06168 | 0.47386 | 0.47386 | 6.26816 | 0.00000 | 0.00000 | 5.14012 | 3.74633 | 3.74633 |
| 2 | 15.84404 | 0.47386 | 0.47386 | 19.57446 | 0.00000 | 0.00000 | 2.65575 | 0.00000 | 0.00000 |
| 3 | 54.29036 | 0.47386 | 0.47386 | 53.00169 | 0.00000 | 0.00000 | 61.35763 | 10.01151 | 10.01151 |
| 4 | 0.00000 | 0.47386 | 0.47386 | 0.00000 | 0.36445 | 0.36445 | 0.00000 | 0.00000 | 0.00000 |
| 5 | 1.50773 | 0.47386 | 0.47386 | 1.58573 | 0.00000 | 0.00000 | 1.93536 | 0.17369 | 0.17369 |
| 6 | 0.21728 | 0.47386 | 0.47386 | 0.17318 | 0.84774 | 0.84774 | 0.00000 | 0.00000 | 0.00000 |
| 20 % Vagueness | | | | | | | | | |
| 1 | 6.27199 | 0.57451 | 0.57451 | 6.54402 | 0.00000 | 0.00000 | 5.18474 | 3.31240 | 3.31240 |
| 2 | 14.83483 | 0.57451 | 0.57451 | 7.80615 | 0.00000 | 0.00000 | 4.51935 | 0.00000 | 0.00000 |
| 3 | 58.45010 | 0.57451 | 0.57451 | 59.50339 | 0.00000 | 0.00000 | 60.81100 | 27.96650 | 27.96650 |
| 4 | 0.00000 | 0.57451 | 0.57451 | 0.00000 | 1.09534 | 1.09534 | 0.00000 | 0.04902 | 0.04902 |
| 5 | 1.49826 | 0.57451 | 0.57451 | 1.84059 | 0.00000 | 0.00000 | 1.79746 | 0.33454 | 0.33454 |
| 6 | 0.20202 | 0.57451 | 0.57451 | 0.10356 | 0.74080 | 0.74080 | 0.04167 | 0.00000 | 0.00000 |

# APPENDIX

Below, some of the basic definitions of *fuzzy numbers* are stated.

1. **Fuzzy Subset:** $A = \{(x, \mu A(x)), \quad x \epsilon X\}$
   $A$ is a fuzzy subset of $X$, where $X$ is a set (universe). Here the $\mu A(x) \epsilon [0,1]$ is the membership of x in $A$. The more x belongs to $A$, $\mu A(x)$ is closer to 1 and the less x belongs to $A$, $\mu A(x)$ is closer to 0. If the membership interval $[0,1]$ is replaced by the set $\{0,1\}$ then $A$ can be regarded as a subset of $X$.

2. **h-level set** of the fuzzy subset A is the set of those elements which have at least h membership:
   $$A(h) = \{x : \mu A(x) \geq h\}$$

3. **Normality** is satisfied if there exists at least one z such that $\mu A(z) = 1$

4. **Convexity** is satisfied if for $a \leq c \leq b, \quad a, b, c \epsilon X$, if $\mu A(c) \geq min(\mu A(a), \mu A(b))$ holds.

5. A **Fuzzy Number** is a fuzzy subset which is normal, convex and defined on the set f r numbers.

## ACKNOWLEDGMENTS

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## REFERENCES

Bardossy, A., (1990). Notes on Fuzzy Regression, *Fuzzy Sets and Systems,* Vol. 37, pp. 65 .5.

Bardossy, A., Bogardi, I., Duckstein, L., (1990). Fuzzy Regression in Hydrology, *Water Res rc Research,* Vol. 26, No. 7, pp. 1497-1508.

Bedient, P. B., Huber, W. C., (1988). *Hydrology and Floodplain Analysis,* Addison-Wesle p 219-225,262-266.

Bras, R. L., (1990). *Hydrology: An Introduction to Hydrologic Science,* Addison-Wesley p 466-474.

Dubois, D., Prade H., (1980). *Fuzzy Sets and Systems:Theory and Applications,* New York, NY Academic Press.

Kaufmann, A., Gupta M. M., (1991). *Introduction to Fuzzy Arithmetic: Theory and Applications* New York, NY, Van Nostrand Reinhold.

Starosolszky, O. , (1987). *Applied Surface Hydrology,* Water Resources Pub., pp. 585-587.

Walpole, R.E., Myers, R.H. (1986). *Probability and Statistics for Engineers and Scientists* pp 397-398.

# ASSESSING FACTORS CONTRIBUTING TO SEDIMENT STORAGE IN HEADWATER STREAMS IN NORTHWEST MONTANA[1]

Hilaire A. Bojonell, Aregai Tecle, and John G. King[2]

**ABSTRACT:** This study was designed to look at factors contributing to sediment storage in first and second-order streams. Sediment storage behind obstructions were measured on eighteen forested, mountainous drainage basins in northwestern Montana. Thirteen of the drainage basins were logged to various degrees while five of them were left undisturbed. The logged drainage basins which differed from each other in their level and age of harvesting were used as treatments while the undisturbed drainage basins were used as controls in the study. The objective of the study was to develop models that describe the effect of non-hydrologic factors in sediment accumulation in upland stream channels. Factors such as different stream channel characteristics, level of harvesting, channel and drainage basin slopes, number and diameter of woody debris pieces, and levels of harvesting and areas of watershed above particular stream reaches were evaluated to determine if they had any significant effect on the amount of sediment stored in first and second-order streams. The models indicate that obstructions and channel characteristics are the major factors that determine the quantity of stored sediment.

## INTRODUCTION

Historically, geomorphologists have studied both hillslope erosion processes and sediment transport in streams and rivers separately, but only few studies have quantified the link between these two areas. This link is sediment storage along stream channels (Madej 1984). Sediment storage in stream channels is an important indicator for the amount of erosion from and the movement of sediment through upland watersheds. The identification of storage sites and quantitative description of the amount of sediment stored in these sites are important steps towards constructing models that describe sediment budget on forested, upland watersheds (Dietrich et al. 1982).

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Channel-sediment storage is especially important on forested drainage basins because of additional storage potential provided by falling woody debris that serve as obstructions (Megahan 1982). Obstructions from logs and other debris occur naturally in forested drainage basins. The size and frequency of the obstructions, however, may be strongly influenced by disturbances such as logging (Froehlich 1973, Swanson et al. 1976).

An important characteristic of debris stored sediment is that the storage sites create a buffer system that regulates the movement of bedload through the fluvial system. This has important ramifications for watersheds impacted by land use changes such as road building or timber harvesting. As the sediment enters the stream channel system, there will be a lag time before the sediment yield or output downstream increases significantly. However, once the storage sites are full, then sediment will be transported more rapidly down the channel through the full storage sites (Mcdonald et al. 1982).

This paper examines the factors influencing sediment storage along particular reach segments in eighteen first and second-order streams in the Kootenai National Forest in northwest Montana. The specific objective was to develop models for estimating the volume of stored sediment in the particular reach segments of these streams.

## STUDY AREA

Eighteen streams on the Kootenai National Forest of northwestern Montana were selected for study (Figure 1). All the streams selected are in the Yaak River drainage basin. Description of the average physical characteristics of the different streams considered in this study are provided in Table 1. Five of the eighteen stream basins studied were undisturbed and thus were designated as controls in this study. The other 13 stream drainage basins were selected from different watersheds previously subjected to varying levels of harvesting and, therefore were considered as treatments for the purpose of this study.

The average precipitation on the different watersheds in the Yaak drainage basin ranges from 59 to 115 cm a year. Approximately 60% of this precipitation falls as rain while 40% of it comes in the form of snow. On the average, these drainage basins experience approximately 210 snow free days a year (Kuennen and Gerhardt 1984).

The dominant soil and surficial geology in the study area consist of materials formed from volcanic ash-influenced loess overlying dense glacial till. The main underlying bedrock and the rock fragments in the glacial till consist of argillites, siltites, and quartzites of the Precambrian Belt Supergroup (Kuennen and Gerhardt 1984).

Naturally, the type of climate and soil characteristics influence the type of vegetation growing in the area. The dominant vegetation types in the study area consist of a mixture of western hemlock (Tsuga heterophylla), western redcedar (Thuja plicata

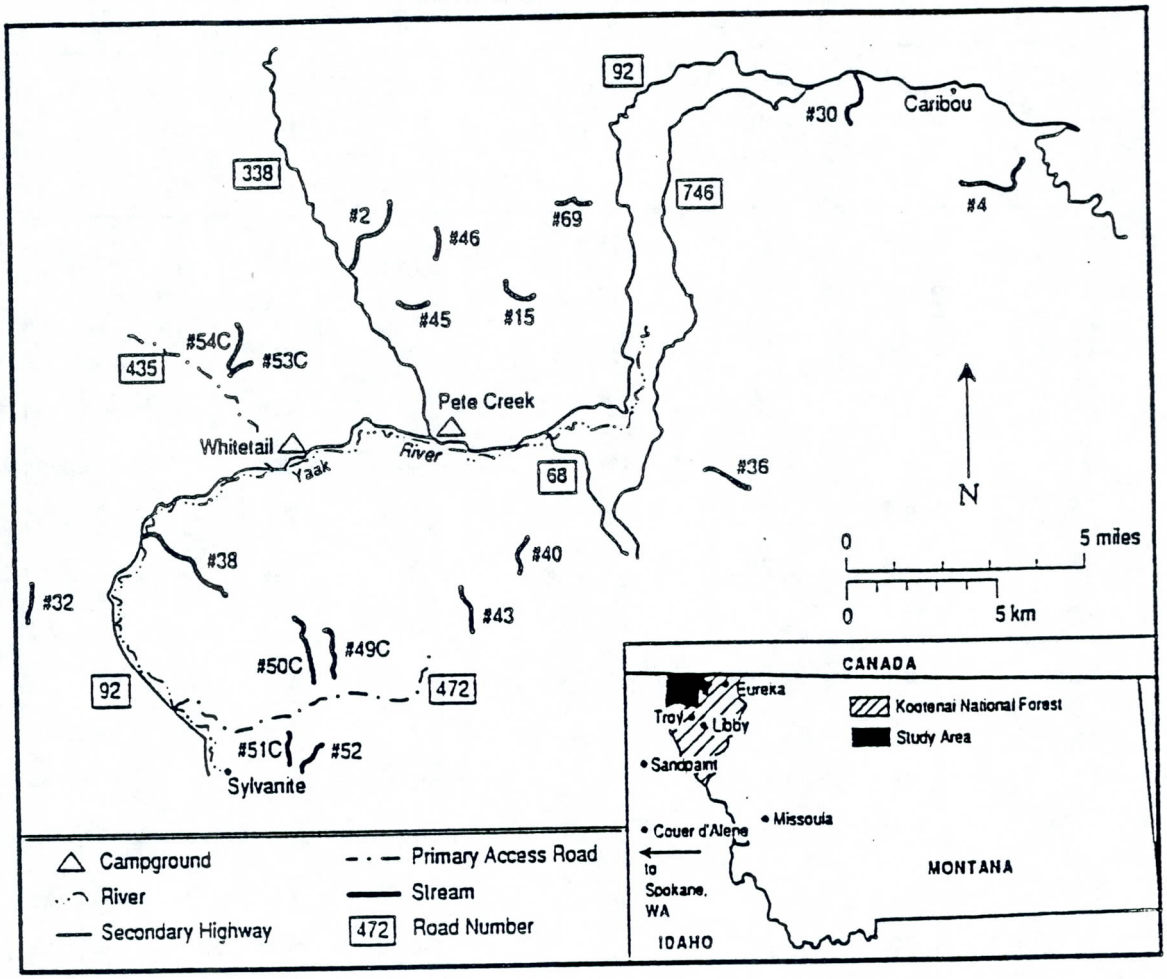


Figure 1. Location of Study Sites, Kootenai National Forest, Montana

lodgepole pine (Pinus contorta), western larch (Larix occidentalis), and Douglas-fir (Pseudotsuga menziesii). Alder (Alnus incana) and cottonwoods (Populus spp.) are also found in the riparian areas.

## METHODS

### Data Collection

Sediment storage behind obstructions was measured at designated reach segments in each drainage basin under study. Eight reaches were selected and delineated along the main stream channel in each drainage basin in accordance with the sampling scheme of Chesney (Chesney, Unpublished Report). The eight reaches were located at regular

Table 1. Summary of watershed characteristics

| Stream Code Number | WS[1] Size ($km^2$) | Avg. WS Slope (%) | Asp[3] | Stream Length (km) | Mean Stream Slope (%) | Hvst Level[4] (%) | Mid-elev[5] (m) |
|---|---|---|---|---|---|---|---|
| 2 | 2.93 | 22 | SW | 3.048 | 14 | 42 | 1392 |
| 4 | 2.07 | 15 | E | 2.743 | 14 | 42 | 1405 |
| 15 | 1.35 | 15 | E | 1.524 | 9 | 83 | 1344 |
| 30 | 1.77 | 25 | N | 1.829 | 18 | 46 | 1360 |
| 32 | 1.01 | 35 | N | 1.524 | 30 | 38 | 1419 |
| 36 | 1.44 | 29 | NW | 1.524 | 24 | 61 | 1320 |
| 38 | 6.36 | 22 | WNW | 3.962 | 16 | 22 | 1405 |
| 40 | 1.74 | 25 | NE | 1.280 | 19 | 38 | 1266 |
| 43 | 1.91 | 20 | NW | 1.981 | 13 | 43 | 1423 |
| 45 | 0.66 | 21 | W | 0.853 | 17 | 88 | 1174 |
| 46 | 0.59 | 14 | S | 1.097 | 10 | 89 | 1343 |
| 40C[6] | 1.83 | 23 | S | 1.768 | 17 | 0 | 824 |
| 50C[6] | 3.38 | 22 | S | 2.591 | 15 | 0 | 1582 |
| 51C[6] | 0.96 | 30 | N | 1.219 | 29 | 0 | 1180 |
| 52 | 0.48 | 27 | NE | 1.155 | 25 | 3 | 1305 |
| 53C[6] | 0.41 | 30 | SW | 0.914 | 29 | 0 | 1378 |
| 54C[6] | 1.30 | 26 | SW | 1.615 | 25 | 0 | 1481 |
| 69 | 1.49 | 24 | E | 1.219 | 15 | 27 | 1282 |

[1]WS = Watershed
[2]Average watershed slope was determined by taking the difference between the high and low watershed elevation and dividing by the length of the watershed.
[3]Asp = Aspect
[4]Hvst Level = Area harvested
[5]Mid-elev = Mid-elevation of the watershed
[6]C = Control watershed

intervals along the entire length of each channel. Each sample reach was designed to be 25 m in length. The first reach was placed 25 m upstream from the mouth of each drainage basin.

Distinctively identifiable obstructions and associated sediment accumulations in the selected reaches were carefully measured. An obstruction in this study is defined as any material in the channel that causes sediment to accumulate because of discontinuities created in the channel gradient. Different types of materials such as logs greater than 5 cm in diameter, rocks, roots, stumps, twigs, leaves and other debris were considered obstructions (Platts et al. 1983). Sampling was restricted to sediment deposits with the following minimum dimensions: average height, 20 cm; average length, 60 cm; and average width, 30 cm. In a similar study on headwater streams in central Idaho, Megahan (1982) found that sediment depositions below these minimum dimensions only accounted for 11 percent of the total stored sediment. The height of an accumulation is defined as the difference between a level rod reading taken on the bed at the downstream side of the obstruction and a rod reading on the sediment deposit immediately upstream from the obstruction. The average of three height measurements was used in this study. The length of an accumulation was the distance from the upstream end of the obstruction to the upstream end of the sediment accumulated behind the obstruction. The average of three lengths was taken. The width of an accumulation was the distance from the left edge of the deposit to the right edge. The width is taken perpendicular to the length of the deposit. Three measurements were taken to obtain the average width of a sediment deposit. Sediment volumes were computed by assuming the deposits to approximate a rectangular wedge in shape. Based on such assumption the following equation was used to determine the volume of sediment deposit behind an obstruction (Platts et al. 1983):

$$V_{sed} = (H/2) * L * W \qquad [1]$$

Where: $V_{sed}$ = Volume of sediment per deposit ($m^3$)
$H$ = Average height of deposit (m)
$L$ = Average length of deposit (m)
$W$ = Average width of deposit (m)

Dimensions of stream channel cross-section were also measured using the sag-tape method. These measurements were input into R4-CROSS (Burton et al. 1991), a computer program used by certain regional offices of the U.S. Department of Agriculture, Forest Service to generate channel cross-sectional areas, depths, and wetted perimeters. Channel widths were directly computed from the data sheets, while channel gradients were determined using a clinometer.

Finally, all pieces of woody debris in the reach were counted and the diameter of each piece was measured at the center of its length. Only woody materials having dimensions greater than 4 cm in diameter and 76 cm in length were counted and measured.

### Statistical Analysis

A series of statistical analyses were conducted using SYSTAT (Wilkinson 1989) to describe the volume of sediment stored in the reaches, in terms of the most important and relevant drainage basin characteristics. The particular factors examined include watershed and channel related characteristics, vegetation treatment levels, and size and frequency of woody debris in the stream channels. All together, there were 24 different variables considered for inclusion in the modeling process. The proposed functional relationship and the independent variables considered during the multiple regression analyses of the problem included:

$$V_{sed} = f(OBSD, CHC, Asp, HVST, A, SS, NLOD, NOBS, Age, WSS) \quad 2]$$

Where $V_{sed}$ = Volume of Sediment
OBSD = Diameter of debris causing the deposit
CHC = Channel characteristics [width (W), depth (D), cross-sectional area (Xarea), wetted perimeter(Wp)]
Asp = Aspect
HVST = Harvest level above reach
A = Watershed area above a particular reach
SS = Average reach slope
NLOD = Number of woody debris pieces per reach (total number of pieces of a particular average diameter/reach)
Age = Age of harvest
WSS = Watershed slope (%)
NOBS = Number of obstructions

However, preliminary tests to determine the relationship of the stored sediment to the individual variables revealed that most of the variables did not significantly contribute to the amount of stored sediment. As a result, only 8 of the variables that showed to have relatively significant impact on the amount of stored sediment were used in the final model development. The eight variables are number (NOBS) and mean diameter (OBSD) of obstructions, mean depth (D) and mean cross-sectional area (Xarea) of measured reaches, percent watershed area harvested above each reach (HVST), mean bankfull width (BW) and number of large organic debris (NLOD).

## RESULTS AND DISCUSSION

### The Modeling Process

The initial idea in this study was to develop watershed-based models for estimating the amount of sediment stored in first and second order upland stream channels. Preliminary analysis of the data obtained, however, showed the presence of too much variability from one reach to another within the same stream in a watershed. Under

these circumstances, lumping of the different reach characteristics in a watershed could result in loss of important details in the data. To minimize this kind of problem, the models were developed on a reach- rather than on a watershed-basis. In the process, each reach was described using its own unique attributes and treated as a subwatershed for the purpose of this study. This approach enabled the data to more closely reflect actual field conditions.

As pointed out previously, a total of eight reaches were measured in each stream except in streams 51 and 52. Only six and seven reaches can be measured in these two streams, respectively, because they are too short to have eight 25 m reach segments in them. All together, there were 141 reaches measured in the study area.

A preliminary statistical analysis of the data collected from the 141 reaches exhibited the presence of significant outliers. Graphical displays were used to identify the outliers. Once identified, the problem of outliers in the modeling process was minimized by removing 4 of the reaches resulting in a total of 137 reaches for use in the final modeling process.

In addition to eliminating channel reaches, the development of sediment storage models also involved reducing the number of variables used in the modeling process. As pointed out previously, 24 variables were considered initially as potential contributors to the amount of sediment stored in stream channels. But, several of the variables identified such as age of harvest, contributing watershed area above each reach, channel slope, and aspect were determined to have little or no significant effect on the amount of stored sediment. Since age of harvest was hypothesized to have an important effect on the amount of sediment stored, particular attempts were made during the modeling process to look at the effects of age of harvest on sediment storage. However, it was found that various parts of a single drainage basin were harvested at different times. This kind of temporal variation in harvesting has resulted in major differences in vegetation patterns even among stands within the same reach. This made it difficult to attribute certain sediment volumes to specific ages of harvest. Further attempts were made to evaluate the impacts of the weighted averages of the age of harvest upon sediment storage, but these attempts also proved fruitless. As a result, age of harvest was dropped form consideration.

The contributing area above each reach was also thought to be an important factor in estimating the amount of sediment stored in stream channels. However, the effect of this factor on the stored sediment was also found to be not significant ($R^2=0.02$). Thus, we suggest that it is the immediate or closest sources of sediment rather than those sources located away from the stream that have the greater effects on sediment storage. This may be especially true in forest covered areas, or in fully re-vegetated previously harvested areas. In such cases sediment sources such as nearby roads, landslides, or stream bank erosion probably play a greater role than the overall contributing area.

Channel slope and aspect were other variables that did not significantly contribute to the stored sediment. Even though small headwater channels such as the ones under

decreasing effect on the overall stream gradient by forming log steps. As a result, in these kinds of small streams, effective gradient may prove to be a more important variable than the overall stream gradient in estimating stored sediment. Similar attempts were made to look at the effect of aspect on amount of sediment stored in the stream channels, but no consistent relationship was evident. As a result channel slope and aspect were also dropped from consideration.

**Choice of Model**

Several non-linear regression models were developed to describe the volume of sediment stored in first and second order upland streams. The models are quantitatively described in terms of 2 to 8 of the 24 factors that were considered to contribute to the amount of sediment stored in stream channels (see Table 2). These models are found to be statistically significant ($p < 0.05$) with respect to their parameters, and display homogeneous variance in their residuals.

The developed models, however, are not equally satisfactory; some could be more preferable than others. Selection of a preferred model may be done by comparing the models developed with each other on the basis of their coefficient of determination. But, it is also important that satisfactory models conform well with the general physical processes involved. A structural comparison of the 6 sediment storage models developed is shown in Table 2. In this list, models 6, 7, and 8 have relatively better fit compared to models 3, 4, and 5 on the basis of their individual $R_A^2$ values. But, the first group of models require more labor intensive data gathering in order to be used. The choice of a model for use then depends on the level of prediction needed and the availability of adequate time and resources to develop and run the model.

The selected model, in this study, may be used for estimating the volume of sediment stored in a 25 m reach of a first or second-order stream in a forested, upland watershed. The amount of stored sediment so determined is expressed in terms of the total sediment volume stored within the reach, and the volume is estimated using equations 3 to 8 shown in Table 2. The equations are expressed as a function of two to eight variables.

All the variables in the models presented are positively correlated with the total volume of stored sediment except for average channel cross-sectional area and the number of pieces of large woody debris in the reach, both of which happen to show negative correlations. This phenomenon may be due to the effect of buffers, that is buffered stream sides may yield smaller amounts of sediment while providing the stream channels with large amounts of woody debris. Thus, the negative relationship between sediment storage and the number of pieces of large woody debris may be the indirect result of such conditions. The negative relationship between sediment storage and channel cross-sectional area may be partly due to both horizontal spread of the stored sediment and its easier movement downstream along wider channels. But, it is important to remember that these preliminary conclusions are based on a single year data only, therefore more observations over a lengthy period of time would be needed to ascertain

Table 2. Models developed to predict the volume of stored sediment

| Model | SEE | $R_A^2$ | Eqn No. |
|---|---|---|---|
| $V_{sed}$ = (0.210814 + 0.013390 nobs + 0.011937 obsd + 0.001761 nobs*obsd)$^2$ | 0.38983 | .741 | [3] |
| $V_{sed}$ = (0.058209 + 0.014370 nobs + 0.013062 obsd + 0.001475 nobs*obsd + 0.944244 d)$^2$ | 0.37604 | .761 | [4] |
| $V_{sed}$ = (0.017121 + 0.016034 nobs + 0.013651 obsd + 0.001394 nobs*obsd + 0.006454 wss*hvst + 0.864377 d)$^2$ | 0.37192 | .768 | [5] |
| $V_{sed}$ = (0.172723 + 0.019575 nobs + 0.014090 obsd + 0.001026 nobs*obsd - 0.200304 xarea + 1.280632 d + 0.116301 w)$^2$ | 0.34619 | .800 | [6] |
| $V_{sed}$ = (-0.276451 + 0.019452 nobs + 0.014157 obsd + 0.001066 nobs*obsd - 0.255592 xarea + 1.542261 d + 0.009006 wss*hvst + 0.123910 w)$^2$ | 0.33663 | .813 | [7] |
| $V_{sed}$ = (-0.136239 + 0.020001 nobs + 0.010933 obsd + 0.001297 nobs*obsd - 0.263253 xarea + 1.747379 d + 0.006987 wss*hvst -0.005687 nlod + 0.126835 w)$^2$ | 0.33015 | .821 | [8] |

SEE = Standard error of estimate
$R_A^2$ = Adjusted coefficient of determination
$V_{sed}$ = Total volume of stored sediment $(m)^3$
nobs = Number of obstructions
obsd = Mean obstruction diameter (cm)
xarea = Mean channel cross-sectional area ($m^2$)
d = Mean channel depth (m)
wss = Watershed slope (%)
hvst = Area harvested above reach (%)
nlod = Number of large organic debris
w = Mean bankfull width (m)

them. The problem is more complex than it seems; there are many factors which may jointly but not individually have some significant effect on the amount of stored sediment (Bojonell 1993). Such factors are not included in the models. In all of the models developed, the number of obstructions had the largest relative effect on the total volume of stored sediment compared to the other independent variables. Average channel depth and cross-sectional area contributed the second and third largest relative effect on the stored sediment volume, respectively. However, when the cross-sectional area term was omitted from the models (models 3, 4, and 5) then the interaction term, number of obstructions times obstruction diameter (NOBS*OBSD), had the second largest relative

effect on the volume of stored sediment. The term with the lowest relative effect on the volume of stored sediment was the interaction term watershed slope times area harvested above the reach (WSS*HVST).

## CONCLUDING REMARKS

Several models to predict stored sediment in headwater streams were developed in this study. The models indicate that obstruction and channel characteristics are the major factors that determine the quantity and location of sediment storage. But, because the ability of the models to estimate the amount of accumulated sediment improves with model complexity, the choice for a particular model depends on the level of prediction needed and the time and resource available to collect all the inputs needed to run it.

The models developed may be used to estimate stored sediment from a knowledge of mostly physical channel characteristics. However, they can also be used with caution for other forest watershed management purposes. For instance, they can abe used for sediment and debris load monitoring purposes on a year-to-year as well as for estimating sediment budget in upland forested watersheds. The use of these models, however, should be confined to first or second-order streams in northwestern Montana, with possible extension to northern Idaho, until they are tested for their applicability anywhere else. Because the models developed in this study were based on a one-year data and used harvested areas that were older than four years, these facts should be considered in using the models.

Because the models developed in this study were strictly based on non-hydrologic inputs, it would be interesting to see how the models would behave with hydrological data like precipitation inputs added. One approach that can be taken is coupling the non-hydrologic models with hydrologically-based models like that suggested in Tecle et al. (1990). Such coupling would have a better representation of most of the relevant hydrologic factors and possibly improve the predictive capacity of the models developed.

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## LITERATURE CITED

Bojonell, Hilaire A. 1993. Assessing factors contributing to sediment storage in headwater streams in northwest Montana. A Master's Thessis, Northern Arizona University, Flagstaff, Arizona.

Burton, T., J. Potyondy, and F. Hernandez. 1991. R4 stream channel hydraulics. Boise National Forest. Boise, Idaho.

Dietrich, W.E., T. Dunne, N.F. Humphrey, and L.M. Reid. 1982. Construction of sediment budgets for drainage basins. pp. 5-23. In: Sediment Budgets and Routing in Forested Drainage Basins. USDA Forest Service General Technical Report PNW-141. Pacific Northwest Forest and Range Experiment Station. Portland, Oregon.

Froehlich, H.A. 1973. Natural and man-caused slash in headwater streams. Loggers Handbook, vol. 33, Pacific Logging Congress. Portland, Oregon. 8p.

Kuennen, L.J., and M.N. Gerhardt. 1984. Kootenai National Forest area land system inventory. USDA Forest Service, Kootenai National Forest, Libby, Montana.

Mcdonald, A., E.A. Keller, and T. Tally. 1982. The role of large organic debris on stream channels draining redwood forests in Northwestern California. pp. 226-245: In: Harden, D.K., D.C. Marron, and A. Mcdonald eds. Friends of the Pleistocene 1982 Pacific Cell Field Trip Guidebook, Late Cenozoic History and Forest Geomorphology of Humbold County, California.

Madej, M.A. 1984. Recent changes in channel-stored sediment. Technical Report 11. Redwood National Park, Aracata, CA.

Megahan, W.F. 1982. Channel sediment storage behind obstructions in forested drainage basins draining the granitic bedrock of the Idaho batholith. pp. 114-121. In: Sediment Budgets and Routing in Forested Drainage Basins. USDA Forest Service General Technical Report PNW-141. Pacific Northwest Forest and Range Experiment Station. Portland, Oregon.

Platts, W.S., W.F. Megahan, and G.W. Minshall. 1983. Methods for evaluating stream, riparian, and biotic conditions. Intermountain Forest and Range Experiment Station. Ogden, Utah. General Technical Report INT-138. 70p.

Swanson, F.J., G.W. Lienkaemper, J.R. Sedell. 1976. History, physical effects, and management implications of large organic debris in western Oregon streams. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon. General Technical Report PNW-56. 15p.

Tecle, A., D.P. Dykstra, W.W. Covington, and L. D. Garret. 1990. Proposed methodology for soil loss prediction from southwestern forests. Hydrology and Water Resources in Arizona and the Southwest, 20: 113-129.

Wilkinson, L. 1989. SYSTAT, the system for statistics. SYSTAT, Inc., Evanston Illinois.

# Part V

# MODEL UTILIZATION AS A TOOL TO ADDRESS CRITICAL WATER RESOURCES MANAGEMENT ISSUES

# GROUNDWATER FLOW MODEL OF THE SALT RIVER VALLEY, PHOENIX ACTIVE MANAGEMENT AREA[1]

Steven W. Corell & Edwin F. Corkhill[2]

**ABSTRACT:** The Arizona Department of Water Resources (ADWR) has developed a groundwater flow model for the Phoenix Active Management that focuses on the hydrologic system of the Salt River Valley (SRV), one of the most intensive water use areas of Arizona. The model is to be used as a planning tool to study the impacts of various water management and conservation scenarios. Currently the model is being used to simulate the impacts of potential groundwater recharge projects in the West SRV sub-basin. Eventually, contaminant transport capabilities may be added to the model. Reports documenting the SRV model are available from the ADWR Hydrology Division.

The model was developed using the U.S. Geological Survey Modular Three-Dimensional Groundwater Flow Model (MODFLOW). The three-dimensional model simulates steady-state groundwater flow (circa 1900) and transient-state groundwater flow (1983 - 1989). The model has three layers and simulates groundwater underflow, groundwater pumpage, seepage to and from perennial river reaches, and groundwater recharge from agricultural irrigation, major flood events, and canals.

The model was calibrated for both steady-state and transient-state groundwater flow conditions. The transient model calibration final simulated water levels and flow directions reasonably matched the final measured water levels. A sensitivity analysis is to be conducted on the model output to determine how sensitive the model solution is to variations in model input parameters.

Recommendations to improve future modeling efforts include: 1) development of a more comprehensive aquifer test database, 2) revision and enlargement of the SRV water level measurement index line, 3) improvement of the current stream gage network in the SRV, 4) an extended transient calibration period, 5) seasonalize model pumpage and recharge, 6) improved estimates of recharge, 7) incorporate a re-wetting option in the model code to permit the model to resaturate "dewatered" cells, 8) incorporate a subsidence package in the model code to simulate aquifer compaction resulting from groundwater storage changes in compressible beds.

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## BACKGROUND ON MODEL DEVELOPMENT

### Introduction.

Arizona's Groundwater Management Act of 1980 was enacted to address the groundwater overdraft problem occurring in several areas of the state. The Act established the Arizona Department of Water Resources (ADWR), and also established four administrative areas in Arizona, known as Active Management Areas (AMA's). The groundwater flow model discussed in this report was designed to serve as a planning tool for groundwater management in the Phoenix AMA.

The Phoenix AMA is located in Central Arizona covering 5,646 square miles and consists of seven groundwater sub-basins: East Salt River Valley (ESRV), West Salt River Valley (WSRV), Hassayampa, Rainbow Valley, Fountain Hills, Lake Pleasant, and Carefree. The ESRV and WSRV are collectively referred to as the Salt River Valley (SRV). The focus of this modeling study is the SRV, the largest and most populous urban area in Arizona (Figure 1). The area modeled within the SRV is approximately 2,240 square miles.

Extensive water use occurs within the SRV. The combined water demand of the agricultural, municipal, and industrial sectors is the greatest of any area in the state. The historic trend in groundwater depletion, coupled with continued intensive demand on the groundwater system calls for careful management of the groundwater resources of the SRV. To aid the Phoenix AMA in water management planning the modeling section of the Hydrology Division of the ADWR began the development of a three-dimensional groundwater flow model of the SRV area in November 1987.

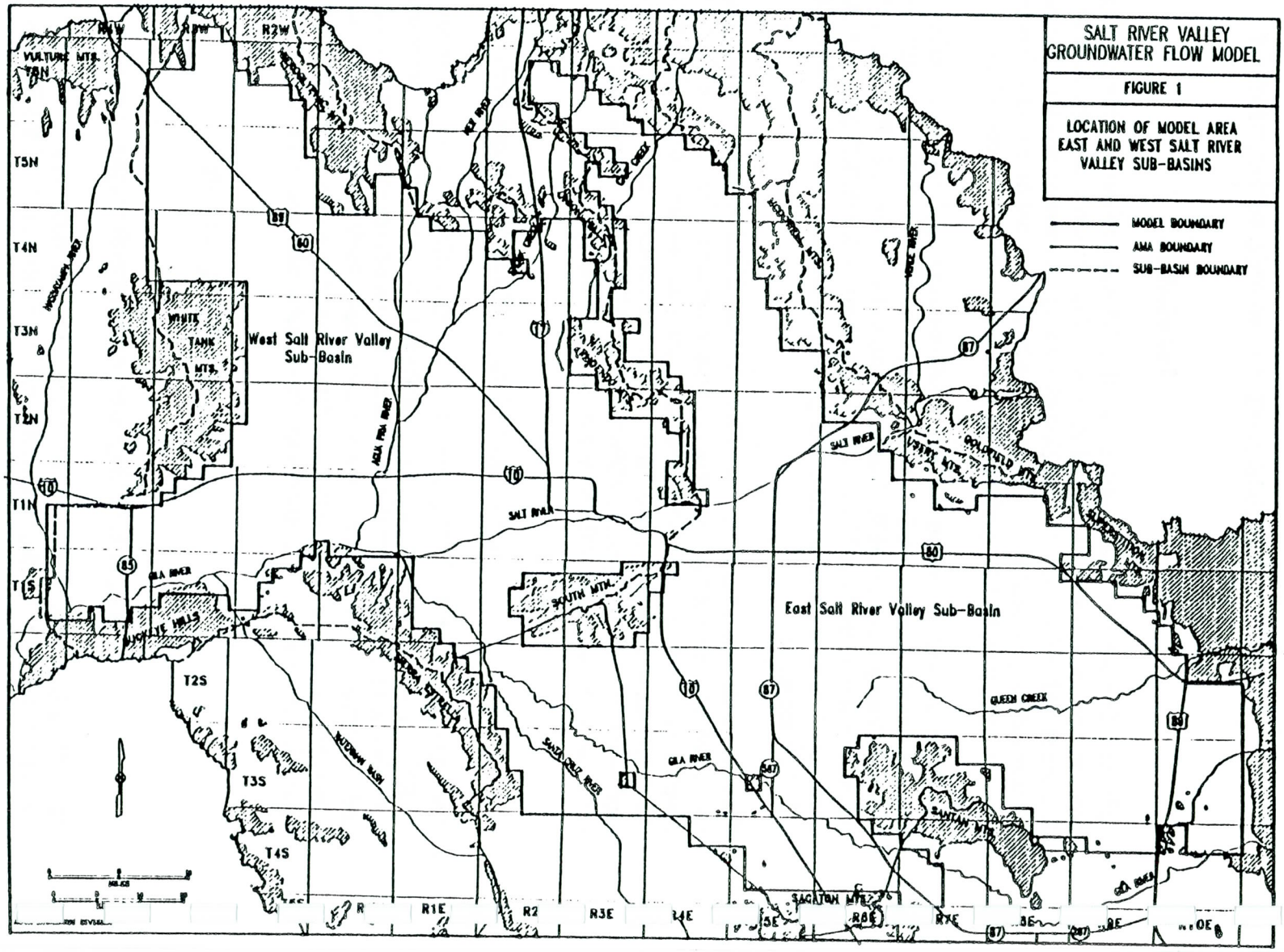
### Goal And Objective Of The Modeling Effort.

The ultimate goal of the SRV groundwater modeling effort is to provide an analytical tool capable of quantifying the effects of various groundwater management and conservation scenarios on the groundwater resources within the study area. The objectives were: 1) perform a comprehensive search and collection of all current and historic hydrologic, geologic, and land use parameters, 2) develop a groundwater database of the assembled data, 3) develop a three-dimensional groundwater flow model, 4) develop recommendations concerning future data collection and model improvement efforts.

## CONCEPTUAL MODEL

### Regional Setting: Geography, Physiography, And Climate.

The SRV is located in central Arizona (Figure 1). The study area encompasses the heaviest water use area of the state and includes : the ESRV and WSRV sub-basins of the Phoenix AMA, and the northern


SALT RIVER VALLEY
GROUNDWATER FLOW MODEL
FIGURE 1
LOCATION OF MODEL AREA
EAST AND WEST SALT RIVER
VALLEY SUB-BASINS
MODEL BOUNDARY
AMA BOUNDARY
SUB-BASIN BOUNDARY
West Salt River Valley
Sub-Basin
East Salt River Valley Sub-Basin
VULTURE MTS.
WHITE TANK MTS.
SOUTH MTN.
SALT RIVER
GILA RIVER
QUEEN CREEK
SACATON MTS.
T6N
T5N
T4N
T3N
T2N
T1N
T1S
T2S
T3S
T4S
R2W
R1W
R1E
R2
R3E
R4E
R5E
R6E
R7E
R8E
R9E

portion of the Maricopa-Stanfield sub-basin of the Pinal AMA. The study area is part of the Basin and Range physiographic province and consists of gently-sloping alluvial plains separated by predominantly north to northwest trending mountain ranges (Anderson and others, 1990). Elevations on the basin floor range from 1,000 to 2,500 feet above mean sea level.

The climate of the study area is semi-arid, with hot summers and mild winters. Average annual precipitation ranges from 7 to 8 inches (ADWR, 1991). A small majority of the precipitation occurs in winter, however, July and August recieve considerable amounts from thunderstorms associated with the summer monsoon.

The model area is drained by three major streams--the Salt, Gila, and Agua Fria Rivers. The Salt River below Granite Reef Dam is ephemeral, flowing only in response to local flooding and releases from upstream reservoirs. The Gila River from Ashurst-Hayden Dam to near its confluence with the Salt River is also ephemeral, flowing only in response to flooding and reservoir releases. Below the confluence with the Salt River, the Gila River flows perennially due to effluent discharge from the City of Phoenix 91st Avenue Wastewater Treatment Plant. The Agua Fria River is also ephemeral.

## General Hydrogeologic Framework

### Structure.

The SRV consists of two distinct but interconnected alluvial groundwater basins. The western alluvial basin is approximately equivalent to WSRV sub-basin and the eastern alluvial basin includes the ESRV sub-basin and the northern part of the Maricopa-Stanfield sub-basin of the Pinal AMA. The alluvial basins are connected between South Mountain and the Sierra Estrella Mountains and between South Mountain and the Papago Buttes (Figure 1).

The alluvial basins are defined and partially surrounded by predominantly north to northwest trending fault-block mountain ranges. The alluvial basins and most of the surrounding mountains characteristic of present-day Basin and Range physiography were formed during a period of high-angle block faulting that occurred between approximately 15 and 8 million years ago (Shafiquallah and others, 1980). South Mountain is a northeast-trending arch structure that was formed prior to Basin and Range faulting (Reynolds, 1985).

The crystalline and extrusive rocks form nearly impermeable boundaries to groundwater flow and are collectively referred to in this report as the hydrologic bedrock unit. The mountain ranges surrounding the basins also include sedimentary rocks of Late Tertiary age referred to as the red unit (Arteaga and others, 1968). Because the red unit is limited in areal extent and typically well cemented, it is not a significant source of water on a regional scale. The red unit has therefore been included with the basin-fill deposits for modeling purposes.

**Basin-Fill Deposits and Hydrogeologic Units Defined For The Model:**

The alluvial basins of the SRV consist of thick basin-fill deposits of unconsolidated to semiconsolidated clastic sediment of Late Tertiary to Quaternary age. The basin-fill deposits range in thickness from less than 100 feet near the basin margins to over 10,000 feet in the central areas of the basins. The basin-fill deposits consist of interbedded sequences of conglomerate, gravel, sand, silt, clay and evaporites. These clastic sediments represent sequences of alluvial fan, playa and fluvial deposits formed during the development of the alluvial basins. The basin-fill deposits comprise the regional aquifer in the SRV and are the primary focus of the modeling effort. These deposits were subdivided into three hydrogeologic units for modeling purposes. The three hydrogeologic units are designated in ascending order: 1) Lower Alluvial Unit (LAU), 2) Middle Alluvial Unit (MAU), 3) Upper Alluvial Unit (UAU). The stratigraphic relationships among the three hydrogeologic units of the basin-fill deposits are illustrated in Figure 2. The hydrogeologic units as defined for the model are discussed in the following sections.

**Lower Alluvial Unit (LAU).**

The LAU overlies or is in fault contact with the hydrologic bedrock unit and the red unit. This unit consists mainly of conglomerate and gravel near the basin margins, grading into mudstone, gypsiferous and anhydritic mudstone and anhydrite in the central areas of the basin. The LAU locally contains interbedded volcanic rocks.

**Middle Alluvial Unit (MAU).**

The MAU overlies the LAU and consists mainly of clay, silt, mudstone, and gypsiferous mudstone with some interbedded sand and gravel. Near the margins of the alluvial basins the MAU is predominantly sand and gravel and is difficult to distinguish from the other units.

**Upper Alluvial Unit (UAU).**

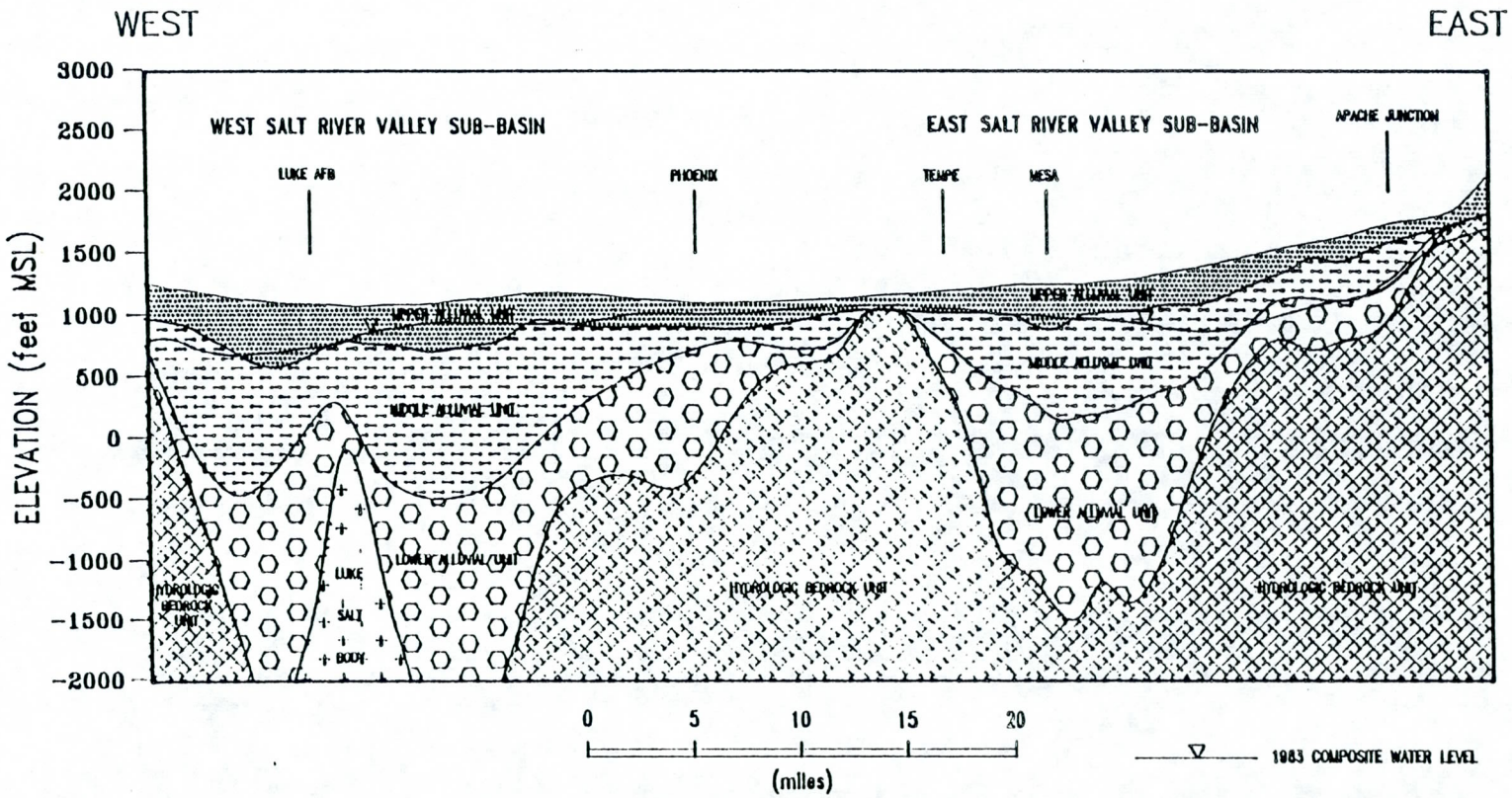
The UAU overlies the MAU and consists primarily of silt, sand, and gravel. The composition of the UAU is dominated by sand and gravel near the present day Salt and Gila Rivers, along the former course of the Salt River east and south of South Mountain, and near the margins of the alluvial basins. In other areas, the unit is typically dominated by silt and sand.

**The Predevelopment Hydrologic System -- Circa 1900:**

The predevelopment hydrologic system of the SRV has been studied to serve as the time-frame for the steady-state calibration of the groundwater flow model. The various components of groundwater inflow and outflow have been identified and analyzed and include underflow, perennial and ephemeral stream channel infiltration, mountain front recharge, and evapotranspiration.

FIGURE 2

# SALT RIVER VALLEY
## GENERALIZED HYDROGEOLOGIC CROSS-SECTION




ADWR HYDROLOGY DIVISION

**The Modern Hydrologic System -- 1983 to 1988:**

The modern hydrologic system of the SRV (1983 to 1988) has been studied to serve as the time-frame for the transient-state calibration of the groundwater flow model. The various components of groundwater inflow and outflow have been identified and analyzed and include underflow, multiple sources of recharge, pumpage, and evapotranspiration.

## NUMERICAL MODEL

This model has been used to simulate the steady-state groundwater flow conditions of the predevelopment era (Circa 1900), and the transient flow conditions of the modern era (1983 to 1988). The model is quasi three-dimensional, and simulates the three major hydrogeologic units (UAU, MAU, and LAU) using three model layers. The model simulates groundwater underflow into and out of the model area, groundwater recharge, pumpage, evapotranspiration, and seepage losses from and to the aquifer along the perennial reaches of the Salt and Gila Rivers. A brief description of the model development follows.

### Selection Of The Model Code.

The model code selected to simulate groundwater flow was the Modular Three-Dimensional Finite Difference Groundwater Flow Model, or MODFLOW, developed by the U.S. Geological Survey (McDonald and Harbaugh, 1988).

### Model Layers And Aquifer Conditions.

Three model layers were used in the model to represent the three hydrogeologic units modeled. The uppermost layer, Layer 1, corresponds to the UAU which is modeled as an unconfined aquifer. The middle layer, Layer 2, corresponds to the MAU which is modeled as a confined/unconfined aquifer, confined when the overlying UAU is saturated and unconfined when the UAU is dewatered. The bottom layer, Layer 3, corresponds to the Lower Alluvial Unit (LAU). The Red Unit which occurs in the subsurface in East Phoenix and Scottsdale is included in the LAU due to its similar hydraulic properties and limited areal extent. The LAU is also modeled as a confined/unconfined aquifer, confined when the overlying MAU is saturated and unconfined when the MAU is dewatered.

Near the basin margins, the bottom of Layer 3 corresponds to the geologic contact of basin-fill deposits with the Hydrologic Bedrock Unit near the basin margins. Toward the basin centers where basin-fill deposits are very thick, the bottom of Layer 3 parallels the land surface elevation with a maximum thickness of 3,000 feet. The maximum thickness of 3,000 feet below land surface was selected, in part, because there are no pumping wells in the model study area deeper than 3,000 feet. In addition, the

hydraulic conductivity and storativity of the LAU are likely lower below this depth due to consolidation caused by higher overburden pressures. The thickness of each model layer is defined by the elevation of each hydrogeologic unit contact.

## Model Data Requirements

### Water Levels.

The water-level data for the steady-state model simulation was adapted mainly from the depth to water map constructed by Lee (1905), and predevelopment water level maps constructed by Anderson (1968), and by Thomsen and Baldys (1985). This map is assumed to be representative of predevelopment groundwater levels. The same water-level elevation was used for all three model layers as it was assumed there was little vertical hydraulic gradient in the predevelopment era. The transient model simulation (1983 - 1988) required initial and final water level data from GWSI (ADWR database: Groundwater Site Inventory). Unit-specific water level maps were created for each model layer.

### Recharge.

Recharge represents the major inflow to the modern groundwater system. The sources of recharge identified and simulated in the model include incidental recharge from agricultural and urban irrigation, canal seepage, artificial lakes, treated effluent discharged into river channels, and naturally occurring recharge from flood flows along the major drainages and mountain fronts within the SRV. The maximum potential recharge for each recharge source was calculated to provide a high end estimate for the potential range of recharge. These recharge values served as initial transient model inputs, during the model calibration some of these recharge values were reduced.

### Pumpage.

There was little groundwater pumpage during the predevelopment era, therefore groundwater pumpage was not simulated in the steady-state calibration. Significant groundwater pumpage was simulated for the transient model calibration. Annual well pumpage was totaled for each model cell and summarized into a single volumetric pumpage rate ($ft^3$/day).

### Evapotranspiration.

Evapotranspiration from phreatophyte growth has occurred along the Salt and Gila Rivers during both the predevelopment and modern eras. However, substantial changes have occurred in the riparian community since the predevelopment era. Indigenious species of plants have been replaced, and the areal extent of phreatophyte growth has been reduced due to decreased water levels (Graf, 1980). Due to the changes in the riparian community since the predevelopment era it was necessary to develop

seperate estimates of evapotranspiration rates and distributions for the steady-state and transient calibration periods.

**Aquifer Parameters.**

Initial hydraulic conductivity (K) estimates were developed using aquifer test data from groundwater contamination site studies, specific capacity data from GWSI and other sources, recovery test data from the Salt River Project (SRP), and particle size data from the USGS. Hydraulic conductivity values were adjusted during the calibration of the steady-state model.

Storativity estimates were provided from aquifer test data and other sources. Estimates of the potential range of storage coefficient were also obtained from published data. In addition, storage coefficient estimates were calculated by multiplying compressible aquifer thicknesses by appropriate values of specific storage (1/Ft). Ultimately, a constant storage coefficient of 0.005 was assigned to all model cells in Layers 2 and 3.

## MODEL CALIBRATION

### Steady State Calibration.

The SRV groundwater flow model was initially calibrated to the steady-state conditions which characterized the predevelopment era. The primary purpose of the steady-state calibration was to refine the original estimates of hydraulic conductivity and river conductances. The steady-state calibration also provided estimates of invariant boundary fluxes and mountain front recharge which were later used as transient model inputs.

The steady-state calibration process involved making adjustments to K values and river conductance values to obtain an acceptable match between model simulated water levels and measured water levels. In most locations a reasonable match was achieved. The combination of an acceptable head match and comparable water budget totals indicated that the model reasonably simulated the steady-state groundwater flow conditions of the predevelopment era.

### Transient Calibration.

Following the steady-state calibration the model was calibrated to the transient groundwater flow conditions of the period, winter 1983 (initial water levels) to winter 1989 (final water levels). The main purpose of the transient calibration was to adjust storativities and recharge rates, and also to demonstrate that the model could reasonably simulate the effects of changing hydrologic stresses. Measured water level data from winter 1983 were mapped and used as initial head inputs for the transient model calibration. Other inputs to the transient model included the K-arrays which were developed during the steady-state calibration.

River conductances developed during the steady-state model calibration were used for the transient-state model inputs. However, the number of model cells used to simulate perennial flow conditions were substantially reduced due to the fact that the perennial reaches of the Salt and Gila Rivers have decreased from the predevelopment era. Perennial reaches were simulated on the Salt River downstream of the 91st Avenue Wastewater Treatment Plant, and the perennial reach of the Gila River from approximately 2 miles upstream of the Salt and Gila River confluence to the southwestern model boundary near Arlington.

The transient-state calibration consisted of identifying areas within the model that did not adequately simulate observed field measured heads and then modifying the model input data. The input data was modified to achieve a better match between the model calibrated results and observed field measured water levels. Data were modified based on the level of confidence of the original data. The transient model calibration was considered complete when the final simulated water levels and flow directions reasonably matched the final measured water levels.

## SUMMARY AND RECOMMENDATIONS

The purpose of the SRV groundwater modeling effort is to provide an analytical tool capable of quantifying the effects of various groundwater management and conservation scenarios on the groundwater supplies within the study area. The SRV model provides a regional understanding of the inter-relationships between the groundwater flow system and groundwater pumpage and recharge.

The SRV model reasonably simulates both steady-state and transient-state groundwater flow conditions within the ESRV and WSRV sub-basins of the Phoenix AMA. The final calibrated transient model simulated a model wide increase in the volume of groundwater in storage of approximately 600,000 acre-feet for the six year period of 1983 to 1988.

The SRV model provides a cumulative source of hydrologic and geologic data for the Phoenix AMA. The model is also to be used as planning tool to study the impacts of various groundwater management and conservation scenarios. Currently, the model is being used to simulate the impacts of potential groundwater recharge projects in the West SRV sub-basin. A sensitivity analysis is to be conducted (Fall '93) on the model output to determine how sensitive the model solution is to variations in model input parameters. Eventually, contaminant transport capabilities may be added to the model.

The SRV modeling study has identified several data deficiencies which partially limit the models' predictive accuracy. Recommendations to improve future data collection and analysis efforts include: 1) development of a more comprehensive aquifer test database, 2) revision and enlargement of the Salt River Valley water level measurement index line, 3) improvement of the current stream gage network in the Salt River Valley, 4) an extended transient calibration period, 5) seasonalize model pumpage and recharge, 6) improved estimates of recharge, 7) incorporate a re-wetting option in the model code to

permit the model to resaturate "dewatered" cells. 8) incorporate a subsidence package in the model code to simulate compaction resulting from groundwater storage changes in compressible beds.

## References


Anderson, T.W., 1968. Electric-Analog Analysis of Groundwater Depletion in Central Arizona. USGS Water Supply Paper 1860. 21 p., 4 plates.

Arizona Department of Water Resources, 1991. Second Management Plan, 1990-2000, Phoenix Active Management Area, 348 p.

Arteaga, F.E., and others, 1968. Groundwater in Paradise Valley. Maricopa County, Arizona, Water--Resources Report Number 35, Arizona State Land Department. 76p.

Corkhill, E.F., and others, 1993. A Regional Groundwater Flow Model of the Salt River Valley - Phase I, Phoenix Active Management Area, Hydrogeologic Framework and Basic Data Report. Modeling Report No. 6 - ADWR. 120 p. 2 appendices.

Corell, S.W., and Corkhill, E.F., 1993. A Regional Groundwater Flow Model of the Salt River Valley - Phase II, Phoenix Active Management Area, Numerical Model, Calibration, Sensitivity, and Recommendations. Modeling Report No. 8 - ADWR. (DRAFT)

Graf, W.L., 1980. Introduction and Growth of Phreatophytes in the Channels of the Salt and Gila Rivers, Central Arizona. U.S. Army Corps of Engineers, Phoenix Urban Studies Office, Contract 09-79-G0059. 190 p.

Lee, W.T., 1905. The Underground Waters of the Salt River Valley, Arizona. USGS Water Supply and Irrigation Paper 136. 196p. 2 plates.

McDonald, M.G., and Harbaugh, A.W., 1988. A Modular Three-Dimensional Finite-Difference Groundwater Flow Model - Techniques of Water-Resources Investigation USGS, Book 6, Chapter A1.

Reynolds, S.J., 1985. Geology of the South Mountains, Central Arizona: Arizona Bureau of Geology and Mineral Technology, Bulletin 195, 61p.

Shafiquallah, M., and others, 1980. K/Ar Geochronology and Geologic History of Southwestern Arizona and Adjacent Areas. Arizona Geological Society Digest, V. 12, pp. 201-260.

Thomsen, B.W., and Baldys, III, 1985. Groundwater Conditions in and near the Gila River Indian Reservation, South-Central Arizona. USGS Water-Resources Investigations Report 85-4073. 2 plates.

# USE OF A NUMERICAL MODEL FOR SOLUTIONS TO SHALLOW GROUND WATER LEVELS IN THE YUMA AREA ARIZONA, CALIFORNIA, AND MEXICO[1]

Bradley M. Hill, R.G.[2]

ABSTRACT: The Yuma area has experienced agricultural development since the late 1890's. Groundwater levels have risen over 70 feet due to the irrigation of crops, unlined canals and flooding along the Colorado and Gila Rivers. These shallow water levels have seriously impacted residential areas and prime agricultural land.

The Arizona Department of Water Resources in conjunction with Yuma County Flood Control District have developed a regional three-dimensional groundwater/surface water flow model of the Yuma area. The purpose of the model is to assist local agencies in evaluating remedial water management alternatives to mitigate their shallow groundwater level problems.

The model domain incorporates over 900 $mi^2$ of Arizona, California and Mexico and simulates groundwater pumpage, all primary canals and drains, deep percolation from agricultural irrigation, evapotranspiration from phreatophytes and both the Colorado and Gila Rivers. The model contains four layers with over 30,000 model cells ranging in size from 40 acres to 640 acres.

Model scenario simulations were conducted to evaluate the effectiveness of proposed water management alternatives on lowering groundwater levels within the northern portion of Yuma Valley. These scenarios include evaluating the impacts from the spring 1993 Gila River flooding, effectiveness of the existing drainage well network, lining a portion of the East Main canal, lining the entire All-American canal, and simulating a decrease in deep percolation recharge from agricultural irrigation on the Yuma Mesa and northern portion of Yuma Valley.

## INTRODUCTION

The Yuma area is located geographically at the downstream end of the Colorado River basin and is comprised of portions of the United States and Mexico (Figure 1). This region has experienced agricultural development since the late 1890's. Ground water levels have risen over 70 feet since the early 1900's due to the recharge of excess irrigation water and leakage from unlined canals, creating shallow water levels which have water logged residential areas and prime agricultural land. The

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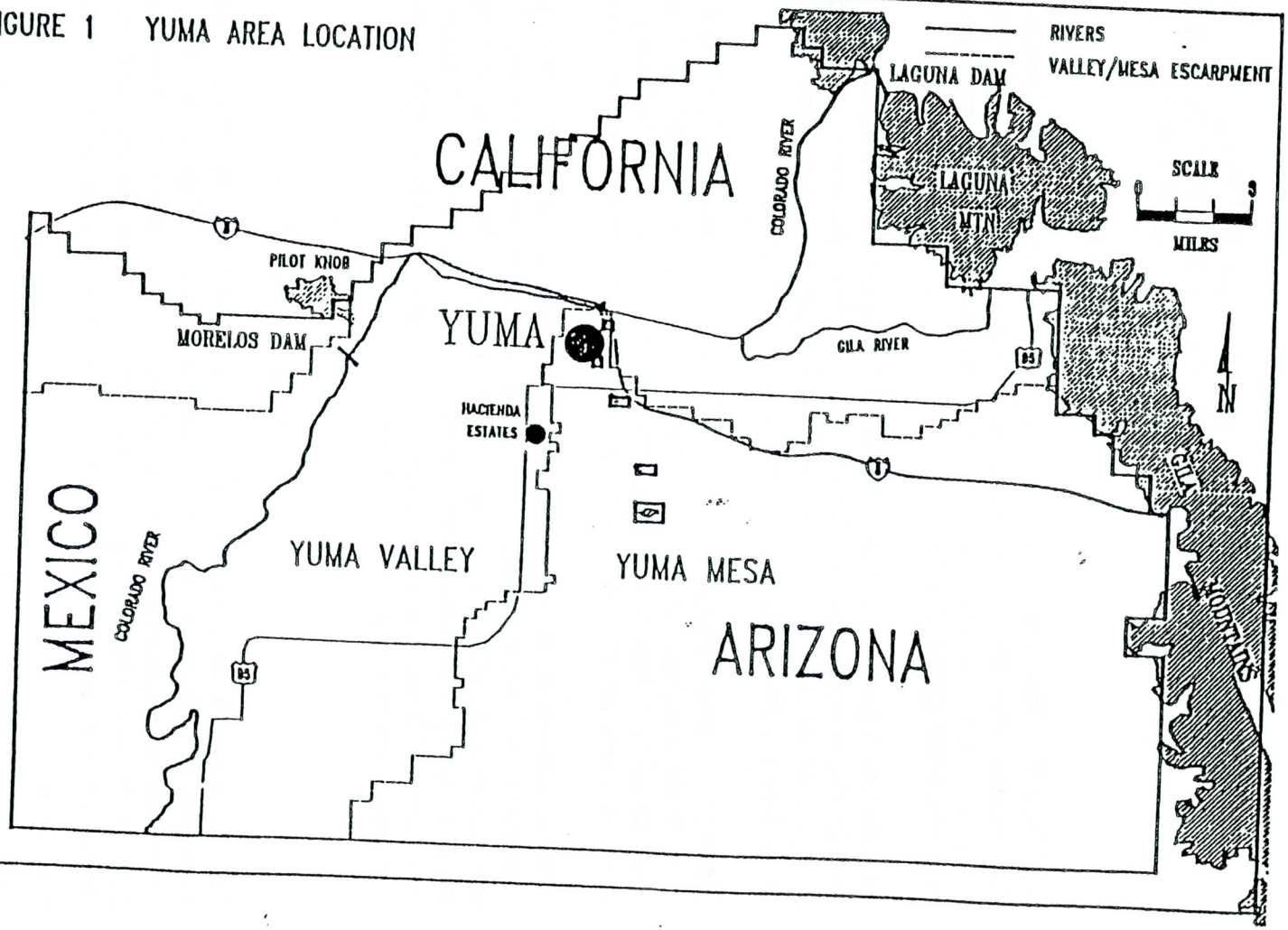
[1] Paper presented at the Sixth Annual Symposium of the Arizona Hydrological Society, Casa Grande, Arizona, September 23-24, 1993

[2] Bradley M. Hill, Hydrologist, Groundwater Modeling Section, Arizona Department of Water Resources

FIGURE 1 YUMA AREA LOCATION



Colorado and Gila Rivers flooded the region between 1983 through 1986 which compounded the existing shallow ground water level problem. Yuma County Flood Control District approached the Arizona Department of Water Resources (ADWR) in 1988 to assist in addressing the problems associated with rising ground water levels.

The Gila River flooded during the spring of 1993 creating severe problems within the agricultural regions near Yuma. Local government officials wanted to use the model to predict what effect, if any, the current flooding would have on the ground water system and if the existing drainage well network would be sufficient to mitigate any potential problems from rising ground water levels.

The purpose of this investigation was to develop a regional 3-dimensional ground water flow model that would be useful for Yuma County in its evaluation of remedial water management alternatives to mitigate their shallow ground water level problems. The objective was to effectively simulate the regional hydrologic regime and test various water management scenarios to determine which would be the most effective in lowering the shallow water levels near the Hacienda Estates subdivision.

## HYDROLOGIC REGIME

A detailed analysis of the hydrogeology and water resources was conducted for the Yuma area (Hill, 1993). Ground water flow in the Yuma area is very complex because of its close interrelationship with the surface water system. In general, ground water flows from the north to south-southwest, except beneath the Yuma Mesa where ground water flows radially away from a prominent ground water mound (Figure 2).

Three lithologic water-bearing zones were identified within the upper several hundred feet of sediments by the U.S. Geological Survey (Olmsted and others, 1973). These layers are extremely transmissive and consist of basin-filling fluvial and deltaic sediments deposited by the Colorado and Gila Rivers. From lowest to uppermost, these are the wedge, lower coarse-gravel and upper, fine-grained zones. Hydraulic characteristics of each of these water-bearing zones were quantified and several multiple-well aquifer pumping tests were conducted on the upper, fine-grained zone as part of this study. Horizontal hydraulic conductivity was estimated to range between 50 and 1000 Ft/Day between the upper, fine-grained and lower, coarse-gravel zones, respectively (Hill, 1993).

The Yuma area has an extremely complex surface water system consisting of the Colorado and Gila Rivers, numerous canals including the large All-American and Gila Gravity Main, and an extensive network of drainage canals (Figure 3). Surface water data were collected for the region including streamflow gaging data and construction characteristics for most of the canals and drains.

FIGURE 2 1989 WATER LEVEL ELEVATIONS IN THE YUMA AREA

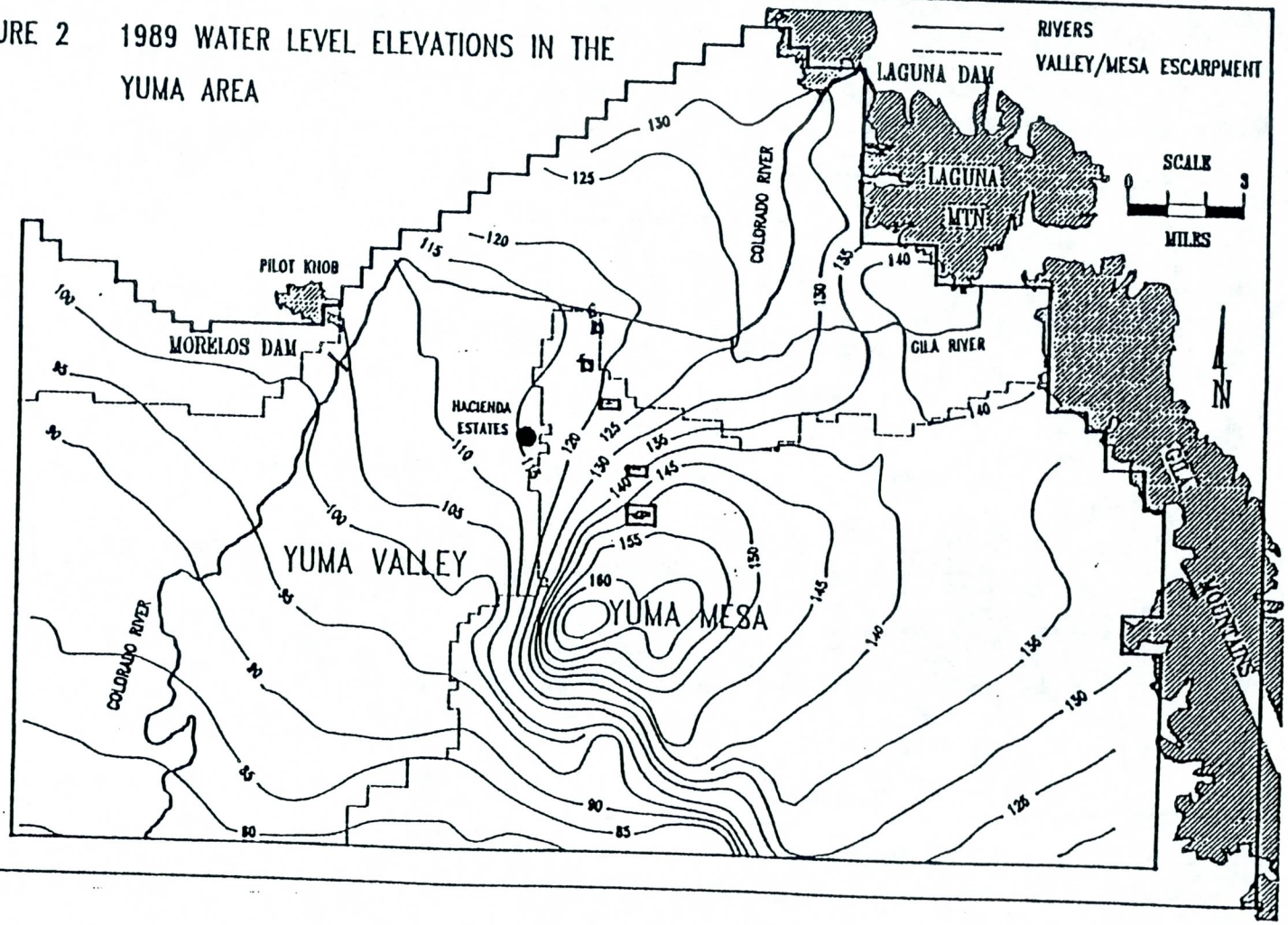
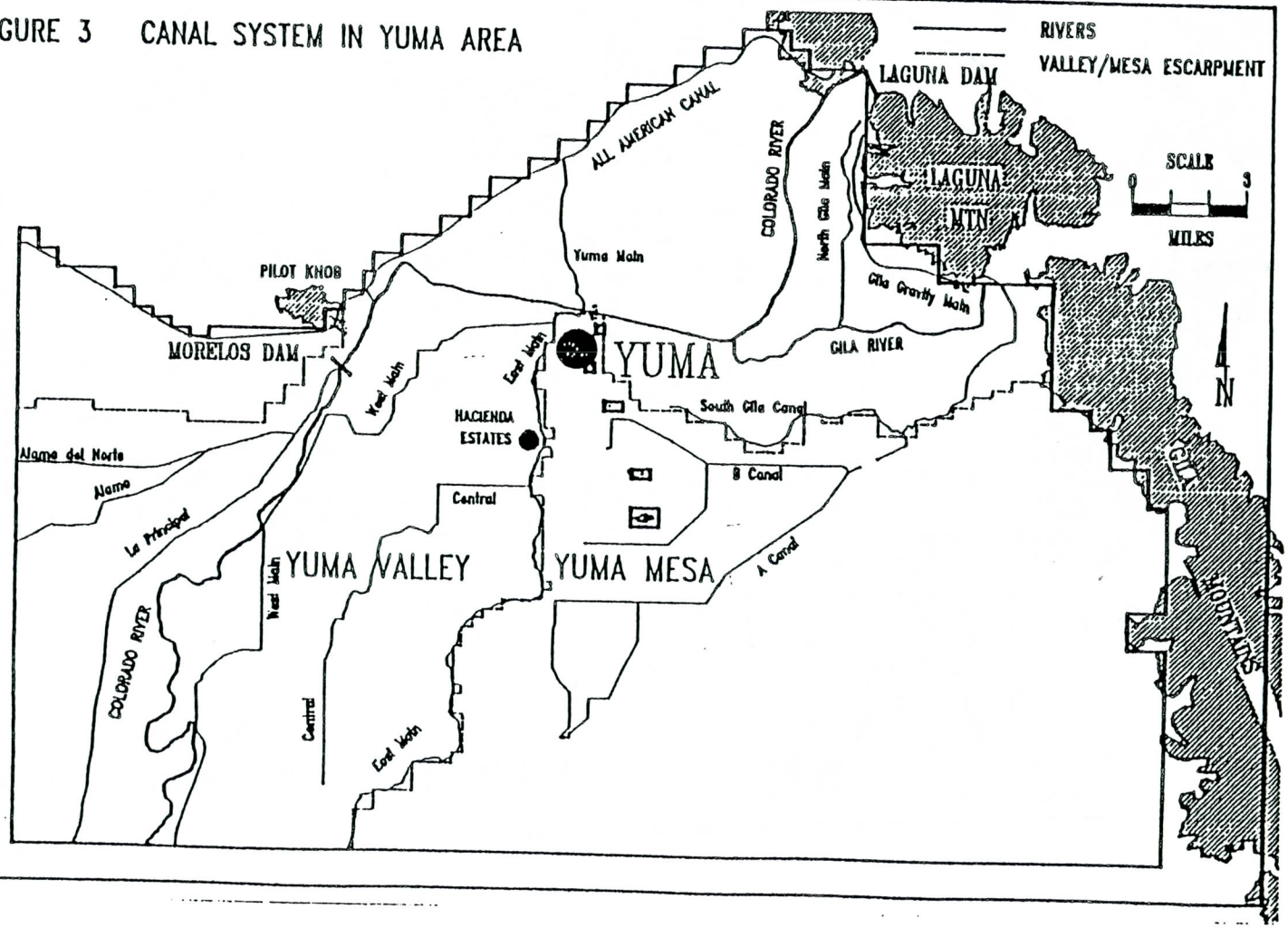


FIGURE 3 CANAL SYSTEM IN YUMA AREA



## NUMERICAL MODEL

A regional model was constructed using the U.S. Geological Survey computer code MODFLOW and simulates ground water flow from April 1978 through March 1989. The active model domain encompasses 900 square miles including portions of Arizona, California, Sonora, and Mexicali Valley, Mexico (Figure 1). The model has approximately 30,000 model cells distributed among four layers, each layer simulating a distinct hydrogeologic unit. Model cells range in size from 40 acres to 640 acres. The model simulates the hydraulic interconnection between the surface water features and the ground water system.

Model Layer One corresponds to the upper, fine-grained zone beneath the Yuma Mesa and the All-American canal. Layer Two corresponds to the thin silt and clay layer that composes the river valley floor and Clay B beneath the Yuma Mesa. Model Layer Three corresponds to the upper, fine-grained zone beneath the clayey-silt layer throughout the Yuma area and Layer Four is a combination of the lower, coarse-gravel zone and the upper portion of the wedge zone.

The model was calibrated for steady-state and transient-state ground water flow conditions. Summer 1978 (i.e., April through September) was assumed to be representative of steady-state conditions. The transient-state model was calibrated in two parts: pre-Colorado River flooding (October 1978 through March 1983) and Colorado River flooding and post-flooding (April 1983 through March 1989).

Results of the transient-state calibration indicate that the model replicates measured water level elevations, ground water flow directions, and water budget components very well. The model simulates ground water levels within an average of 3 feet near the Hacienda Estates subdivision in Layer 2 (ie., silt and clay layer that comprises the valley land surface).

## MODEL SCENARIO SIMULATIONS

Nine model scenario simulations were conducted for several purposes. First, the severe spring 1993 flooding along the lower Gila River prompted local governmental officials to utilize the model to evaluate what the potential impacts this flooding might have on the ground water system. Second, the model was utilized to determine which water management alternative would be most effective in lowering the shallow water levels within the northern portion of Yuma Valley near the Hacienda Estates subdivision.

## Spring 1993 Gila River Flooding

The first scenario involved simulating the spring 1993 Gila River flooding to predict where the maximum ground water level rises might be in the Yuma area due to the flooding. The second scenario simulated the identical flooding while pumping the existing drainage well network to determine if the well configuration would be effective in minimizing the impacts from ground water level rises due to the recent flooding.

The results of these two simulations indicate that the spring 1993 Gila River flooding should have a minimal impact on the ground water system in the Yuma area. Water levels were predicted to rise several feet adjacent to the Gila and Colorado rivers after 6 months of flooding. However, the maximum water level rises were predicted to be within one to two miles away from the rivers and should not adversely impact agricultural or residential areas. The simulation predicted that the configuration of the existing drainage well network significantly reduced any impacts from water level rises due to the flooding, especially in northern portion of Yuma Valley where the majority of the wells are located.

## Management Alternatives to Lowering Water Levels

The next five scenario simulations addressed potential water management alternatives to lowering the shallow ground water levels in the northern portion of Yuma Valley near the Hacienda Estates subdivision. These simulations included: lining four miles of the East Main canal adjacent to the Hacienda Estates subdivision; lining of the East Main canal and pumping the new drainage wells DW 14 and DW 15 located near the subdivision; reducing deep percolation recharge from excess agricultural irrigation by 25 percent within the Yuma Valley and on Yuma Mesa; and lining the entire All-American canal within the Yuma area.

The model results of lining four miles of the East Main canal adjacent to the Hacienda Estates subdivision predicted lower ground water levels of a maximum of one foot after four years. Lining the canal and pumping the new drainage wells DW 14 and DW 15 had the greatest impact on lowering ground water levels of all the scenario simulations. This scenario predicted that water levels would decline a maximum of six feet after four years near the subdivision.

Reducing deep percolation recharge from excess agricultural irrigation by 25 percent also had a significant impact on lowering water levels near the Hacienda Estates subdivision. The results indicate that reducing recharge by 25 percent on Yuma Mesa would lower water levels adjacent to the subdivision over two feet, while lowering water levels on the ground water mound beneath Yuma Mesa over nine feet after four years. Reducing recharge by 25 percent in Yuma Valley was predicted to lower

water levels by approximately one foot after four years near the subdivision. These scenarios illustrate the potential influence excess agricultural irrigation has on ground water levels within the Yuma area. However, the model could not accurately simulate the maximum local effects from deep percolation recharge since the areal location of where the crops were grown and water was applied could not be identified precisely.

Lining the entire All-American canal within the Yuma area had a significant impact on lowering water levels on the north side of the Colorado River near the Quechan Indian Reservation in California. Ground water levels were predicted to decline up to nine feet adjacent to the canal and a range between one and four feet within the reservation area after four years. This simulation predicted that water levels also would decline near the Hacienda Estates subdivision a maximum of over one foot after four years. The impacts from lining the canal on ground water levels south of the Colorado River near the subdivision can be attributed to the fact that the river only partially penetrates the aquifer in the Yuma area.

The final scenario simulation was conducted to evaluate the hydrologic importance of the clayey-zone beneath the Yuma Mesa. This clayey-zone, informally identified as Clay B, is though to play an important role hydrologically by inhibiting the vertical movement of ground water flow beneath the Yuma Mesa. The results indicate that in conjunction with recharge from excess agricultural irrigation, Clay B has a great impact on creating the ground water mound beneath the Yuma Mesa. Ground water levels declined over 16 feet after four years beneath Yuma Mesa.

## CONCLUSIONS

Shallow ground water levels that exist in the Yuma area are a cumulative result of several factors which include seepage from unlined canals, and deep percolation recharge from excess agricultural irrigation. Each of these factors has a relative impact on creating shallow ground water levels near the Hacienda Estates subdivision.

Utilization of a numerical model as a tool in evaluating the impacts of various water management alternatives was very useful. The model permitted the ability to predict the cumulative effect of each water management alternative on the ground water and surface water systems and identifying the greatest effects on lowering ground water levels.

Model scenario simulations indicated that the spring 1993 Gila River flooding should have a minimal impact on rising ground water levels within the Yuma area. The existing drainage well network configuration was predicted to be effective in minimizing any potential adverse impacts on the ground water system due to the Gila River flooding.

The model predicted that the water management alternative of pumping drainage wells DW14 and DW15 and lining four miles of the East Main canal would have the greatest impact on lowering groundwater levels in the vicinity of the Hacienda Estates subdivision. However, the simulation predicted pumping the drainage wells would greatly overshadow any effects from lining the canal. The model also predicted that reducing deep percolation from excess agricultural irrigation within the Yuma Valley and on Yuma Mesa also had a significant impact on lowering ground water levels in northern Yuma Valley near the subdivision.


## ACKNOWLEDGEMENTS

I would like to recognize Frank G. Putman for his general oversight and Dale A. Mason for his direct technical assistance both with the ADWR Hydrology Division.

Yuma County must also be recognized for their partial funding for the project and initial impetus for getting this project off the ground. Roger Schoenherr from Yuma County Flood Control played an instrumental role in the coordination and management of this project.

The U.S. Bureau of Reclamation - Yuma Projects Office must be recognized for their technical assistance and data development. Special thanks is extended to Earl Burnett and Fred Croxen for their contribution in providing and collecting data and their assistance in understanding the hydrologic complexities of the Yuma area.


## REFERENCES


Hill, B.M., 1993, Hydrogeology, Numerical Model and Scenario Simulations of the Yuma Area Groundwater Flow Model, Arizona, California and Mexico: Arizona Department of Water Resources - Hydrology Division, Modeling Report No. 7, 113p.

Olmsted, F.H., Loeltz, O.J. and B. Irelan, 1973 Geohydrology of the Yuma area, Arizona and California: U.S. Geological Survey Professional Paper 486-H, 227p., 17 plates

# RESULTS FROM A HIGHLY SIMPLIFIED GROUNDWATER/SURFACE WATER MODEL[1]

John Linkswiler[2]

**ABSTRACT:** Using a set of equations and simplifying assumptions, a model was developed to demonstrate the interrelationship of groundwater and surface water for both quality and quantity. "Symphony" software was used to develop the model. Runoff data for 98 years of record on the Salt and Verde Rivers, and, a fixed consumptive use value were used so that effects of various efficiency levels could be evaluated for a long term period. For various levels of efficiency, model output is presented in graphical form for reservoir storage, release, pumping, groundwater level and quality.

Model results show increased reservoir levels are associated with higher efficiency. Associated with higher reservoir levels are increased surface water deliveries during drought periods. Groundwater pumping is also reduced at higher efficiencies, and short term costs are less. However, long term groundwater levels and groundwater quality show that adverse effects can be associated with high efficiency levels. Model output suggests that great care be exercised in some conservation programs or unexpected damage may be done to the resource.

## INTRODUCTION

The wide use of P.C.s along with spreadsheet software programs such as Lotus 123 and Quattro Pro creates the opportunity to develop simple models which can be used to demonstrate various hydrologic relationships and evaluate long term effects of various hydraulically interactive management options. The development of models which are extremely easy to use and understand may have value as an educational tool. The model which has been developed is easy to operate, as changing just one value, the DEMAND, results in 98 years of re-computation of all reservoir parameters and groundwater parameters. Simple edit options allow recharge operations to be considered along with supplemental supplies.

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[1]Paper presented at Sixth Annual Symposium of the Arizona Hydrological Society, Casa Grande, Arizona, September 23-24, 1993.

[2]John Linkswiler is a Professional Engineer registered in California and Arizona. He has 30 years experience in water resources.

## DESCRIPTION OF MODEL

The schematic diagram in Figure 1 shows the major features which the model is meant to simulate. The drawing of these features suggested the name for the model: **GEOMETRYLAND**. The important features are as follows:

1. A conservation reservoir with the shape of an inverted pyramid has a capacity of 1.7 million acre feet (af). A side of the base of the pyramid has a value of 130 times the height. (Reservoir parameters were selected on the basis of the Salt River Project's (SRP) Bartlett, Horseshoe, and Roosevelt reservoirs.)

2. A second reservoir with a rectangular shape has an area of 4,800 acres, and is meant to represent a lake with large hydroelectric and recreation values. (This area was selected on the basis of the surface area of the lakes behind Horse Mesa, Mormon Flat, and Stewart Mountain Dams.)

3. A zero datum is set between the two reservoirs so that at zero the conservation reservoir is empty and a second reservoir is full. Negative reservoir storage values indicate the amount of drawdown in the second reservoir.

4. A conjunctive (surface water and groundwater) use area covers 315,000 acres which is the estimated effective aquifer area under the exterior boundaries defined by the SRP's canals.

5. A groundwater use area has 67,000 acres which is the estimated effective aquifer area under the Roosevelt Water Conservation District and the Roosevelt Irrigation District.

6. An aquifer which underlies the two areas has a thickness of 60 feet over the bottom of the surface drain. The bottom of the drain is defined as the zero datum for groundwater calculations. The aquifer has a depth of 1,000 feet below the zero datum and a storage coefficient of 0.12.

7. A surface drain conveys spill water through the area, and drains the aquifer when the groundwater level exceeds the bottom of the drain. This would, in effect, simulate a perennial stream which is sustained by local groundwater.

8. An underground drain located 200 feet below the zero datum allows groundwater to discharge downstream. This simulates a limited aquifer connection to the downslope area such as might result from a hard rock unit 200 feet below a river channel.

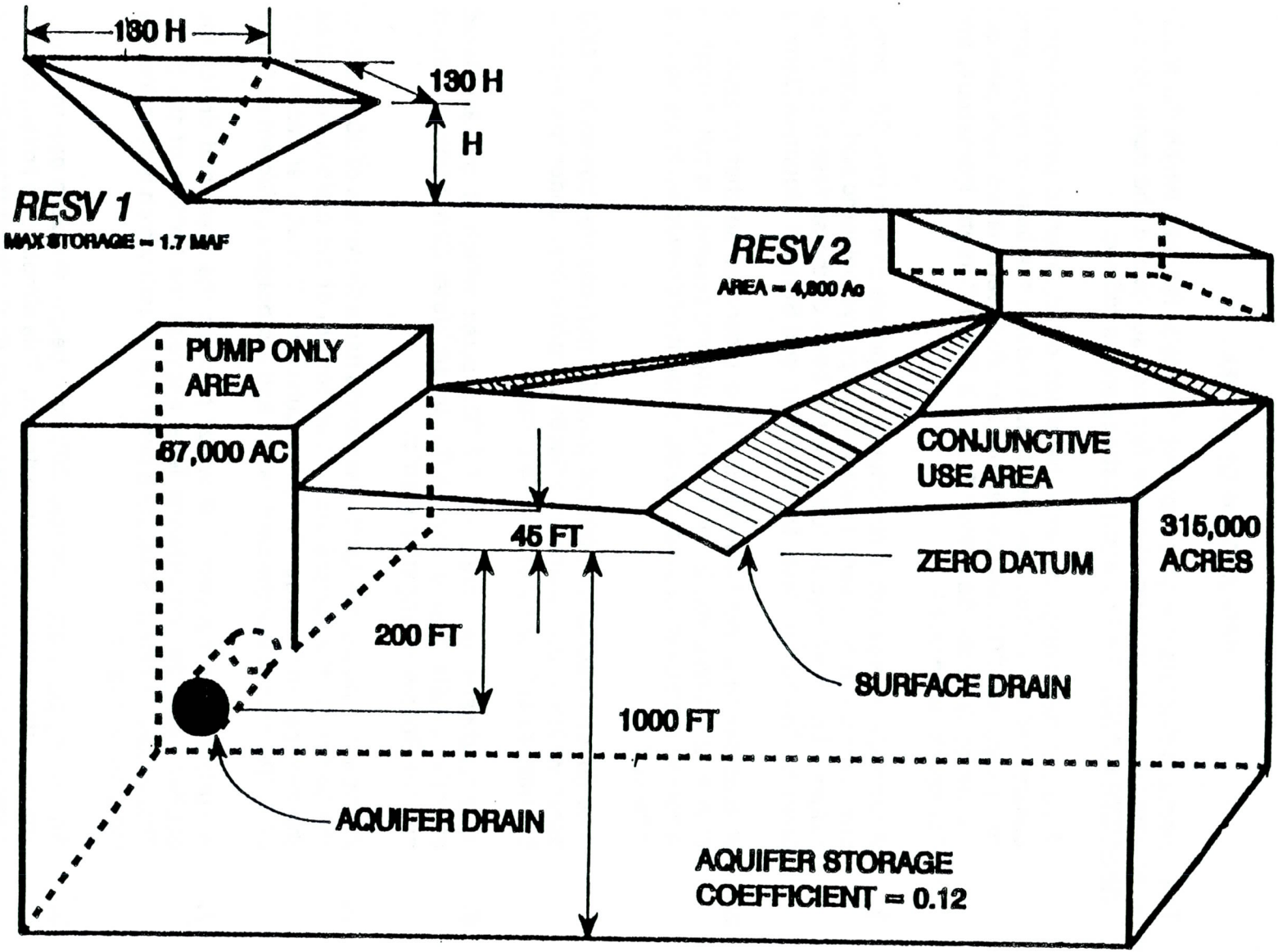


Figure 1. Schematic model representation for simulating conjunctive water resource

## BASIC DATA AND CALIBRATION

The U.S. Geological Survey (USGS) records for the annual flows of the Salt and Verde Rivers were used as the inflow values in the model, and represent the only data input to the model. Runoff data is available since 1888; however, gate locations have changed as reservoirs have been built. The gaged inflow values upstream from the dams on the Salt River were added to the gaged inflow values upstream from the Verde River, and the sum of the two on an annual basis are the only basic data input to the model. USGS water quality records (1965-1986) for the gages just downstream from the Salt and Verde River dams were used to develop the equation for the dissolved salts in terms of tons per acre foot coming into the reservoir.

USGS and Salt River Project (SRP) records for diversions at the Verde Treatment Plant, Granite Reef Diversion Dam, and Jointhead Dam were used to develop the equation for "reservoir release" in the model. Computed reservoir releases are a direct function of the computed reservoir storage. Buckeye Irrigation Company records for diversions from the Gila River along with the SRP records for Jointhead Dam and the USGS records for groundwater level changes were used to develop the equations for 1) natural recharge, 2) spill recharge, 3) groundwater discharge to the river (drain on schematic), 4) "water logged" groundwater discharge to the river, and the groundwater discharge to a downstream are (aquifer drain on schematic).

Baseline demand and depletion values were selected on the basis of analysis conducted for the Arizona Water Commission's "State Water Plan: Phase I." For the general area bounded by the SRP canals, the Agua Fria River, and the Gila River Indian Reservation Boundary, the "normalized" demand value was 1.45 million acre feet in 1970 and the associated depletion was about 768 thousand acre feet for an overall efficiency of about 53 percent. These values were used to calibrate the model and represent the baseline case in the graphs which have been prepared.

## MODEL OPERATIONS

Because groundwater discharge to the drain and aquifer drain and from the conjunctive use area to the pump area is calculated on the basis of the preceding year's groundwater levels, initial values must be input for the groundwater levels in the two designated aquifers. Initial salinity values must input for the water in the reservoirs and in the two aquifers. Additionally, a starting storage value must be input.

A model simulation is started by inputting a value for the demand (the depletion is a constant). A function of the annual inflow is added to the previous year's end-of-year reservoir storage to determine the maximum storage for the year. The maximum storage is used to set release for year. Other reservoir parameters are based on the equation:

$$\text{Inflow} = \text{release} + \text{evap} + \text{spill} + \text{storage change}$$

Annual pumping in the conjunctive use area is calculated as the set demand minus the previously calculated reservoir release. Inflow to the conjunctive use aquifer is calculated as the sum of three components: 1) incidental recharge which is a constant value for any particular demand level, 2) spill recharge which is a function of the previously calculated spill and the groundwater level, and 3) natural recharge which is calculated as a function of the reservoir inflow. Discharge from the conjunctive use aquifer is calculated as the sum of three components: 1) the amount pumped, 2) the amount discharged to the drain (surface) which is estimated on the basis of the previous year's groundwater level, and 3) the amount which flow to the adjoining "pump only" aquifer, and the amount is a function of the preceding year's difference in elevation between the two aquifers. The storage change in the aquifer is based on the following equation:

$$\text{Recharge} = \text{pumping} + \text{drain} + \text{grn to grn} + \text{storage change}$$

Annual pumping in the "pump only" area is established by the selected demand level. Inflow to the aquifer is from two components: 1) incidental recharge which is a constant for each selected demand level, and 2) the amount of the flow from the conjunctive use area aquifer. The amount of water leaving the aquifer is the amount pumped plus the discharge to the aquifer drain which is calculated on the basis of the previous year's groundwater level. Storage change is estimated by the following equation:

$$\text{recharge} + (\text{grn to grn}) = \text{pumping} + \text{aquifer drain} + \text{storage change}$$

Water quality in terms of tons of dissolved salt per acre foot is brought into the model by the following equation:

$$\text{tons/af} = 0.45(2{,}800{,}800\ \text{af/inflow})^{0.52} - 0.105$$

The annual tons of salt coming into the reservoir is the annual inflow (which is the only data input) multiplied by the amount of salt per acre foot. The tons of salt coming into the reservoir area is added to the tons of salt in the stored water from the previous year. The effect concentrating the salinity by evaporation is accomplished by adding the volume of inflow to the storage volume and subtracting the amount of evaporation. The reduced volume is divided into the total tons of salt to establish the salinity level (in terms of tons per acre foot) of the reservoir release. A similar process is repeated for each of the aquifer areas. The water goes away - the salt stays, causing increasing salinity levels from the reservoir to the conjunctive use area to the "pump only" area and on out of the modelled area.

## MODEL OUTPUT

Because of the very large array of numbers included, most of the output is best displayed in graphical form or averages for the entire period. The following graphs and tables present some of the major outputs (Because of limited space, several graphs have been deleted from this paper. A complete set of the graphs and their narratives are available from the author).

Figure 2 shows the accumulated difference diversion minus model release. The equation for reservoir release was developed for the period 1940-1975. This graph demonstrates the accuracy of the equation. For each year the value for computed reservoir release is subtracted from the historic release, and the difference is added to the sum of the differences for the preceding years. Each time the accumulated difference line crosses the zero line, the computed release has exactly balanced with the historic diversions. As may be noted, the line declines rapidly after 1980. Apparently, the demand for surface water has been reduced and the equations developed for the 53 percent efficiency baseline case are no longer valid.

Figure 3 shows the computed groundwater levels for the 53 percent baseline case and historic groundwater levels. As may be noted, the computed values track fairly well from 1920 to 1980 when a divergence starts. The reduction in surface diversions is believed to be a major factor in groundwater levels not coming up faster.

Figure 4 is a chart generated from a model which includes effluent production at the City of Phoenix's 23rd and 92nd Avenue Wastewater Treatment Plants. The 53 percent baseline case computes spill for only one year (1941) from 1921 to 1972 (inclusive). The computed Buckeye diversions are estimated as a function of groundwater level, reservoir spill, and effluent production. As spills are infrequent, Buckeye diversions appear to be highly dependent on groundwater discharging to the surface system, and during recent years, effluent has become a major factor in Buckeye diversions.

Table 1 displays the critical values which result in adverse impacts to the groundwater levels and groundwater quality. High efficiency water use reduces the demand for surface water. The computed difference in release for the 53 percent efficiency case and the 85 percent efficiency case is 258,000 acre feet per year. The reduced release causes the reservoir levels to be higher which causes increased evaporation (values indicated in table) and increased spill. The difference in calculated spill for the 53 percent case and the 85 percent case is 228,000 acre feet; however, all of this water is not lost. The estimated recharge from spill is 33,300 acre feet for the 53 percent case and 99,500 acre feet for the 85 percent case. The net loss of recharge to the aquifer for the 53 percent and 85 percent cases is 192,000 acre feet per year. This value is based on long term averages and has no validity for any one year.

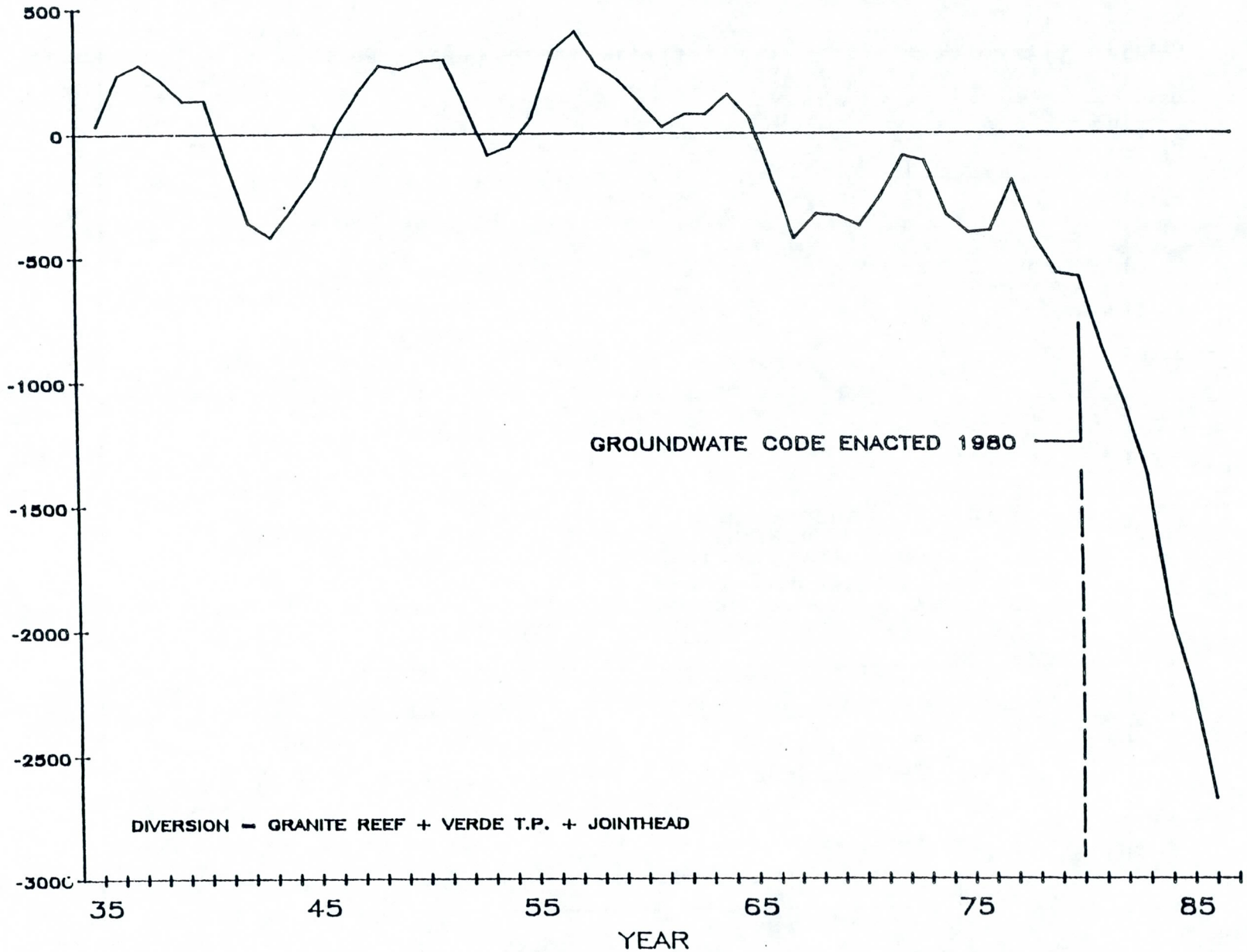


Figure 2. Accumulated difference diversion minus model release

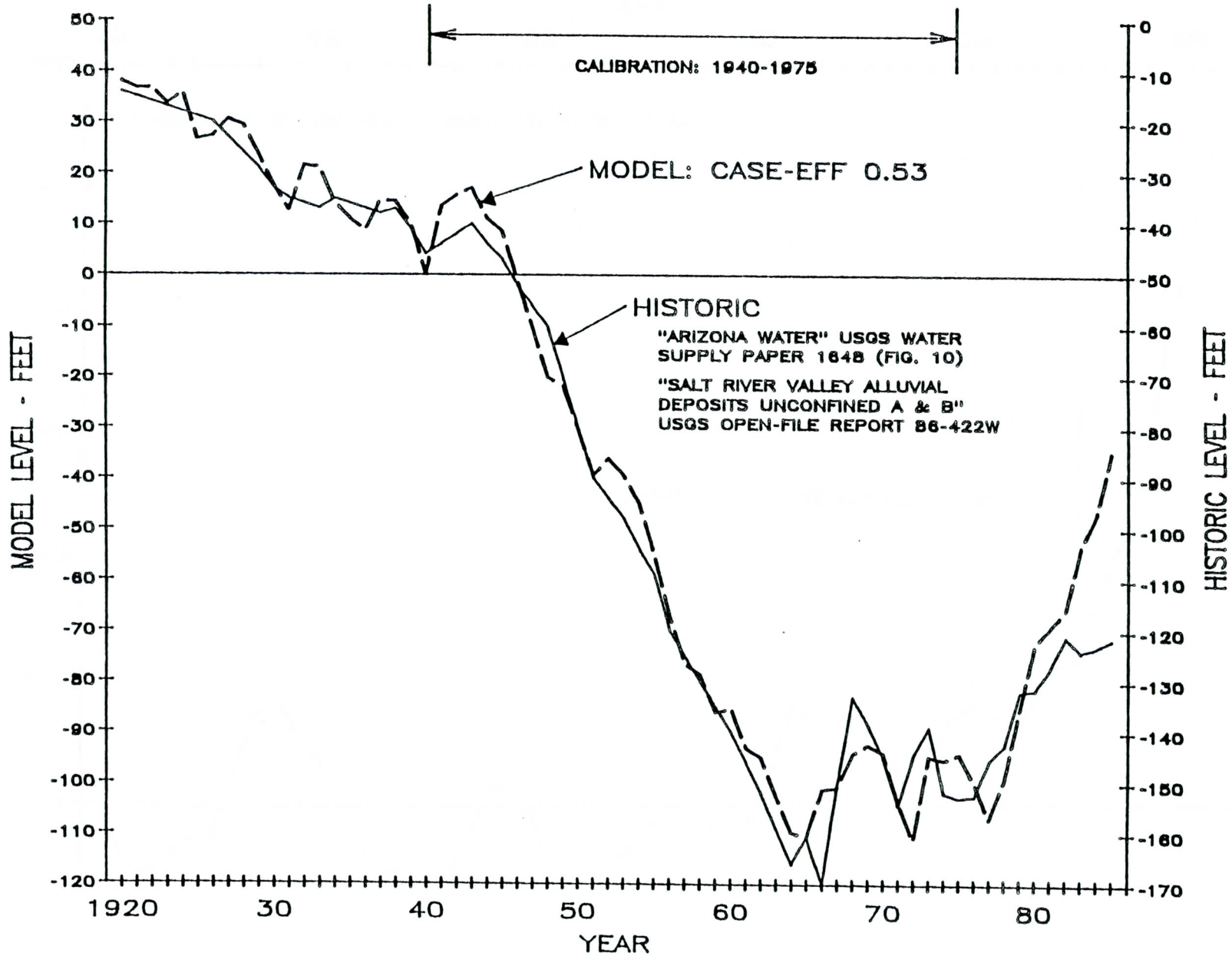


Figure 3. Groundwater levels

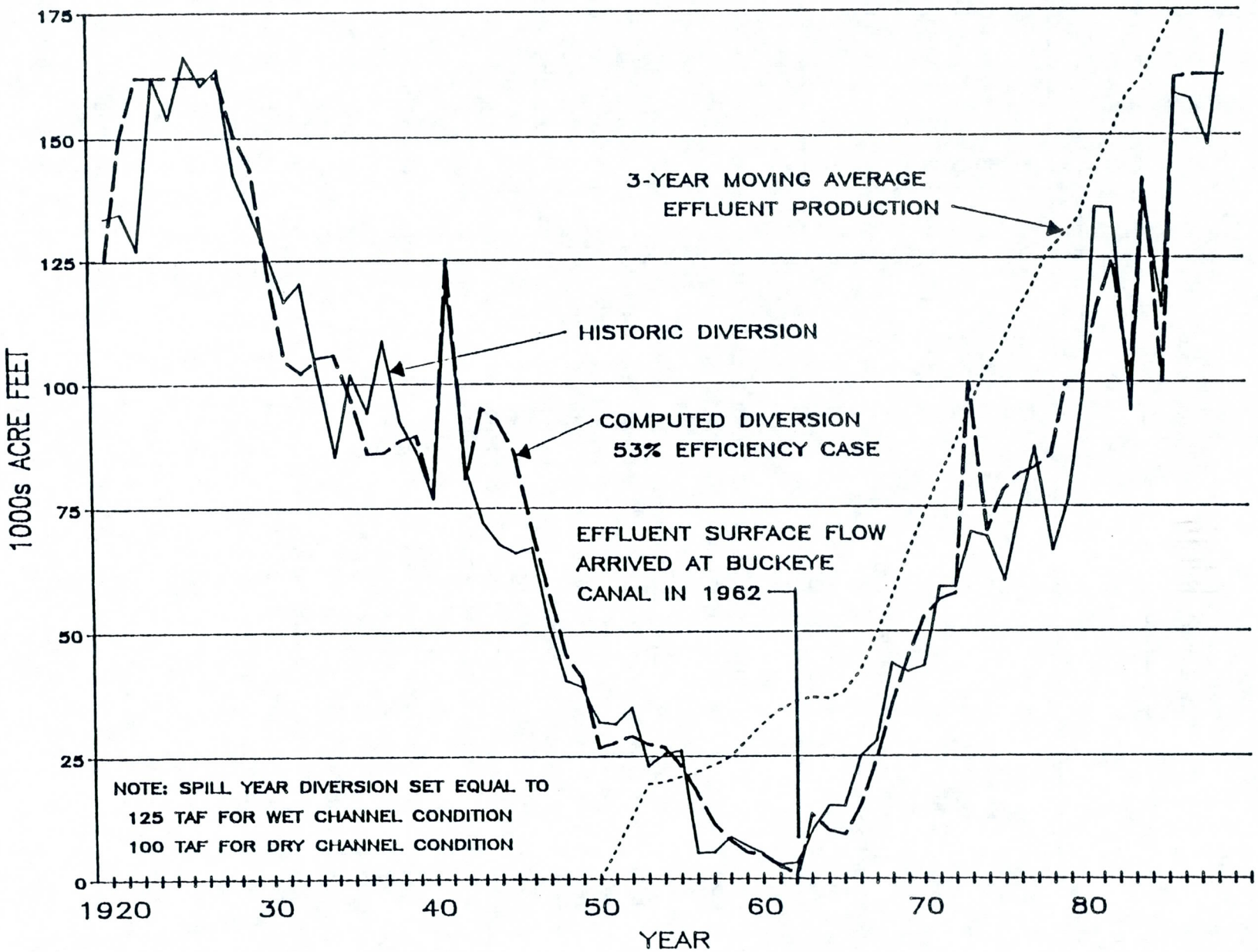


Figure 4. Buckeye diversions

Table 1. 98-year averages for selected efficiency levels (in Thousands of acre feet)

| | Efficiency | | |
|---|---|---|---|
| | 53% | 70% | 85% |
| Reservoir: | | | |
| Release | 1000.9 | 861.9 | 743.0 |
| Evaporation | 92.6 | 108.2 | 117.8 |
| Spill | 167.6 | 287.2 | 395.7 |
| Pumping (Conjunctive Use Area) | 449.1 | 238.1 | 137.1 |
| Spill Recharge | 33.3 | 74.1 | 99.5 |

The loss of water to recharge is the critical factor in the charts which show computed groundwater levels and groundwater quality.

Figure 5 shows the groundwater levels for the entire period 1889 to 1986. The initial groundwater level for each efficiency level was set at a value of minus 29.1 feet. The adverse impact of high efficiency is clearly shown on this chart. The basic data set of 98 years of inflow was run two times with the groundwater level at the end of the first period input as the initial level for the next 98 years. The shape of the 70 percent efficiency case suggests that a long term balance might be achieved at a level considerably lower than the 53 percent efficiency case. The shape of the 85 percent efficiency case clearly shows that the aquifer must eventually be drained.

Figure 6 shows the quality of water in the "pump only" area. Groundwater with its salt load flows into this area where the water is reused and an additional concentration of salts results as the water is reused. As with the conjunctive use area, a long term balance can be achieved at the 0.53 efficiency level; however, when the groundwater level drops below the 200-foot level in the high efficiency case, the groundwater outflow with its salt load stops. The salt accumulates in the "cone of depression" and the quality continuously degrades to unusable levels.

## CONCLUSIONS

1. Long term overdraft can be created where none should exist.

2. Analysis that includes water quality parameters adds a new dimension to the expression, "Use it or lose it."

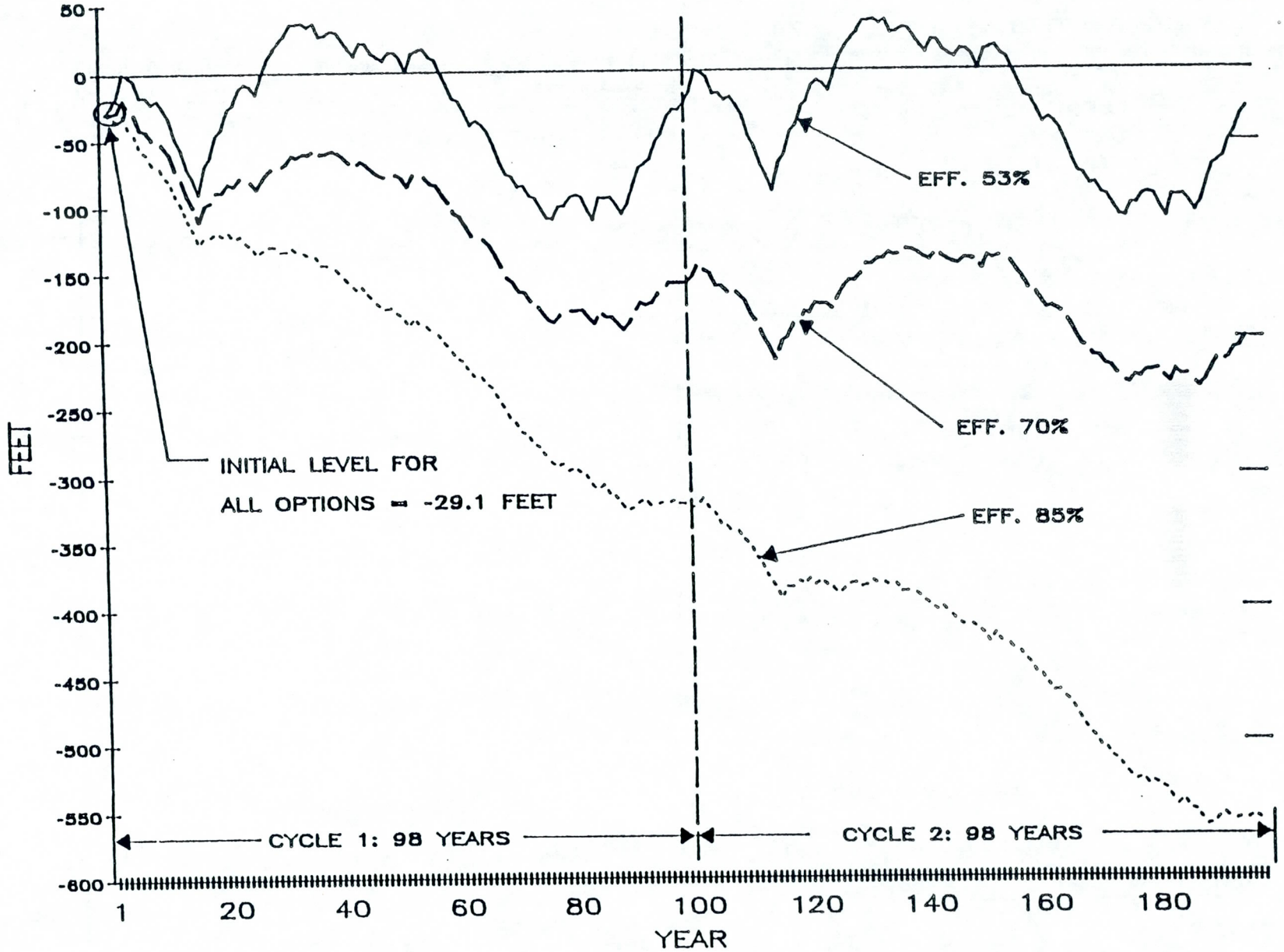


Figure 5. Groundwater level

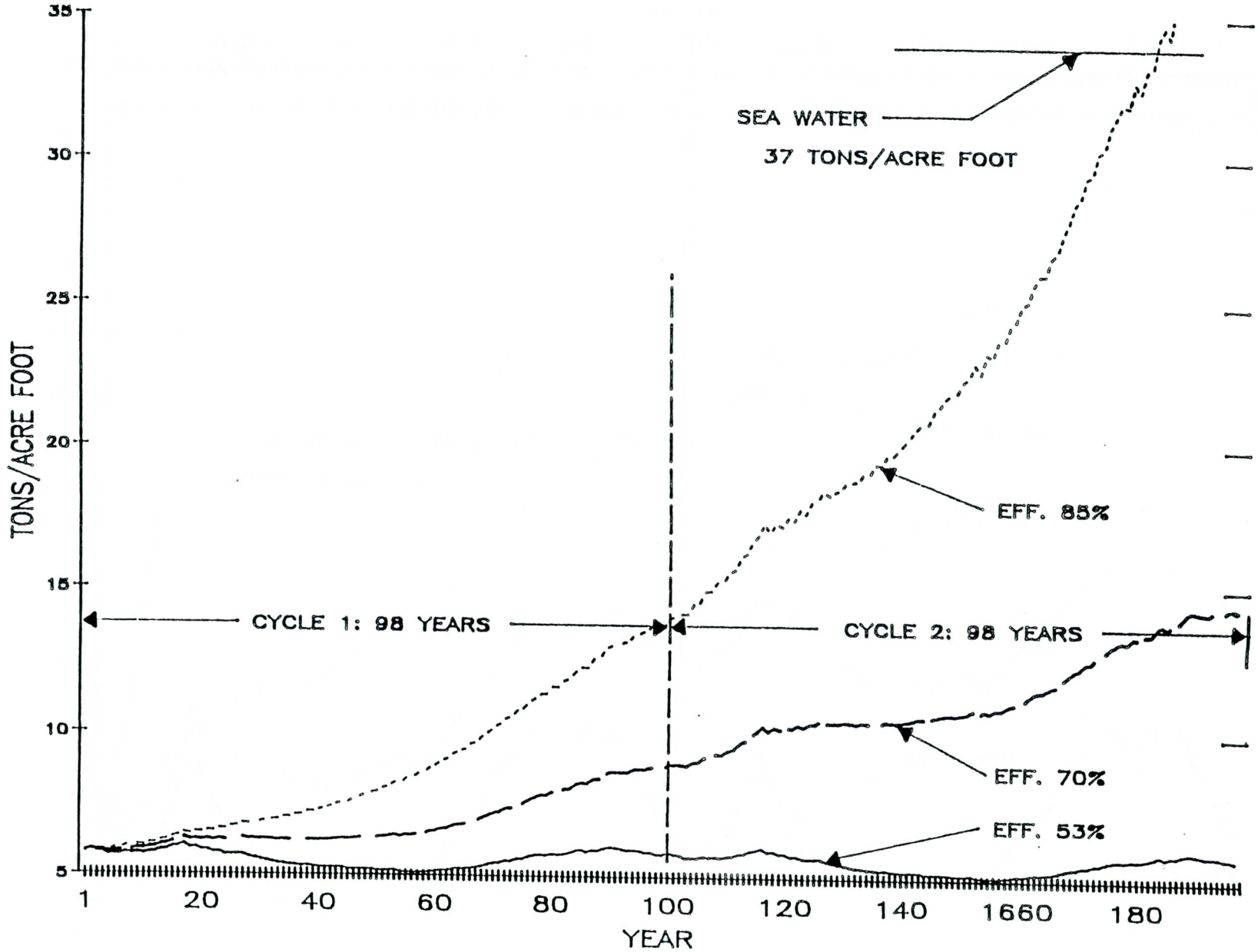


Figure 6. Groundwater quality - pump area

3. Conservation should never mean less use but should mean wise use. Any conservation program based on reduced gallons per capita per day or reduced acre feet per acre should be subjected to careful analysis. To SAVE WATER, one must REDUCE DEPLETIONS.

4. One group of water users may save money to the detriment of another group of users.

5. Groundwater pumpers have a large interest in the operational inefficiencies of the surface water users.

# Part VI

# CRITICAL LEGAL AND REGULATORY ISSUES: CONSTRAINTS AND OPPORTUNITIES

# LEGAL CONSTRAINTS ON THE ADOPTION OF A SOUND GROUNDWATER REMEDIATION POLICY[1]

Roger K. Ferland, Esq.[2]

ABSTRACT: This paper will examine the legal constraints under state and federal law that have been cited as preventing the adoption of what the author believes are sound groundwater remediation policies. It is the author's conclusion that in most instances it is not the law itself but government interpretation and implementation of the law that has driven decision-making on remedial actions. These interpretations and policy judgments have usually been driven, not by the actual language of the applicable laws or informed technical judgment, but the perception of public officials as to the most politically acceptable "solution" to a groundwater contamination problem.

The author will summarize the legal standards governing the selection of groundwater remedial actions under federal (e.g., CERCLA, Section 121; the National Contingency Plan, etc.) and state (e.g., A.R.S. §§ 49-282 D. and C.) law. He concludes that these legal standards require the consideration of cost effectiveness and technical practicability in determining groundwater cleanup levels, technologies and goals and, in the case of state law, assign a weight to cost effectiveness in remedy selection that is equal to the weight accorded protection of public health and the environment.

The reason that groundwater remediation determinations have frequently been unreasonable and impracticable is not necessarily because the law has been faulty but because government implementation policies have been misguided. Such "guidance documents" as EPA's *Guidance on Remedial Actions for Contaminated Ground Water Superfund Sites* have tended to "interpret" such concepts as technical impracticability out of existence. EPA and its state counterpart, the Arizona Department of Environmental Quality, have adopted policies based upon what they believe is responsive to the public's desires. However, the author notes that groundwater remediation policies in Europe that rely upon technical and economic feasibility as a primary criterion for remedial policy have been more effective at achieving environmental cleanup precisely because they are seen as a means of shaping public perception rather than being shaped by a subjective view of "what the public demands."

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[1] Paper presented at the Sixth Annual Symposium of the Arizona Hydrological Society, Casa Grande, Arizona, September 23-24, 1993.

[2] Roger K. Ferland is an attorney and Head of the Environmental Practice Section, Streich Lang, P.A., Phoenix, AZ.

The following is an excerpt from the Record of Decision ("ROD") for the Hassayampa Landfill CERCLA Site:

> The groundwater component of the remedy includes extraction of contaminated groundwater, treatment of the water using air stripping, reinjection of the nntreated water, and continued groundwater monitoring to measure the effectiveness of the remedy.
>
> * * *
>
> Continued groundwater monitoring will be performed to ensure the effectiveness of the remedy. The number of monitoring wells and frequency of sampling will have to be sufficient to measure the effectiveness of the remedy.
>
> Federal MCLs have ben selected as groundwater cleanup standards for the Site.
>
> * * *
>
> For those chemicals for which MCLs do not exist, ADEQ HBGLs (Health-Board Guidance Levels) have been selected as cleanup standards.

If the above-quoted language sounds familiar, it should. Of the 323 remedial actions involving contaminated groundwater for which a ROD was issued from October 1, 1987 to September 30, 1991, 270 of the RODs stated the goal for groundwater cleanup was to restore groundwater to drinking water quality through pump and treat technology.[3] In contrast, two of the RODs adopted institutional controls and only one ROD described containment of its goal.[4]

The cost of employing pump and treat technology is staggering. According to a 1990 University of Tennessee study the total cost of cleaning up the various contaminated sites then listed as requiring remediation under CERCLA, the RCRA Corrective Action Program and analogous programs administered by the Department of Defense, Department of Energy and state and local government ranged from $478 to $1,046 billion. A large percentage of that cleanup cost is attributable to the government's reliance on pump and treat cleanup technology rather than containment or isolation of

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[3] EPA, ROD Annual Report FY 1991: Volume 1 at 6, 10 (OSWER No. 9355.6-05-1, 1992).

[4] Id.

groundwater contamination.[5] One reason that pump and treat technology is so incredibly costly is that it has no end point. The Hassayampa ROD is typical in that it specifies no termination date for treatment. Indeed, the Oak Ridge National Laboratory found that most RODs requiring the use of pump and treat technology also require that such technology continue to be employed until there is sufficient assurance that drinking water standards have been reached in the aquifer even when there is no evidence that attaining drinking water standards is possible.[6]

While there are instances in which pump and treat technology is entirely appropriate, there are strong arguments against its widespread use as the technology of choice for groundwater remediation. There are three general criticisms of pump and treat technology:

First, it is not cost effective. The abandonment of pump and treat technology for remediation strategies based upon institutional controls or the containment and isolation of contamination makes virtually no difference as far as ultimate impacts and risk posed to human health and the environment and could save as much as $268 billion in remediation costs.[7]

Second, pump and treat technology is simply incapable of achieving groundwater cleanup to the level of drinking water standards in most hydrogeologic regimes in which it is used. EPA and other experts have cited the following reasons for the failure to pump and treat technology:

- Binding to Soil: Particularly where contaminants have been present for a long time, they tend to adhere to particles of soil and to resist being drawn up by the groundwater flow created by the pumping process. Because the contaminant cannot be removed from the groundwater any faster than it is released from the soil, the attainment of cleanup levels is rate limited by the process of diffusion. Under these circumstances the cleanup process can take thousands of years.

- Channelization: The pumping process causes the groundwater to flow through those soils that have the highest permeability (i.e., those which impede the flow the least) and contaminants in soil with lower permeability are not picked up by the groundwater extraction.

- Non-Aqueous Phase Liquids: Certain contaminants, called non-aqueous phase liquids (NAPLs), do not mx with water. If they are denser than water (DNAPLs), they will

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[5] Russell, Colglazies and English, Hazardous Waste Remediation: The Task Ahead, Hazardous Waste Remediation Project, Waste Management Research and Education Institute, Univ. of Tenn. at p. 8 (Dec. 1991).

[6] Travis and Doty, Can Contaminated Aquifers at Superfund Sites be Remediated? 24 Env't. Sci. & Tech. 1465 (1990).

[7] University of Tennessee Report, supra, note 3, p. 18.

sink downward through groundwater and will be more responsive to gravity than to the flow established by pumping. If they are lighter than water (LNAPLs), they will tend to float on top of the groundwater and pumping may simply remove the groundwater from beneath them while they remain in place.

- Gradual "Recontamination": Whether bound to the soil, floating, or sunk to the bottom of the groundwater, NAPLs do dissolve very gradually, over very long periods of time. Thus, after pumping stops, groundwater that has reached a certain level of cleanliness can become recontaminated, perhaps even to its original levels.[8]

EPA has conceded that in instances where there are large pools of DNAPLs no aquifer has been restored to drinking water quality.[9] A similar inability to achieve standards has been observed when the contaminants of concern are certain metals such as chromium and mercury.[10] Indeed, Oak Ridge National Laboratory was unable to find a single aquifer in the United States that had been successfully restored through pumping and treating.[11]

A third problem with pump and treat technology is its potential for negative ecological impacts. Dewatering from pumping can cause significant land subsidence and destruction of an aquifer as occurred at the IBM Site in San Jose, California. Also, drilling too deep or lowering a water table too far can result in a NAPL pool of contaminants migrating to a deeper, pristine aquifer as happened at the Department of Energy's Savannah River, South Carolina site.

In addition to these general criticisms of pump and treat technology, there are two problems with the technology as applied to the Arizona situation.

First, in Arizona, EPA and the Arizona Department of Environment Quality ("ADEQ") have frequently designated huge areas as CERCLA or WQARF sites rather than restricting designations to specific facilities such as landfills. Utilizing pump and treat technology to cleanup a contaminated aquifer that is several dozen square miles in areal extent is impractical. Attempting to treat billions of gallons of water to drinking water quality would not only be economically infeasible but depending upon design and timing of the pumping could seriously impair the usefulness of the groundwater resource the treatment is supposed to restore.

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[8] EPA, Consideration of Groundwater Remediation at Superfund Sites--Update, p. 3. See also Can Aquifers at Superfund Sites be Remediated, supra, note 4.

[9] EPA, Estimation Potential for Occurrence of DNAPL at Superfund Sites, at 1 (OSWER No. 9355.4-07FS, Jan. 1992).

[10] Arthur D. Little, Technology Capabilities Versus Superfund Cleanup Requirements: Is There a Gap? 66252 (February 1992).

[11] Can Aquifers at Superfund Sites be Remediated? supra, note 4.

Second, groundwater typically serves a different function in Arizona than in many other states. In Arizona, groundwater should be viewed as primarily an economic resource rather than as a public health or environmental resource. This is particularly true in the case of contaminated groundwater underlying urban areas since such groundwater seldom impacts surface ecosystems and only becomes a threat to public health if the decision is made to deliberately pump the groundwater for drinking water purposes without treatment or blending. In other words, the loss of pristine water due to contamination should be viewed as primarily an economic loss since it requires the substitution of more costly sources of water for drinking or agriculture uses. If groundwater is seen as a purely an economic resource then the decision whether to pump and treat or utilize some other technology to deal with contamination can be made on an economic, empirical basis rather than on the basis of the more emotionally loaded criteria of jeopardy to public health or the environment. An economic benefit analysis of pump and treat technology will, as has been shown in a number of different contexts, invariably result in the rejection of that technology in all but a few cases.

In view of the difficulty of justifying pump and treat technology on any rational technical or economic grounds the obvious question is: Why is it so popular and why aren't other groundwater remediation strategies more accepted by goverment decision-makers?

There are usually two reasons given by bureaucrats asked to defend their selection of pump and treat technology to cleanup groundwater to drinking water standards rather than less expensive alternative remediation strategies:

1. The law requires it.

2. The public demands it.

It is beyond the scope of this analysis to evaluate whether the latter reason has any validity, although the issuance of public acceptance is dealt with briefly at the end of this paper. However, we would take strong issue with the first rationale for the adoption of pump and treat technology. Indeed, we would argue that a careful reading of the law requires rejection of pump and treat technology as a choice in most aquifer cleanups.

## LEGAL STANDARDS FOR REMEDY SELECTION.

### 1. Cost-Effectiveness.

Advocates of pump and treat technology point to language in Section 121(b) (42 U.S.C. §9621(b)) of CERCLA and counterpart language in the National Contingency Plan ("NCP") (40 CFR (300.430(f)(i)(E)) as requiring a permanent treatment technology like pump and treat rather than containment, institutional controls or point-of-use treatment technologies. It is true that the cited sections of CERCLA and the NCP create a bias for a technology like pump and treat. However, merely

reading those sections in isolation creates an incomplete picture of the legal criteria for selection of cleanup technologies and standards. The language of both the NCP and particularly CERCLA when viewed as a whole is both confusing and internally contradictory, reflecting the desire of Congress and EPA to reconcile the politically and technically irreconcilable.

Section 121(b) states that "[R]emedial actions in which treatment which permanently and significantly reduces the volume, toxicity or mobility of the hazardous substances, pollutants, and contaminants is a principal element, are to be preferred over remedial actions not involving such treatment." However, in the same subsection there is a requirement that the President "...select a remedial action that is protective of human health and the environment, that is cost-effective, and that utilizes permanent solutions and alternative treatment technologies or resource recovery technologies" but only "to the maximum extent practicable." (Emphasis supplied.) Moreover, in Section 121(a) the President is specifically directed to select a "cost-effective response" and instructed that "[I]n evaluating the cost-effectiveness of proposed alternative remedial actions, the President shall take into account the total short- and long-term costs of such actions, including the cost of operation and maintenance for the entire period during which such activities will be required."

If the weight to be given cost-effectiveness as a technology and cleanup level selection criterion is not entirely clear under CERCLA, cost-effectiveness has been accorded primary importance by the State Legislature in the administration of the WQARF program. The statutes governing the WQARF program establish three requirements for all remedial actions. One of those requirements is that remedial actions shall "[B]e cost-effective over the period of potential exposure to such substances. A.R.S. §49-281.D.3. Perhaps more importantly, in characterizing the technology that is to be chosen for remedial actions there is no preference expressed for permanent treatment technology over other means of remediation or contaminant control. Instead, the State Legislature requires that remedial actions shall "[T]o the extent practicable, provide for control, management or cleanup of the hazardous substance so as to allow the maximum beneficial use of the waters of the state." (Emphasis added.) A.R.S. §49-282.D. In short, the legislature took great pains to establish criteria for remedy selection that would discourage the use of pump and treat technology and encourage the use of alternative, less costly technologies if such technologies were capable of protecting human health and the environment.

2. Technical Impracticability.

A factor that appears to drive the selection of pump and treat technology by EPA at CERCLA sites is the perceived necessity to meet the goal of cleaning up aquifers to drinking water standards. Even though there is serious question whether pump and treat technology (or any technology) is capable of cleaning up an aquifer to the Maximum Contaminant Levels ("MCLs") established for public drinking water supplies, government officials can at least point to pump and treat technology as working toward that end. However, EPA has either ignored or substantially down-played language in Section 121 that limits the requirement that MCLs be attained in all cases. Attainment of MCLs may be waived when "compliance with such requirements is technically impractical from an engineering point of view." CERCLA Section 121(d)(4)(C); 42 U.S.C. §9621(d)(4)(C). Unfortunately, Congress failed to further define what it meant by technical impracticability and the NCP contains no guidance as to its meaning.

What informal guidance there is appears to be contradictory. On the one hand EPA has stated that cost "may be considered in determining what is ultimately practicable."[12] On the other hand, in its guidance on groundwater cleanups, EPA states that costs are "not generally a factor in the determination of impracticability."[13] What is perhaps more disturbing, EPA has sought to structure RODs and consent decrees intended to implement RODs in such a manner as to rob the concept of technical impracticability of any meaning. In about a dozen RODs and consent decrees issued before 1991 EPA recognized the legitimacy of technical impracticability considerations by either providing impracticability waivers of MCL cleanup goals in the ROD or explicitly providing in consent decrees dispute resolution or general modification provisions for obtaining impracticability waivers at some future date.[14] In more recent RODs and consent decrees, however, it has become EPA policy to refuse impracticability waivers for all but a few cases and to absolutely deny mention of technical impracticability as a basis for invoking dispute resolution or a modification under a CERCLA consent decree.

The Arizona Legislature has made it essentially impossible for ADEQ to ignore technical impracticability in choosing cleanup level and technologies under the WQARF program. In addition to listing general practicability and cost-effectiveness as two of the three guiding criteria in the selection of a remedial action, the WQARF statute requires the consideration of "[T]he technical practicality and cost-effectiveness of remedial actions applicable to the site" as one of the eight factors that must be considered in setting "the level and extent of cleanup." A.R.S. §49-282.E. The ADEQ rules intended to govern the selection of remedial actions similarly require consideration of "[T]he technical practicability, reliability, cost-effectiveness and demonstrated effectiveness of a proposed remedial action, . . ." A.A.C. R18-7-104(A)(7).

### 3. ARARs.

Section 121(d) of CERCLA requires the cleanup levels be established so as to comply with all "applicable or relevant and appropriate requirements" ("ARARs") established under other federal or state environmental laws. In another paper to be presented at this seminar, Debbie Jamieson has provided a superb analysis of how ARARs are determined under CERCLA and the interrelationship of federal ARARs, the Arizona Aquifer Water Quality Standards and WQARF and CERCLA cleanups. I will not attempt to repeat Ms. Jamieson's analysis here. For our purposes, however, there are several points about the use of ARARs to set cleanup levels and select cleanup technologies that are worthy of note:

First, as stated previously, the requirement that cleanup levels be established to achieve ARARs is limited by the technical impracticability provisions of Section 121(d). The fact that EPA has tended to automatically chose MCLs or even more stringent state water quality standards as minimum cleanup levels regardless of practicability does not repeal the language of CERCLA requiring that practicability

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[12] Preamble to the NCP, 56 Fed. Reg. 8,666 at 8,748.

[13] EPA, Guidance on Remedial Actions for Contaminated Ground Water at Superfund Sites at 6-2.

[14] See, e.g., the Consent Decree in United States v. BASF Corp.

be considered. Moreover, if technical impracticability no longer is given its due weight in the selecti n of cleanup levels, it should at least be considered in selecting cleanup technologies. Thus, while groundwater contaminated with mercury may have to be cleaned up to two parts per billion (the MCL for mercury), natural contamination, location, actual groundwater usage and the volume of contaminat d groundwater may justify the selection of point-of-use treatment (albeit to MCLs) rather than using pump and treat.

Second, to the extent that ADEQ rules create a presumption that groundwater cleanups under the WQARF program must bring an aquifer into compliance with the MCL-based Arizona Aquifer Water Quality Standards (as Ms. Jamieson has suggested), those rules are directly contrary to the statute th are intended to implement. See A.A.C. R18-7-109.D.2. A statutory scheme that stresses cost-effectiveness and practicality as two of the primary criteria for remedy selection and that establishes "control and management" of aquifer contamination as a goal equal to "cleanup" in remedial action cannot legitimately be read as creating a presumption in favor of either MCLs as cleanup levels or pump and treat as a cleanup technology. Indeed, the statutory language is more susceptible to an interpretation opposing the adoption of MCL's as cleanup level except for those rare cases when such cleanup leve can be justified as cost-effective and necessary to protect public health or the environment.

Finally, EPA has incorrectly applied the ARARs standards to Arizona cleanup requirements in tw contexts.

One of EPA's reasons for applying MCLs as cleanup levels in Arizona is the fact that MCLs ar identical to the state's own Aquifer Water Quality Standards. What EPA disregarded is that Aquifer Water Quality Standards, for the reason described above, cannot be used as the primary basis for setting state cleanup levels under the WQARF program. Thus, Aquifer Water Quality Standards are neithe "relevant" nor "appropriate" as CERCLA cleanup standards.

A second incorrect adoption by EPA of state standards as ARARs is the agency's use of stat HBGLs as cleanup levels for substances for which there are no Aquifer Water Quality Standards. Fo a state standard to be designated as an ARAR it must be "adopted by formal means." CERCLA Section 12(d)(2)(C)(iii)(I). The HBGLs were never officially adopted as state cleanup standards formally o informally. Indeed, the documents containing the HBGLs all have a disclaimer to the effect that they are for guidance purposes only and are not to be interpreted as rules or standards. Thus, under Section 121 EPA cannot designate HBGLs as ARARs.

In sum, when the actual language of the applicable statutes governing CERCLA and WQARF is examined that language does not lead to the conclusion that groundwater must be cleaned up to drinking water quality using pump and treat technology. Instead, it suggests that if government decisionmakers give the weight to considerations of cost-effectiveness and technical impracticability that these laws require, they will reject pump and treat technology in favor of more technically feasible and economically reasonable cleanup methods that provide a comparable level of environmental and public health protection.

When it has been proposed that federal and state government officials deemphasize pump and treat technology and cleanup to drinking water standards the inevitable response has been that even if the law does not compel adoption of this less cost-effective technology, the public demands aquifer cleanup and restoration to drinking water quality. While it would serve no purpose to engage in a debate on what the public does or does not demand, we think it is worth noting that to the extent that government claims it is motivated to make economically or technically unjustifiable cleanup level or technology decisions by public opinion, such public opinion is the result of government's inability or unwillingness to adequately or accurately portray such concepts as environmental risk to the public. Thus, as has been proven on numerous occasions, the public has an entirely exaggerated perception of the risk posed by hazardous substance contamination[15] and it is this inaccurate perception of risk that drives whatever public sentiment exists for unrealisitc cleanup levels and impractical cleanup technologies. Such need not be the case, however, as demonstrated by the Dutch experience.

In the Netherlands public opinion influences environmental decisions to even a greater extent than in this country. The Green Party is a significant factor in Dutch politics and environmental protection is a key element in every politician's agenda. The Netherlands has an environmental cleanup program that is considered a model in the EEC. The Dutch program differs from the CERCLA and WQARF programs in several key respects. Under the Dutch program cleanup standards are relatively uniform and are tied to current groundwater use. Cost-effectiveness is the first criterion for cleanup technology selection. The most extensive remedial alternative cannot be selected unless its total cost is not greater than a specified ratio times the cost of the second best partial cleanup. This cost ratio varies from 5 at law costs, to 1.5 at higher costs. There is no bias under the Dutch program for treatment.

The Dutch program has been extremely effective at a much lower cost than its U.S. counterpart. One of the reasons for that success is the government's extensive efforts to accurately portray risk to the public--emergency chemical releases are treated as the greatest risk and the mere presence of hazardous substance in soil or groundwater is down-played as creating significant risk to public health or the environment.[16]

While there is no "perfect" groundwater cleanup program there are clearly better approaches to groundwater remediation than the current state and federal programs. The Dutch experience demonstrates that the public will accept a reasonable groundwater remediation approach if they are given the information needed to understand how it works and the disadvantages of alternatives such as pump and treat. As the foregoing demonstrates, the legal impediments to implementation of a cost-effective,

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[15] See, e.g., EPA Administrator Reilly's testimony to The Committee on Environment and Public Works, United States Senate, during hearings on The Report of the Environmental Protection Agency's Science Advisory Board, Hearing Report (January 25, 1991) at 22.

[16] For a more detailed description of the Dutch program see Dutch National Institute of Public Health and Environment Protection and Dutch Institute for Inland Water Management and Waste Water Treatment, Sustainable Use of Groundwater (1991); Levebre, Enforcement of Environmental Regulation in the Netherlands, Int'l Env't Rptr. (BNA) 401 (1990).

technically practical groundwater cleanup strategy have been overblown. The current CERCLA and WQARF laws, while deficient in many respects, still provide the latitude necessary to abandon the current reliance on pump and treat in favor of better, more effective technology. What is lacking is the will of government officials to make the right choices.

# APPLICATION OF AQUIFER WATER QUALITY STANDARDS TO GROUNDWATER PROTECTION AND REMEDIATION PROGRAMS[1]

**Deborah A. Jamieson[2]**

## ABSTRACT

This paper discusses the relevance of Arizona's aquifer water quality standards to three regulatory programs: the Arizona aquifer protection permit program, the Arizona Water Quality Assurance Revolving Fund program, and the federal Comprehensive Environmental Response, Compensation and Liability Act program (CERCLA or Superfund). This paper poses questions about the most effective means of protecting groundwater quality and remediating groundwater contamination. This paper raises concerns about the conflicting goals and policies of ADEQ, ADWR and EPA. An argument is made that more attention should be paid to the financial and other costs involved in protecting and remediating groundwater, and a closer look taken at the benefits resulting from existing regulatory approaches.

## I. INTRODUCTION

This paper discusses Arizona's Aquifer Water Quality Standards (AWQS)[3] from a practical perspective: how the standards are applied in Arizona. This paper is not a discussion of what the AWQS are, but rather how they are used. To accomplish their purpose of protecting Arizona's groundwater quality the AWQS must

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[1] Paper presented at the Sixth Annual Symposium of the Arizona Hydrological Society, Casa Grande, Arizona, September 23-24, 1993.

[2] Deborah A. Jamieson is in-house environmental counsel for Salt River Project, Phoenix, Arizona.

[3] The statutory framework for the AWQS is in A.R.S. §§ 49-221 and 223. The AWQS are published at Arizona Administrative Code Title 18, Chapter 11, Article 4, (A.A.C. R18 -11-401 et seq.). Amendments to the AWQS were proposed in May, 1993, by ADEQ and public comments were taken in July, 1993. The amendments would incorporate the latest federal maximum contaminant levels for primary drinking water pollutants.

be enforced. The AWQS are currently enforced through prospective and retrospective state regulatory programs, such as the Aquifer Protection Permit (APP) and Water Quality Assurance Revolving Fund (WQARF) programs, the Underground Storage Tank program and the Hazardous Waste Management Program. There are programs designed to protect against future degradation of groundwater from ongoing activities that could impact groundwater, and there are programs designed to remedy existing groundwater contamination. The AWQS may also be implemented under the federal Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). In addition, the AWQS can be enforced directly, either by the ADEQ, the Attorney General, or an adversely affected citizen.

This paper focuses on three regulatory programs in which AWQS play an important role: the APP program, the WQARF program, and the CERCLA program. This paper also briefly explores two methods of directly enforcing AWQS: compliance orders issued and litigation commenced specifically to stop violations of the AWQS.

It is important to remember that state law has classified all aquifers in the state for drinking water protected use;[4] thus, the AWQS that apply to all the state aquifers are drinking water standards. State law requires that ADEQ adopt all federal primary drinking water maximum contaminant levels (MCLs) under the Safe Drinking Water Act as AWQS, unless the Director finds no scientific evidence to support the standard. A.R.S. § 49-223.A. To date, ADEQ has adopted only the MCLs as state AWQS, although ADEQ has the authority to go beyond the MCLs and adopt drinking water AWQS for pollutants which do not have MCLs set. To do so, however, ADEQ must base its decision on "credible medical and toxicological evidence that has been subjected to peer review." A.R.S. § 49-223.B.

## II. APP PROGRAM[5]

ADEQ has recently stated in its draft revised AWQS dated March 12, 1993, that the "[AWQS] establish the water quality goals for groundwater in Arizona. The purpose of the [AWQS] is to maintain and protect groundwater quality for drinking water use." This is accomplished largely through the APP program.

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[4] A.R.S. § 49-224.B. A process exists for changing the classification of an aquifer, but it has never been used and is unlikely ever to be used because the criteria cannot be met. See A.R.S. § 49-224.C.

[5] The APP statutory framework is at A.R.S. §§ 49-241 to 251. The APP rules are at A.A.C. R18-9-101 et seq.

The AWQS provide the foundation for the APP program. The APP program is prospective: prevention of future groundwater contamination is its purpose. All facilities that discharge pollutants directly to an aquifer or to the land surface or the vadose zone in such a manner that there is a reasonable probability that the pollutant will reach an aquifer must obtain an APP. A.R.S. §§ 49-241, 201.10. A permit will not be issued unless the pollutants that are discharged "will in no event cause or contribute to a violation of [AWQS]" A.R.S. § 49-243.B.2.[6]

The ADEQ has two means within the APP to protect against AWQS being violated by a facility discharging pollutants that may impact groundwater: discharge limitations and alert levels. A.R.S. § 49-243.F. A discharge limitation is "any restriction, prohibition, limitation, or criteria ... on quantities, rates, concentrations, combinations, toxicity and characteristics of pollutants." A.R.S. § 49-201.12. "Alert level" is not defined in the statute, but ADEQ adopted a definition in the APP rule. An alert level is a "numeric value, expressing either a concentration of a pollutant or a physical or chemical property of a pollutant ... which serves as an early warning indicating a potential violation of either ... [AWQS] ... or any permit condition. A.A.C. R18-9-101.1. Sometimes it is not easy to tell the difference between a discharge limitation and an alert level; however, in general, violating a discharge limitation will be violating the permit, while exceeding an alert level triggers contingencies which are permit conditions, but the exceedance is not itself a violation of the permit.

Discharge limitations for the pollutants being discharged are meant to ensure that the discharge will not cause or contribute to a violation of AWQS. Discharge limitations may take the form of numeric limits applied to the pollutant at the point it is discharged to the permitted facility, or at the point a pollutant may leave the permitted facility (e.g., leaking through a liner). In many cases the numeric limit may be zero, meaning that no discharge from the permitted facility will be allowed. "No discharge" is popular with ADEQ because no calculation or prediction is necessary to determine how much of a pollutant may be discharged before AWQS may be violated. "No discharge" is also favored by the statute. A.R.S. § 49-243.B.1.

Alert levels are used by ADEQ two ways: to detect whether a discharge limitation or some other permit condition is being violated, and to provide an early warning that AWQS might be violated by a discharge, unless additional action is taken. In most cases, the APP will contain a contingency plan which must be implemented if an alert level is exceeded. An alert level might be the detection of any liquid below an impoundment or landfill liner, indicating the liner has been breached and pollutants might be migrating to the aquifer. Another example of an alert level

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[6] If the aquifer in question already violates AWQS, a permit will not be issued unless the pollutants will not "further degrade" the quality of the aquifer. A.R.S. § 49-243.B.3.

might be one or more specific numeric limits on pollutants contained in the discharge, which are monitored in the groundwater at some point below or beyond the facility. Exceeding that alert level would require additional measures to be taken to ensure pollutant concentrations would not increase.

The APP applicant must be careful to negotiate the best possible discharge limitations and alert levels with ADEQ, for at least two reasons: to cut down on unnecessary expense and to reduce the likelihood of violating the permit. The discharge limitations and alert levels are designed to protect against violations of the AWQS. They should be realistically related to the AWQS they are designed to protect or unnecessary overregulation will occur. Overly restrictive discharge limitations or alert levels could cost the facility operator unnecessary expense to comply, and could lead to violations of permit conditions that need not have occurred. Reasonable discharge limitations and alert levels should be a primary goal of every APP applicant. The APP applicant should keep ADEQ focused on the fact that the bottom line is protecting against violation of the AWQS. Discharge limitations and alert levels should not be allowed to take on a life of their own.

## III. WQARF PROGRAM[7]

Another use of the AWQS is to establish cleanup levels for actions taken under the WQARF program or the CERCLA program to remedy past groundwater contamination. The WQARF program rules contain a presumption that groundwater-related remedial actions should bring the aquifer in question into compliance with AWQS. A.A.C. R18-7-109.D.2. It is important to note, however, that clean up of groundwater to drinking water standards is <u>not</u> required in every instance. A complex set of remedial action criteria and remedial action requirements must be considered by the ADEQ before a final decision is made concerning remedial actions. The individual circumstances of each case are crucial to decisions on the remedial action to be required. Although it is rarely acknowledged,[8] a remedial action decision may appropriately be no action advisable or required.

The WQARF rules contain two revealing sections. With regard to remedial action requirements, A.A.C. R18-7-109.A.2 states that remedial actions shall provide for the "control, management <u>or</u> cleanup" of a release of a hazardous substance. (emphasis added). Clearly, ADEQ is not limited to choosing remedial actions that require "cleanup" of hazardous substances in soil or groundwater. "Control" and

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[7] The statutory framework for the WQARF program is at A.R.S. §§ 49-281 to 296. The WQARF rules are at A.A.C. R18-7-101 <u>et seq</u>.

[8] In fact, such an acknowledgement would border on heresy.

"management" of the release of hazardous substances are also possible choices. This could include prohibiting the migration of the contamination in groundwater, as well as preventing the further contamination of the groundwater by stopping additional releases of hazardous substances into soils or groundwater. In addition, this same section also makes clear that the evaluation of beneficial use of the aquifer must "include" protection of drinking water. There is no mandate in the WQARF program that the beneficial use of every aquifer be deemed to be drinking water in the context of remedial action.

The second section of interest is A.A.C. R18-7-109.B. This section requires the Director to favor the selection of remedial actions that permanently and significantly reduce "the volume, toxicity, or mobility" of a hazardous substance. (emphasis added). A remedial action that stops the migration of contamination, but does not decrease the amount of that contamination, could qualify as a "favored" remedial action under this section. Moreover, this same section goes on to state that this "favoring" is limited anyway to when it is "practicable, cost-effective, and necessary to protect public health or welfare or the environment".

To date, there have been only a few groundwater-related remedial actions undertaken pursuant to the WQARF program. It is still too early to know how ADEQ will apply AWQS in the WQARF context. The ADEQ is facing significant groundwater contamination issues in the Phoenix area and throughout the state. In Phoenix alone, the WQARF areas designated due to hazardous substance groundwater contamination are many square miles in size. The ADEQ is grappling with the feasibility of "cleaning up" groundwater contamination, including issues of technical practicability as well as cost. While Jane and John Q. Public want "clean" (e.g., drinkable) groundwater, the reality is that it may not be possible to make all groundwater in our aquifers drinkable. There is a distinction between standards being applied to water that is actually being used for drinking water and standards being applied to potential drinking water while in an aquifer.

Not many people would agree to drink water that did not meet appropriate drinking water standards. Arizona citizens are protected in this regard by the laws and rules which govern the providing of drinking water by municipal and private providers. Depending on where one lives in Arizona, groundwater comprises all or some of our drinking water. Depending on the quality of groundwater from various aquifers, this pumped groundwater may be treated to a lesser or greater extent before it is delivered to the user for drinking water purposes. This groundwater is water treated so that it complies with drinking water standards at the point of use. Most people are probably thinking of the water that comes into their homes and work places when they think that they want "clean" drinking water. How necessary is it to embark upon a program (call it a "groundwater remedial action program") that requires aquifers contaminated with certain pollutants to be "cleaned up" so that the water in the aquifers becomes "pristine", e.g., treated so that AWQS are met in the

aquifer? Perhaps we should focus more on treating contaminated groundwater when it is ready to be used rather than crusading for cleanup of aquifers.

Many millions of dollars are being spent across the United States every year for remediation programs to reduce groundwater contamination because it is there, not because the groundwater is needed for current or imminent drinking water use. Until recently, there has been little discussion about whether it made sense to impose stringent drinking water standards on so many groundwater remediations, or whether to even require a remediation at all. But there seem to be some signs that such discussion may be coming.

An article by Keith Schneider appeared in the March 21, 1993 Sunday New York Times, which exemplifies concerns now being expressed by scientists, state and federal environmental agencies and even some politicians, that government has gone way too far in attempting to regulate health risks from environmental pollutants. In response to increasing public and environmental group pressure, our government has gone further every year in ratcheting down environmental standards. The adoption in 1986 of the law that established AWQS[9] can be traced to growing hysteria about Arizona's scarce ground water supply and growing information about the extent of contamination of our aquifers. Hence, all of Arizona's aquifers are protected for the most stringent use: drinking water.

In his article, Schneider quotes William Reilly, former EPA Administrator, as stating that the United States has had enough environmental agenda-setting by "episodic panic", and the Science Advisory Board as concluding that policy decisions are more reflective of "public perceptions of risk than of scientific understanding of risk." One high-ranking EPA official responsible for policy planning stated that EPA is now in a position of saying, in quite a few of EPA's programs, "[o]ops, we made a mistake." Growing louder, voices from many sectors are complaining that billions of dollars are being thrown away on programs that are yielding little discernible benefit. Very strict standards have been adopted ostensibly to protect the public health, but the various standard-setting processes have come under fire for being short on scientific basis and lacking even rudimentary cost-benefit analyses. Indeed, for many years now any consideration of cost or economics in the setting of standards has been all but prohibited. In the decade of the 1980's, when many new laws and regulations were adopted, there was less pressure to consider the cost of environmental policy, perhaps because, as Mr. Schneider points out, Congress was operating under an economy that seemed healthier. Ironically, this was a decade of Republican administration. Just when the administration in Washington has swung back to the Democrats, it appears that the economic costs of standard setting may become vogue.

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[9] The Environmental Quality Act, A.R.S. §§ 49-101 et seq.

One of the programs under the most criticism is the CERCLA cleanup program. Although that program is taking a lot of abuse on many different fronts, one of the reasons for its high cost and less than satisfactory results in "cleaning up" groundwater, is that the standards for clean up have been set unreasonably high and the EPA has relied almost exclusively on one technology, often called "pump and treat." One EPA hazardous waste specialist has said that it does not make sense to clean up wastes at costs that frequently exceed $10 million an acre. The ADEQ has been taking heat recently also for its alleged failure to achieve more progress on Arizona groundwater contamination problems.

Consistent with this new wave of cost/benefit analysis, perhaps the application of Arizona's AWQS in the WQARF program should be considered. More thought should be given to the interplay between the goals of the Arizona Groundwater Management Act[10] (GMA) and the WQARF program. Requirements that contaminated aquifers be cleaned up "now", regardless of the need for the water "now", create significant problems in conventional "pump and treat" programs.

Questions that have not been answered include:

1) How much water must be pumped to achieve AWQS in an aquifer that is significantly contaminated or contaminated over a widespread area?

2) What use will be available for the groundwater pumped after it is treated? If there is no current need for the water for a drinking water use, will the water be discharged to a surface water directly or indirectly through a sewer system, or recharged to the same contaminated aquifer from which it was pumped?

3) How will the water be accounted for for purposes of GMA conservation and fee/penalty requirements? There is a significant possibility that ADEQ could require groundwater pumping to clean the groundwater even though such pumping could be a depletion of groundwater in contravention of the GMA's goals.[11]

Where it doesn't make good sense from a technical or an economic viewpoint to impose a "pump and treat" remedial program, or to require the

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[10] A.R.S. §§ 45-401 et seq.

[11] Conflict between ADEQ's programs and the Arizona Department of Water Resources' programs exists despite the fact that ADEQ's remedial action decisions are required by law to be consistent with A.R.S. Title 45, Chapter 2. A.R.S. § 49-282.F.

achievement of drinking water standards in a contaminated aquifer, ADEQ should seriously consider other alternatives, including monitoring aquifer conditions, containment of the migration of contamination, prevention of additional contamination of the aquifer, and postponement of any pump and treat remedy until such time as there is a beneficial use for the groundwater to be pumped (preferably a drinking water use). Cleaning up groundwater contamination as the groundwater is needed for a beneficial use, rather than incidentally trying to find a use for groundwater required to be pumped to achieve a clean up of the aquifer, would go a long way to making the WQARF (and CERCLA) programs more practical and cost-effective. Toward this end, more consideration should be given to using existing wells pumping from contaminated aquifers for a remediation project, rather than drilling new remediation wells, and when feasible installing well(s)-specific treatment systems rather than constructing new stand-alone treatment plants.

Arizona should look at New Jersey's amended groundwater quality standards adopted on February 1, 1993.[12] The New Jersey Department of Environmental Protection and Energy adopted regulations that recognize the existing uses and quality of groundwater. High quality groundwater that is pristine, or naturally clean enough to drink, will receive the highest protection to maintain its potability. In areas with heavy ground water pollution some remediation may be required but the main strategy will be to rely on the chemicals' natural tendency to become less toxic over time. The agency is trying to strike a balance between "ensuring appropriate remediation while avoiding the enormous, and often futile, expense of impractical technologies for badly polluted groundwaters."[13]

## IV. CERCLA PROGRAM[14]

The EPA has its own process under CERCLA for determining cleanup standards for groundwater, based on relevant federal environmental statutes, at each site where remediation will occur.[15] Section 9621(d) of CERCLA, however, also requires that federal remedial actions comply with legally applicable or relevant and appropriate requirements (ARAR) of more stringent state laws, except under delineated circumstances.

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[12] See article in BNA Environment Reporter, Current Developments, February 5, 1993, p. 2655.

[13] BNA Environment Reporter, Current Developments, February 5, 1993, p.2655.

[14] The statutory framework for the federal CERCLA program is at 42 U.S.C.A. §§ 9601 et seq.

[15] See the National Contingency Plan (NCP) at 40 C.F.R. Part 300.

The AWQS could be required as the cleanup level at a federal CERCLA site in Arizona if they are more stringent than federal requirements would be. The NCP requires that primary drinking water MCL goals under the Safe Drinking Water Act be applied to groundwater cleanups of drinking water aquifers, as long as the MCL goals are above 0. 40 C.F.R. § 300.430(e)(2)(i)(B). The MCL goals are often more stringent than the MCLs. Since the AWQS are currently equivalent to the federal primary MCLs, the state standards would not be more stringent than the likely federal standards that would be imposed on a CERCLA groundwater cleanup in Arizona. So whether AWQS should be ARARs in a CERCLA cleanup has not been a big issue in Arizona to date. What is not clear, though, is whether Arizona's designation of all its aquifers for drinking water use will be considered an ARAR, or whether EPA is free to make its own determination of the aquifer's protected use.

There are 3 cases, however, in which AWQS could be more stringent than EPA's chosen clean up standards, and thus possibly ARARs. If EPA were to propose a standard less stringent than primary MCLs for a federal site in Arizona, ADEQ could oppose that proposal on the grounds that AWQS, which are primary MCLs, are more stringent and must therefore be the cleanup standards adopted. In view of the increasing controversy over the costs and benefits of cleanups, it is conceivable that EPA might reach a point where standards less stringent than primary MCLs are deemed sufficient for some groundwater cleanups. There could be some future conflict, unless ADEQ moves in the same direction as EPA and agrees that cleanup standards other than drinking water standards are acceptable.

A second case in which a conflict could possibly arise between the EPA and ADEQ is if ADEQ adopts in the future any AWQS which are more stringent than the primary MCLs. It will not be easy, however, to adopt more stringent standards under the existing statutory regime, because ADEQ must rely on technical protocols and base the proposed standards on credible medical and toxicological evidence that has been subjected to peer review. The ADEQ's scarce resources really do not permit it to undertake the kind of research and study necessary to meet this criteria. This conflict is occurring in other states, however.

In California, the Water Resources Control Board has imposed standards on the cleanup of groundwater in state actions that are ten times more stringent than the primary MCLs. The state has sought to require EPA to use the state's more stringent standard, for instance for trichloroethylene (TCE) (.5ppb), at federal cleanup sites in California, instead of the primary MCLs. The argument seems to be that because technology exists to reduce TCE to below detectable levels, and California requires such best available technology, EPA should require such technology also.

The D.C. Circuit Court of Appeals decided in July, 1993, a case brought by Ohio, and joined in by other states, challenging the NCP to the extent the NCP does not provide for cleanups to the MCL goals when such MCL goals are 0. Ohio v. EPA,

No. 86-1096, D.C. Cir. (July 20, 1993). The argument in that case was whether the MCL goals are attainable, EPA arguing that they often are not attainable and therefore cannot be the standards applied. The appellate court upheld EPA's decision not to use MCL goals set at zero as ARARs. The court said that it is impossible to detect true zero, which is the total absence of contaminants.

The third case involves the future modification of a clean up standard, making it less stringent, if after a lengthy period of operating the remedial action facilities, the parties determine that the cleanup standard is not attainable due to "technical impracticability." The EPA has just started to recognize "technical impracticability" as a reason to modify a cleanup standard, and only a few consent decrees have reflected EPA's new position.[16] If EPA proposes to lower a cleanup standard because the drinking water standard is not attainable, this could create a conflict with the more stringent AWQS. On the other hand, this is unlikely to happen because the state statute allows the ADEQ, as part of the remedial action criteria, to consider the "technical practicality and cost effectiveness of remedial actions....." A.R.S. § 49-282.E.7. The ADEQ's WQARF rules expand on this statutory language, requiring ADEQ to consider "technical practicality, reliability, cost effectiveness, and demonstrated effectiveness" of a proposed remedial action. A.A.C. R18-7-104.A.7. (emphasis added). Nevertheless, as evidenced by the Ohio v. EPA lawsuit, whether or not standards are attainable can be a question of considerable debate.

After discussing the potential future conflicts between EPA and ADEQ on cleanup standards for federal remedial actions at Arizona sites, I must also raise the fact that CERCLA and the NCP give EPA several escape routes to avoid applying state standards that would otherwise be ARARs for a CERCLA cleanup. 42 U.S.C.A. § 9621(d)(4); 40 C.F.R. § 300.430 (f)(1)(ii)(C). Among other exceptions, EPA need not adopt AWQS as ARARs if compliance with AWQS would be technically impracticable from an engineering perspective, or if the state has not consistently applied AWQS at similar state sites.

Using AWQS as ARARs in groundwater cleanups in Arizona under CERCLA, while not yet a pressing issue, should be kept in mind for the future as increasing pressure builds to revamp CERCLA and to refocus agency efforts on cost-effective remedial actions.

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[16] See, e.g. U.S. v. Motorola et.al., Civil Action No.__, D. Ariz., 1992. (Indian Bend Wash Consent Decree #1).

## V. EMERGING APPLICATIONS FOR AWQS

To date, ADEQ has spent a lot of energy and resources on programs to protect groundwater quality, mainly the APP program to stem future contamination, but also the WQARF program to investigate and begin remedying existing contamination. Both programs are powerful tools for the agency. The ADEQ also has authority to bypass the regulatory programs and remedy violations of AWQS directly, by issuance of an administrative order or by seeking injunctive relief in court.

If ADEQ determines that a person is violating an AWQS, the Director may order compliance. A.R.S. § 49-261.A. This section is vague in that no specifics exist as to how the person is to come into compliance. Presumably, if an AWQS is being violated, the violator can be ordered to cease the activity that is causing the violation. It is less clear whether coming into compliance includes remedying the contamination that is causing the AWQS violation.

One question that certainly comes to mind is how Section 261.A relates to the WQARF program if both can be used to order cleanup of groundwater contamination. One logical distinction could be that a Section 261.A order is to be used for individual, facility-specific violations limited in scope, whereas the WQARF program was designed to provide for multiple party scenarios and more widespread contamination.

Another possible use for Section 261.A orders would be to address AWQS violations that cannot be addressed through the WQARF or APP programs, or any other existing state environmental program. Although hard to believe, there is at least one possible factual situation which may not be remediable at all, if not remediable through a Section 261.A order. Petroleum hydrocarbon contamination (not a hazardous substance under the WQARF program), that has not come from an underground storage tank (not subject to the UST Corrective Action Program), that is not a hazardous waste subject to corrective action under the hazardous waste program, and that is not coming from a facility that needs an APP, would appear to be unremediable except through a Section 261.A order.

The ADEQ appears to be reluctant to use this Section 261.A authority, perhaps because of the lack of certainty as to its breadth, or perhaps because a Section 261.A order is subject to preenforcement review. The order may first be appealed to an administrative law judge, then to superior court. A.R.S. § 49-261.D.

To avoid some of the procedural morass that could result from a Section 261.A order, the ADEQ could instead use its authority under A.R.S. § 49-262.A to seek a temporary restraining order, or a preliminary or permanent injunction against the violation of AWQS. The County Attorney or Attorney General have similar authority, independent of the ADEQ. A.R.S. § 49-262.B.

To my knowledge, neither the ADEQ, nor the County Attorney or Attorney General, have yet used Sections 261 or 262 to directly enforce AWQS. Nevertheless, in the coming years the Arizona regulated community may see more use of the Section 261 and 262 "enforcement" provisions of the Environmental Quality Act to directly address violations of AWQS. A lot will depend on the direction the WQARF program takes in the near term.

## VI. CONCLUSION

The AWQS form the foundation of Arizona's groundwater quality protection strategy. The ADEQ has various important tools to assist it in enforcing AWQS, including the APP and WQARF programs, the CERCLA program, and Sections 261 and 262 of the Environmental Quality Act. Used together, these tools give ADEQ significant power to address groundwater contamination in Arizona. For those subject to the agency's jurisdiction over groundwater quality, our goal should be to cooperate with ADEQ in achieving protection of our groundwater resources, but our challenge is to find cost-effective and scientifically defensible ways of doing so.

# HOW WESTERN STATES LEGISLATE ACTIVITIES INVOLVING GROUNDWATER AND SURFACE WATER INTERACTIONS[1]

**Barbara Tellman[2]**

**ABSTRACT:** Arizona is unusual among Western states in managing groundwater and surface water basically as separate entities, as if there were little or no connection between them. An individual with senior surface water rights has no protection from pumping of groundwater in a nearby well. Flowing streams may generally be pumped dry with impunity. Most other Western states treat groundwater and surface water as one interrelated water source and govern that water source in a coordinated manner, at least to some degree. This paper examines how Western states deal with interconnected groundwater and surface water and offers some suggestions for Arizona.

## My Surface Water Rights vs. Your Well

Imagine that Farmer Frank owns a ranch with long-standing surface water rights, dating back to his grandfather's days. Developer Dan buys the land upstream, but Farmer Frank doesn't worry about his water rights because he has senior claims and there's always been plenty of water in the stream. Developer Dan, without surface water rights for his new second-home subdivision decides to dig some wells near the stream. The water table is not too far down and there seems to be plenty of water. What recourse does Farmer Frank have to protect his water rights if he believes that Dan's pumping will affect streamflow and thereby his water rights? Or if his stream starts to dry up?

The answer in Arizona, especially after a recent court decision, is "basically no recourse." Substitute "Salt River Project" or "The Nature Conservancy" for "Farmer Dan" and it becomes clear that no Arizonan's surface water rights are safe from groundwater pumping, whether we are talking about water for farms, cities or preserving streams. The answer in most other Western states is quite different. In New Mexico, for instance, Developer Dan will have to get a well permit and if the State Engineer believes streamflow will be endangered, he can deny the permit. In North Dakota and Kansas, groundwater and surface water rights are managed under a unified system, so Farmer Frank has as much protection of his surface rights from pumping as he does from stream

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[1] A paper presented at the Sixth Annual Symposium of the Arizona Hydrological Society, Casa Grande, Arizona, September 23-24, 1993.

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diversion. In Idaho and Montana, he will have this kind of protection if his farm is in one of the special management areas. In Washington, he can be assured that new groundwater rights will not impair his surface water rights. The purpose of this paper is to examine how this and similar types of situations would theoretically be handled other Western states. No attempt is made to evaluate how well the legal systems are working in practice in those states.

**A Nevada Example**

In case you wonder whether the above scenario is just fantasy, look at Milt Thompson's ranch in Diamond Valley, Nevada. This was once a watering stop and held lush springs, creeks and meadows. Milt Thompson says that dust is now his crop. As soon as deep agricultural pumps appeared up the valley, his surface water supplies began to fail. Although Mr. Thompson has surface water rights dating to 1857, and Nevada has laws which should protect him from excessive groundwater pumping, he now has to truck in even his drinking water from 21 miles away. His livelihood is gone. Why? The State Engineer granted far more pumping permits than the annual recharge could support. Mr. Thompson has argued for nine years that the State should be protecting his water rights, but has been unable to get a lawyer to take his case against the State.[3] If all this is possible in a state where surface water rights are supposed to be protected from groundwater pumping, what would happen in Arizona where there is no such protection?

**An Overview**

The science of hydrology has developed immensely since state constitutions and water management systems were developed in the West. Now it is well acknowledged that most surface and groundwater are related to some extent. What affects one part of the water cycle usually has effects elsewhere. But in states like Arizona, this scientific reality has never been reflected in the laws which for the most part treat both types of water as isolated systems, rather than part of one hydrologic cycle.

All Western states generally consider water to belong to the public and its use is thereby subject to regulation by the state. All of them have provisions to protect people with senior surface water rights from harm from junior surface water users. "First in time, first in right" lends a feeling of security to those senior water users. All except two Western states have provisions to protect senior groundwater pumpers from harm from other groundwater pumpers, at least in certain areas such as the AMAs in Arizona.

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[3] Christensen, Jon. "Now dust is his crop, says Nevada rancher." High Country News. August 9, 1993. pp 1 ff.

Thirteen states have provisions to protect surface water pumpers from harm from groundwater pumping, but Arizona does not. How groundwater-surface water relationships are managed varies enormously throughout the West. Eleven states have a unified management system written into their statutes. The management applies to designated districts (considered critical ones) in some cases. Two states have developed a unified system through court cases. Some states, including Arizona, control pumping to protect surface flow only if the groundwater is pumped from an "underground stream," which is very narrowly defined, and not in line with accepted modern scientific concepts.

**Some Problems with Definitions**

Many of the legal terms used when dealing with groundwater have little scientific basis. Arizona's law, for example, talks about "Water flowing in definite underground channels, underground streams" and "water that passes through or under the surface in a definite channel with ascertainable beds and banks." Such definitions are not generally used by hydrologists.

Examples of how much legal definitions differ from those a scientist would give can be found in Black's *Law Dictionary*[4], a basic reference book for lawyers. Water in underground streams is very different from "subterranean waters" which are defined as "waters which lie wholly beneath the surface of the ground, and which either ooze and seep through the subsurface strata without pursuing any defined course or channel, (percolating waters,) or flow in a permanent and regular but invisible course, or lie under the earth in a more or less immovable body, as a subterranean lake."

Black defines "percolating waters" as "those which pass through the ground beneath the surface of the earth without any definite channel, and do not form a part of the body or flow, surface or subterranean, of any watercourse. They may be either rain waters which are slowly infiltrating through the soil or waters seeping through the banks or the bed of a stream, and which have so far left the bed and the other waters as to have lost their character as a part of the flow of that stream." In Arizona, both subterranean and percolating waters are regulated as groundwater, and the underground streams are regulated as surface water. In most other western states, all three types of water are managed as an integrated system.

I won't go on. Are any of these definitions what you as hydrologists would have used? I think you get the picture that legal and scientific definitions and distinctions may have little in common. From the hydrologist's point of view, most waters are interrelated to some degree - and it is a matter of degree, for the most part. Surface water may become groundwater in a week, a month or a century, but a relationship often exists.

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[4] Black, Henry C. *Black's Law Dictionary.* Revised fourth edition. West Publishing Company. St. Paul MN. 1968. 1882 pp.

From the legal point of view, however, matters of degree are not recognized in Arizona. Concepts such as "gaining streams," "losing streams," or "cones of depression" are irrelevant as far as the law in concerned. Water in Arizona is legally either groundwater or surface water or effluent - there are no other categories.

**States with Unified Management Systems**

There are six states which have one water code for all types of water: Alaska, Colorado, Kansas, Montana, North Dakota, and Utah. In Colorado, for example, this is made clear as follows:

> "It is the policy of this state to integrate the appropriation, use and administration of underground water tributary to a stream with the use of the surface water in such a way as to maximize the beneficial use of all of the waters of this state."[5]

In these states, a well drilling or well deepening application would be reviewed for its impact on prior surface water appropriations. Similarly, a surface water application would be reviewed for any impacts it might have on groundwater pumpers. It is frequently possible for a person with a permit for surface water to trade that for a permit for groundwater if it is determined that basically the same water is involved, even if he wouldn't have been allowed to dig a new well otherwise.

**States with Separate but Related Systems**

Another five states: Idaho, Oregon, South Dakota, Washington, and Wyoming have separate water codes, but have explicitly stated that water must be managed in an interrelated fashion. The Wyoming law states, for example:

> "Where underground waters and the waters of surface streams are so interconnected as to constitute in fact one source of supply, priorities of rights to the use of all such interconnected water shall be correlated and such single schedule or priorities shall relate to the whole common water supply."[6]

In these states, a primary task is making a determination about whether specific ground and surface waters are in fact interconnected, usually on a scientific basis. Again, it is frequently possible for surface and groundwater rights to be interchangeable by a permittee. Applications are reviewed for their impact on all types of water in the area.

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[5] Colo. Rev. Stat. $ 37-92-102(1)(a)(Supp. 1980).

[6] Wyo. Stat. Ann $41-3-916 (1977).

| STATE | G.W. SYSTEM | PERMIT SW | PERMIT GW | SPECIAL DISTRICTS[1] | UNIFIED CODE | CONJ. SYSTEM |
|---|---|---|---|---|---|---|
| Alaska | A | Y | Y | N | Y | N |
| Arizona | A | Y | Y | Y | N | N |
| California | A/R/P | Y | N | Y[3] | N | N |
| Colorado | A | [2] | Y | N | Y | N |
| Idaho | A | Y | Y | Y | N | Y |
| Kansas | A | Y | Y | N | Y | N |
| Montana | A | Y | Y | N | Y | N |
| Nebraska | A | Y | N | N | N | N |
| Nevada | A | Y | Y | N | N | Y |
| New Mexico | A | Y | Y | Y | N | Y |
| North Dakota | A | Y | Y | N | Y | N |
| Oklahoma | A | Y | Y | N | N | N |
| Oregon | A | Y | Y | N | N | Y |
| South Dakota | A | Y | Y | N | N | Y |
| Texas | A | Y | N | N | N | N |
| Utah | A | Y | Y | N | Y | N |
| Washington | A | Y | Y | N | N | Y |
| Wyoming | A | Y | Y | N | N | Y |

A - Appropriation Doctrine
R - Riparian Doctrine
P - Pueblo Rights
1 - This column lists states where different rules apply to special districts within the state. Usually these rules are stricter within districts that have special water problems.
2 - California has a unique water district approach in which conjunctive management may play a role
3 - Colorado has a unique system of adjudication of all rights, rather than permits.

**Figure 1**
**Summary of Western States Water Laws**

### States with Court-based Systems

In New Mexico and Nevada, states with statutes which did not explicitly interrelate the two types of water, court decisions have led to treating both types of water in a conjunctive fashion. The situation in New Mexico is of special interest. Here several lawsuits clarified the Court's position that water should be managed in one integrated system. A person with surface water rights sought a well permit when his surface water rights diminished because of nearby groundwater pumping. Other pumpers objected to a new groundwater permit in the area. The Court ruled that the water came from the same source so that the pumping permit was the same as the surface water permit and had the same priority date.

In another New Mexico case, the landmark case from that state, the City of Albuquerque attempted to stop the State Engineer (Reynolds) from denying it permits to drill wells. The court ruled, among other things, that the State Engineer could indeed prohibit

> "a prior appropriator from obstructing or taking waters from an underground source which would otherwise reach stream and which are necessary to serve stream appropriators' prior right. ...The jurisdiction and duties of state engineer with reference to steams and underground waters are the same; they each relate to public waters subject to use by prior appropriation....while Legislature has provided somewhat different administrative procedure whereby appropriators' rights may be secured from the two sources, the substantive rights, when obtained are identical."[7]

While Nevada theoretically considers groundwater and surface water as related in the law, in Milt Thompson's case cited above, the State argues that since surface water rights have never been adjudicated, the State cannot limit pumping to protect those unadjudicated rights.

### States Without Coordinated Management, except for Special Situations

The remaining five western states: Arizona, California, Nebraska, Oklahoma, and Texas treat ground and surface water very differently, except for water underground, but in definite underground channels (as defined above). Neither California nor Texas even has significant controls on pumping of groundwater - no permits are needed, although they do regulate appropriation of surface water. California's approach is quite unusual. While there is no statewide legislation for conjunctive management of groundwater and surface water, water districts have been established in some parts of the state which do

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[7] City of Albuquerque v. Reynolds. Supreme Court of New Mexico. Dec. 14, 1962.

have a mandate to manage conjunctively. As each district is tailored to the needs of its area, the complexities are beyond the scope of this paper.[8]

Oklahoma deals with interconnected water only if groundwater pumping affects surface water quality. Nebraska recognizes an interconnection only through an interstate water compact.

Arizona has controls over groundwater pumping in Active Management Areas, but not elsewhere, for the most part, but these controls only impact groundwater users. Actually, Arizona's groundwater law can even be interpreted as encouraging pumping at the expense of surface water supplies. Arizona requires proof, for example, that a developer has a 100-year supply of water. A high water table is most likely to exist in good recharge areas - e.g. near streambeds. Outside of AMAs, someone whose surface rights are inadequate is free to pump whatever he wants near the stream, no matter what effect that may have on streamflow or prior water rights.

**How Western States Manage Ground/Surface Water Interconnections**

In some states, a well driller must demonstrate that his new well will **not** impact other users (including surface water rights holders). In other states, the burden of proof is on the state to demonstrate that the new well **will** impact other users. These are very different approaches. In other words, some states assume that ground and surface water are interconnected and the well driller must prove otherwise in a specific situation. Other states make no such assumption. It may be the state's responsibility to make this determination. Arizona appears to be headed in this latter direction, with its current legislation directing ADWR to study interrelationships between ground and surface water.

Another difference between states is how they deal with an interconnected situation. They can deny a new or deeper well permit altogether, or put conditions such as those in New Mexico, where a well drilling permit can be granted in the Rio Grande Underground Water Basin if the driller retires corresponding surface water rights in the Rio Grande River. Another approach is to work out an agreement to the benefit of both parties. Here, the question becomes, "who pays?" Let's return to the example of the developer who wants to drill a well that would impact the farmer. One alternative is for the farmer to drill his own well, when he no longer has sufficient surface water. In New Mexico, if a permit were granted outside the Rio Grande Basin, the farmer and the developer would each have to pay for his own well, while in Colorado, if the developer were allowed to drill a well, he might have to pay for both his well and the farmer's. In this instance, it is

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[8] William Bloomquist. 1992. Dividing the Waters: Governing Groundwater in Southern California. International Center for Self Government. 413 pp.

assumed that the senior rights holder's needs are paramount and if the well driller wants to get the benefits from drilling a well, he should pay for both his and the injured party's new well.

In Arizona, within an AMA, the farmer may be severely constrained in digging his own well, under the well spacing rules, if the developer got there first. He would certainly have to pay for that well himself. Outside of an AMA, however, the farmer can drill as much as he wants, as can the developer, no matter what happens to the stream and downstream users, and each pays his own costs. Here the market prevails and whoever can afford the deeper well will probably win.

**A 1993 Arizona Supreme Court Decision**

On July 27, 1993 the Arizona Supreme Court handed down a major decision which gives prior water rights holders even less control over pumping than they had before.[9] Before this time the "Bright Line" concept applied, as a result of a 1988 court ruling. Under this ruling, a surface water permittee could enjoin a pumper under certain conditions where changes in the water level were demonstrable over a very short period of time. Now, he has no recourse unless the water is withdrawn basically from underneath the stream or from its immediate banks. Water flowing underground directly toward a stream perpendicular to it is not covered.

This new ruling came about as a consequence of the General Adjudication of the Gila River. Several parties asked the Court to make a preliminary ruling not to consider wells in the adjudication. Other parties intervened, some claiming the 1988 ruling was too broad and others that it was too narrow. In making this 1993 decision, the Court bolstered its case by quoting *The Law of Irrigation and Water Rights*, by Clesson Kinney, which was published in 1912 and formed the basis for a previous Court decision, the Southwest Cotton decision, now more than 60 years old.

The Court ruled that the Bright Line Rule was too broad, leaving the situation where it was before 1988. While it questioned the validity of the previous concepts, the Court stated that it was too late for the Court to undo a 60 year old decision, whether or not it was based on outdated science. Underground water outside the immediate stream and its banks is not considered surface water and thus will not be part of the overall Gila River adjudication. The Court expressed doubts about the wisdom of legislators in not updating the law. As the court stated:

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[9] In the Supreme Court of the State of Arizona. Interlocutory Review, Issue No. 2. In re the general adjudication of all rights to use water in the Gila River System and source. Opinion. July 27, 1993.

"...This bifurcated system of water rights was not unique to Arizona. It was typical of western states until around the turn of the twentieth century. At that time, scientific investigation was revealing that most underground water is hydraulically connected to surface water. As scientific knowledge progressed, most states revised their water laws to provide for unitary management of hydraulically connected underground and surface water. Arizona, however, did not, and continues to adhere to a bifurcated system of water rights, with compelling implications for general stream adjudications."[10]

**Some Thoughts for Arizona**

Following the July 27 Court decision in Arizona, anyone who wants to protect surface water rights or streamflow from groundwater pumping has little recourse. The Court made clear that it felt this was an untenable situation, but one which it was powerless to redress. It expressed hope that the Legislature would attempt to deal with this problem.

"We recognize compelling arguments in favor of unified management of Arizona's water resources. Nonetheless, in the decades since Southwest Cotton was decided, the Arizona Legislature has not significantly altered the opinion's reach.... Regulation of water use,... especially in a desert state, does not lend itself to case-by-case definition. In this field, we not only confer private rights and interests, but deal in the very survival of our society and its economy. Simply put, there is not enough water to go around. All must compromise and some must sacrifice. Definition of those boundaries is peculiarly a function for the legislature. It is plainly not a judicial task..."[11]

1994-95 is the ideal time to be doing just that, as the results of studies by ADWR and the Governor's Riparian Advisory Committee are available. Arizona could benefit from looking at how other states treat ground/surface water conflicts. There are eleven different models which Arizona could adopt with or without modification. These are described in more detail in my forthcoming paper, which will be available this winter from the Water Center.

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[10] ibid. Supreme Court of Arizona

[11] ibid Supreme Court of Arizona

As noted legal scholar, Frank Trelease, has noted,

"Where one party has a right to withdraw water from one phase of the cycle and this will affect the availability of water to another person with rights in another phase, the rights must be coordinated by the same law, and the superior right preferred or protected."[12]

This goes along with the prevailing Western tradition of protecting existing water rights and makes a lot of sense. A not insignificant byproduct can also be protection of the public good by leaving water in some of the few free-flowing streams left in this state.

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[12] Trelease, Frank. Conjunctive Use of Groundwater and Surface Water. Rocky Mountain Mineral Law Institute. Vol. 22. 1982. pp. 1853-1894.

# A PROPOSED NEW TYPE OF WATER MANAGEMENT AREA

**By Hugh A. Holub[1]**

**ABSTRACT:** A new type of water management area is proposed, called Basin Management Areas, to address the problem of integrated water resource management.

**INTRODUCTION:** The proposal for Basin Management Areas draws heavily on the current draft of the Model State Water Rights Code being prepared by a task force of the American Society of Civil Engineers (ASCE). I am an advisor to that task force.

The proposed Basin Management Area additions to state water law are offered to spark discussion and are not intended to be the last word in concept or language.

## BASIN MANAGEMENT AREA PROPOSAL:

### Purposes For Basin Management Area

(1) A Basin Management Area may be designated in regions when and where specific water resource problems requiring special attention already exist or are expected to arise.

(2) A Basin Management Area may be used to address such specific water management problems as:

(A) protecting water resources from depletion and contamination for all authorized consumptive and non-consumptive uses;

(B) protecting instream flows and existing surface water rights;

(C) integrated management of total regional water resources, including but not limited to surface water, groundwater, effluent and return flows;

(D) allowing for conflict resolution between all forms of water use, including but not limited to existing, proposed, export, and priority uses; and

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[1] Hugh A. Holub is a Tucson attorney whose practice is concentrated in the areas of water and environmental law.

(E) implementing rules to address such specific water management problems.

(3) Rules related to water allocation and protection that apply within a Basin Management Area may differ from water use rules applied elsewhere in the state.

**Studies of Water Resource Problems**

The Department may initiate, on its own or at the request of a city, town, county, or irrigation district, appropriate studies of the nature and extent of a perceived or apparent water resource problem or combination of problems. The Department shall determine whether the water resource problem warrants designation of a Basin Management Area.

**Department of Water Resources Determination**

(1) The Department may, upon recognition or anticipation of a specific water resource problem or combination of problems, initiate appropriate studies to:

(A) determine the exact nature and extent of the water problems (including, if necessary, quantification of the availability of the water resource and the past, present and projected water demand); and

(B) determine whether those problems warrant special regulatory attention through the designation of a Basin Management Area.

(2) Water problems calling for a Department study include but are not limited to water withdrawals in excess of runoff or recharge, excessive withdrawals are likely to occur in the near future, significant disputes regarding rights, amounts, and priority of water uses, threat of contamination or diminishment to an area of recharge or runoff origin, existence or potential for subsidence, existence or potential for contamination of drinking water supplies, degradation of quality and/or quantity of water supplies for non-consumptive uses, groundwater levels or pressures are declining or have declined, and any other indication of a serious threat to the integrity of a regional water resource system.

**Local Determination**

A city, town, county or irrigation district may request that the Arizona Department of Water Resources conduct appropriate studies to determine the need for designation of a Basin Management Area if and when water problems, such as those listed above, are observed, perceived, or anticipated by residents.

**Designation of Basin Management Areas**

(1) Designation of a Basin Management Area shall be made by the Director of the Arizona

Department of Water Resources with provisions for public hearings once the water resource problem or problems have been identified and evaluated by the Department.

(2) Upon the proposal for designation of a Basin Management Area, the Department may temporarily declare the area to be a Basin Management Area and shall issue a temporary order protecting the water resources in the area with any necessary provisions as outlined in this Article. The order shall remain in effect until a public hearing can be conducted as provided for in this Article.

(3) After completing the necessary studies to determine the nature and extent of the water resource problem or combination of problems, and having determined that the problems require the designation of a Basin Management Area, the Department shall declare its intent to designate a Basin Management Area, and on the earliest date possible, conduct at least one public hearing within the area proposed to be designated as a Basin Management Area.

(A) The Department shall publish notice of the hearing, including the purpose of the hearing, the time and place for the hearing, the legal description and a map clearly identifying the boundaries of the Basin Management Area being considered for designation.

(B) The notice of hearing shall be published at least once each week for at least three consecutive weeks in a newspaper of general circulation in the area proposed to be designated as a Basin Management Area, the first publication being at least 30 days prior to such hearing.

(C) The notice of hearing shall be served by mail upon each public agency known from an examination of the records of the appropriate office to be a claimant or appropriator of surface water, or an owner or user of groundwater in the area in question. The notice shall be mailed at least 15 days before the hearing.

(D) At the hearing, the Director shall present the facts which support designation of the Basin Management Area. Any interested person may appear at the hearing and submit evidence in favor of or opposed to the proposed designation.

(4) After the hearing, the Director shall make written findings of fact regarding the designation of the proposed Basin Management Area, and file an order of the intent to designate or not designate the area. An order to designate may contain provisions that may include, but not be limited to:

(A) provisions closing the area to any further appropriations or surface waters, expansion of existing rights to surface waters, or the development of the regional water resources;

(B) provisions determining the permissible total withdrawal of water in a given time period and means to apportion the total among holders of existing rights, both appropriated and

non-appropriated;

(C) provisions to rank beneficial uses in order of preference;

(D) provisions to allow the Department to limit allowable withdrawals in times of shortage or emergency;

(E) provisions relating to the proof of a 100 year assured water supply for new subdivision development within the management area;

(F) provisions regulating the withdrawal and replenishment of groundwater to protect existing in-stream and off-stream beneficial uses;

(G) provisions to dissolve the management area if and when that is appropriate and desirable;

(H) any other provisions as necessary to protect the existing water resource from depletion and contamination, and to ensure the supply for future needs, both in-stream and off-stream.

(5) The findings of fact and the order shall be published, shall take effect upon publication, and when published shall be final unless appealed from. All factual data considered, a transcript of the hearing, and a copy of the findings of fact and of the order shall be a public record and shall be made available for public examination. A copy of the findings and order shall be made accessible for public examination, and be filed at the county recorder's office of every county within which part of the Basin Management Area lies.

**Preparation of a Management Plan**

(1) Based on information on the nature and extent of the water problem or problems gathered during the determination stage, and based on any further pertinent data deemed necessary to collected, the Department shall develop a management plan in conjunction with the water use representatives from within the management area. The plan shall take into consideration the prevailing hydrology, geology, and climate within the management area, as well as the exact nature of the water problem or problems.

(2) An appointed Basin Management Committee of not less than five individuals residing in the designated management area shall be formed to help develop and review the management plan prepared by the Department. The members of the Basin Management Committee shall be appointed by the county board or boards of supervisors within the boundaries of the management area. There shall be at least one member of the Basin Management Committee appointed representing the largest municipal water utility within the management area, one appointed member representing agricultural water users within the management area, one appointed member

representing non-agricultural and non-municipal water users within the management area, one member representing Arizona Corporation Commission regulated private water companies (if there are private water companies in the management area), and one appointed member representing public interest or environmental interests in the management area. The actual number of the members of the Basin Management Committee for each Basin Management Area shall be determined by the Director, taking into account the need to provide adequate representation for all major water use sectors within each management area. Appointed members of the Basin Management Committee shall serve for terms of six (6) years. The duties of the Basin Management Committee shall include reviewing and commenting on the general management goals as stated in the management plan, and on the specific management mechanisms for achieving the goals of the management plan. The county board or boards of supervisors shall reserve the right to appoint new Basin Management Committee members each time the management plan is reviewed or updated.

(3) The Department shall, in conjunction with the appointed Basin Management Committee, determine management goals for the management area, and devise specific regulations or provisions to achieve those goals. The preparation of the management plan shall not exceed one year from the designation of the management area, and the duration of the management plan shall not exceed ten years. Management plans shall be reviewed and updated at least once every ten years. Management plans may include provisions for regulations including, but not limited to such things as:

(i) well spacing requirements
(ii) water use permit requirements
(iii) water use reporting and metering
(iv) water conservation requirements
(v) and any other provisions that are found necessary to achieve the stated goals of the management area, or to prevent water depletion and contamination.

(4) The Department shall provide the Basin Management Committee with opportunities to make both written and verbal comments on the proposed management plan, and, to the extent that it is possible, take the management committee's comments into consideration when preparing the plan. If and when the management committee disagree on the management plan's contents, the Department shall have the authority to make the final determination.

**Implementation of a Management Plan**

(1) The provisions of the management plan shall be implemented (i) directly by the Department, or (ii) by the management committee. In either case, there shall be specific provisions for resolution of conflict among water users within the management area.

(2) The Department shall directly oversee all provisions specified in the management plan, including such things as conducting any necessary ongoing hydrologic studies, maintaining current data on water supply and demand within the management area, reviewing all applications for water

use and withdrawal, and any other administrative, scientific, and planning studies related to the operation of the management area.

(3) The management committee shall oversee all provisions specified in the management plan, including the duties listed in this Article.

**Conflict Resolution**

(1) All Basin Management Area management plans shall contain specific provisions for the resolution of conflict among water users within the boundaries of the management area.

(2) Any person may bring an action in the superior court of the county in which a groundwater well or surface water withdrawal facility is situated for damages or for injunctive relief with respect to any alleged impairment of existing water rights, both surface water and groundwater. When such suit has been filed, the court shall order the joinder of the Department as a party upon motion of any party. If the Department is joined, the court shall defer to the department to present factual evidence bearing on the issues of the case which is reasonably available to it.

(A) Administrative Review: Upon petition by any person who is adversely affected by an action of the Department, or upon the Department's own initiative, the Department may review any action or failure to act by its own office, pursuant to the Arizona Administrative Procedure Act (ARS 41-1001 et. seq.)

(B) Judicial Review: Any person who is adversely affected by a final determination or a final order of the Department under the provisions of this Article may appeal to the superior court of the county in which the majority of the management area is located, pursuant to the provisions of the Administrative Procedure Act. The record for purposes of review shall consist of the record of the proceedings in the designation hearing and in the administrative review, together with all records and files containing data relied upon in making the final determination or order appealed from.

**Funding**

Basin Management Areas shall obtain funding for all activities related to water resource planning and management, costs associated with administration of the management area, and any other reasonable costs associated with operation of the Basin Management Area. Funding sources may include, but are not limited to, general state revenues, special pumping taxes not to exceed $2.00 per acre foot per annum, application/registration fees, water use fees not to exceed $2.00 per acre foot for each acre foot of surface water uses per annum or ten cents per 1,000 gallons of water provided by a city, town or private water company to its customers, and any combination of the above mentioned.

The Basin Management Committee shall make recommendations to the Director for the sources of funding, and the amounts thereof, to be derived from special pumping taxes and water use fees to be levied within the management area. The Director shall make the final determination of the amounts of such special pumping taxes and water use fees to be levied and collected within the management area.

**Basin Management Area Within Existing Active Management Area**

A Basin Management Area may be designated by the Director within in any existing Active Management Area for a sub-basin within that Active Management Area, if any two of the following applies:

(1) The sub-basin proposed to be designated has been found to have a significant hydrologic connection between surface water and groundwater that requires a sub-basin specific management plan to preserve natural stream flows or existing surface water rights and uses; or

(2) The water resources of sub-basin proposed to be designated is influenced by surface waters and groundwaters originating from water sources in another state or foreign country or by water uses in an other state or foreign country, and an agreement has been entered into between the state and the other state, or the United States and the foreign country, for management of the sub-basin in conjunction with that other state or foreign country; or

(3) The mayors and councils of all cities and towns and the boards of supervisors of any county located wholly or in part in the proposed Basin Management Area pass resolutions requesting the Director to designate the Basin Management Area. The resolutions shall specify the area to be designated within the existing Active Management Area as a Basin Management Area.

**Provisions Applicable to Basin Management Area Within an Existing Active Management Area**

The following provisions shall be applicable to any Basin Management Area designated within an existing Active Management Area:

(1) For purposes of the existing Active Management Area, the Basin Management Area designated within that Active Management Area shall be deemed to remain a part of that Active Management Area and shall have the same management plan goal as the Active Management Area. The management plans for that Active Management Area shall include the management plans for the Basin Management Area.

(2) At least one member of the Groundwater Users Advisory Council for the Active Management Area shall be appointed from among the members of the Basin Management Committee.

(3) Upon designation of a Basin Management Area within an existing Active Management Area no Type 2 Grandfathered Groundwater Right shall be transferred from within the Basin Management Area to any area in the Active Management Area outside the Basin Management Area, or from outside the Basin Management Area to the Basin Management Area. All other grandfathered groundwater use rights established in the Active Management Area shall not be modified or abrogated by designation of the Basin Management Area.

(4) Upon designation of a Basin Management Area within an existing Active Management Area the amount of renewable groundwater, from both natural and artificial recharge, shall be credited to the Basin Management Area for purposes of the management plans for both the Active Management Area and the Basin Management Area.

(5) All groundwater withdrawal fees, augmentation fees, conservation assistance fees, pump taxes, water use charges and other fees charged and collected by the Department from water withdrawals or uses within the Basin Management Area shall be used exclusively for the benefit of that Basin Management Area.

## PROVISIONS APPLICABLE SOLELY WITHIN BASIN MANAGEMENT AREAS

The following provisions shall only be applicable in any area which has been designated as a Basin Management Area.

## GROUNDWATER CLASSIFICATION AND REGULATION

### Definitions:

"Tributary Groundwater" shall mean that groundwater which is tributary to, and physically connected to the surface water stream system and shall mean the same as "underflow", where withdrawal and use of this groundwater depletes the surface stream in the same manner as a surface diversion.

"Non-tributary groundwater" shall mean that groundwater, which if withdrawn, will not, within a period of 100 years, deplete the flow of the stream at an annual rate greater than one-tenth of 1 percent of the annual rate of withdrawal from the well being pumped, and shall means the same as "percolating groundwater".

### Applicable Law:

Tributary groundwater shall be subject to the surface water laws of this state.

Non-tributary groundwater shall be subject to the groundwater laws of this state.

No new tributary groundwater use right, as expressed by a permit to appropriate, shall be

permitted in a Basin Management Area, expect upon a showing, by a preponderance of the evidence by the applicant, that such new tributary groundwater use will not adversely affect existing surface water rights and uses in the management area.

**DEFINITIONS:**

"Basin Management Area" means a hydrogeographically defined area of the state for which the Department has determined that the level or supply of the waters of the state are potentially inadequate to meet the requirements of both instream and offstream beneficial and reasonable uses.

"Beneficial Use" means the application of water to any useful or productive purpose, including agricultural, commercial, domestic, ecological, industrial, livestock, municipal, power generation, and recreation uses.

"Beneficial and Reasonable Use" means a use that is both beneficial and reasonable as defined in this Article. Determination of whether a use is beneficial and reasonable requires consideration of the interests of off-stream water uses, instream uses, and the broader interests of society.

Factors to be considered in a determination of beneficial and reasonable use include, but are not limited to:

(A) the supply potential of the water source in question, considering quantity, quality and reliability;

(B) the nature and size of the water use in question and of other water uses sharing the source of supply;

(C) the economic and social importance of the water use in question and other water uses sharing the source of supply;

(D) the impact of the use in question on other off-stream and instream water uses; and

(E) the effects of the use in question on any other significant aspect of public interest, including effects on the environment.

"Conservation" refers to any measures adopted by a water right owner to reduce the pumping, diversion or consumptive use, or all of the aforementioned, of water associated with the exercise of a water right,including, but not limited to, improvements in water transmission and water use efficiency, reduction in water use, enhancement of return flows, and reuse of return flows.

"Consumptive Use" is any use of water which is not a "non-consumptive use" as defined in this Article, including, without being limited to, evaporation or the incorporation of the water into a product or crop.

"Duty of Water" means the maximum annual quantity of water reasonably required for a certain beneficial and reasonable use. The duty of water for irrigation shall be calculated as the maximum quantity of water reasonably required to irrigate crops typically grown in the management area using reasonable conservation methods for the application and use of the water. The duty of water for municipal use shall be calculated as the maximum quantity of water reasonably required for a given particular municipal system using reasonable conservation methods to limit water usage and to minimize water losses.

"Municipal Use" means uses of water by a publicly or privately-owned public water supply system for the life, safety, health, comfort, and nonindustrial business needs of the inhabitants or customers thereof.

"Non-consumptive Use" means a use of water in such a manner that it is returned to its waters of its origin at or near its point of origin without substantial diminution in quantity or quality and without resulting in or exacerbating a low flow condition.

"Waters of the State" include all waters, on the surface or under the ground wholly within or bordering the state or otherwise within the jurisdiction of the state.

"Water Source" includes any lake, pond, river, stream, creek, arroyo, wash, or other water flowing or lying on the surface or contained within an aquifer regardless of the quantity or duration.

" Water Withdrawal Permit" means a document issued by the Department evidencing the right to withdraw the waters of the state from their waters of origin.

## WATER USE PERMITS

### Permit Required

There is no right, power, privilege or interest in the use of waters of the state located within a Basin Management Area for which no valid permit has been issued under this Article or in violation of the terms, conditions or limitations of such a permit.

### Appropriation Rights

Any right to appropriate surface water granted prior to the designation of a Basin Management Area shall be deemed a permit for the use of water under this Article.

## Groundwater Rights

All groundwater uses in existence prior to the designation of the Basin Management Area shall be granted a Groundwater Withdrawal Permit for an annual amount of groundwater withdrawal equal to the highest annual actual withdrawal of groundwater during the five proceeding years before designation. All Groundwater Withdrawal Permits shall be subject to the provisions of the adopted management plan for the Basin Management Area.

In a Basin Management Area designated within an existing Active Management Area, Groundwater Withdrawal Permits shall mean and include Irrigation Grandfathered Groundwater Rights, Type 1 Non-irrigation Grandfathered Groundwater Rights, Type 2 Non-irrigation Grandfathered Groundwater Rights, Industrial Use Permits, Service Area Rights to the withdrawal of groundwater, and all other groundwater withdrawal and use rights then in existence prior to the designation.

## New Surface Water Appropriations and Groundwater Withdrawal Permits

From and thereafter the date of designation of a Basin Management Area, all surface water appropriations and groundwater withdrawal permits shall be subject to the provisions of the management plan for that Basin Management Area.

## ACQUISITION OF WATER RIGHTS

(1) The Department may acquire by grant, purchase, bequest, lease, exchange or other voluntary contractual agreement, from or with any person, such water, water rights or interests in water as it determines may be required for minimum stream flows to preserve the natural environment to a reasonable degree. At the request of any person, the Department shall determine in a timely manner what terms and conditions it will accept in a contract or agreement for the acquisition by it from such person of water, water rights,or interests in water to be held by the Department for minimum stream flows to preserve the natural environment to a reasonable degree. The Department may initiate applications for transfer of water rights it has acquired to change the use of said right to achieve the minimum stream flows to preserve the natural environment to a reasonable degree.

(2) No funds derived from any pump tax or water use fee levied and collected by the Department shall be used for the acquisition of water rights for any purpose.

(3) The Department, and any other agency of the state, shall not have the power of condemnation or eminent domain to acquire any water right for the purpose of maintaining minimum stream flows to preserve the natural environment.

(4) In determining whether to acquire water rights under this section, or in determining to initiate any application, the Department shall request recommendations from state and federal

natural resource agencies.

## INSTREAM RIGHTS

(1) No person or entity, other than the State of Arizona, shall be granted a right to water or interests for instream flows in a stream channel between specific points, for any purpose whatsoever.

(2) An appropriation for minimum stream flows shall be subject to the following principles and limitations:

(A) Any such appropriation shall be subject to the present uses and exchanges of water being made by other water users pursuant to appropriations of surface water, groundwater withdrawals, and practices in existence on the date of the appropriation.

(B) Before applying for an instream flow water right, the Department shall determine that the natural environment will be preserved to a reasonable degree by the water available for appropriation to be made; and that there is a natural environment that can be preserved to a reasonable degree with the Department's water right.

(C) All recommendations, including those of the United States, which are transmitted to the Department for water to be retained in streams to preserve the natural environment to a reasonable degree must be made with specificity and in writing.

(D) Applications filed by the Department, including applications for allocation or transfer of water rights shall comply with applicable state law. The date of appropriation shall be the date of filing.

## SCOPE OF WATER RIGHTS

### Permissible Quantity of Use

(1) The scope of a water right as measured by the volume or rate of flow is limited to its application to beneficial and reasonable use.

(2) No allocation or transfer of water, either absolute or conditional, shall occur when the proposed allocation or transfer is based upon the speculative transfer of rights to persons not parties to the proposed allocation or transfer, as evidenced by either of the following:

(A) The applicant does not have either a legally vested interest or a reasonable expectation of procuring such interest in the lands or facilities to be served by such allocation or transfer, unless such applicant is a governmental agency or agent in fact for the persons to be benefitted by such allocation or transfer;

(B) The applicant does not have a specific plan and intent to divert, store or otherwise capture, possess and control a specific quantity of water for specific beneficial and reasonable uses.

(3) Beneficial and reasonable use shall be the measure for the amount of a water right but in no event shall this quantity exceed the amount allocated for the right. Any approval of a transfer of water right shall limit future uses of a transfer right to an amount no more than was previously applied to beneficial and reasonable use.

(4) Beneficial and reasonable use shall not exceed the duty of water established by the Department for the particular type and location of use unless the permittee can demonstrate that application of water in excess of said duty is reasonable to achieve a certain beneficial and reasonable use. The Department shall establish and review every ten years the duty of water for uses which reasonably can be quantified.

(5) The Department shall periodically review the use of all water rights at a minimum of every ten years, and shall issue findings of total or partial reversion of water rights where appropriate.

(6) The Department shall issue to owners or users of water rights such orders as are necessary for the total or partial discontinuance of any pumping, diversion or storage to the extent that the water being pumped, diverted or stored either:

(A) is not necessary for application for beneficial and reasonable use;

(B) exceeds the legal limits of the water right being pumped or diverted; or

(C) is required by persons entitled to use water under water rights having senior priorities.

(7) The Department has the authority to order any owner or user of a water right in a Basin Management Area to install and maintain, at such owner's or user's expense, necessary meters, gauges or other measuring devices and to report readings of such meters, gauges or other measuring devices. The Department has the authority and duty to enter upon and to order any person to permit entry upon private property at any reasonable time to inspect the various means or proposed means of diversion, withdrawal, transportation, and storage and the uses to which water is being, or is proposed to be, put and to read meters, gauges and other measuring devices.

## WATER CONSERVATION

### Right To Water Developed by Conservation

(1) A permittee is entitled to develop additional water through application of conservation

practices to existing beneficial and reasonable uses of a water right, providing existing water rights are not injured. The burden of proof of non-injury to other water rights rests with the applicant. Development of water by conservation shall be considered transfer of a water right, and is subject to all applicable statutory limitations thereof.

(2) The applicant shall quantify the amount and timing of water developed by conservation based on comparison of water use prior to, and following commencement of the conservation practices, with consideration for natural variations in the use and occurrence of water. This quantification shall be based, to the extent practicable, on actual measurements of water use. If actual measurements are not available, water use estimates shall be prepared using sound engineering principles.

(3) The allocation date for water developed by conservation practices shall be the same as the allocation date of the original water right.

(4) Water may not be developed by application of conservation practices to water rights whose uses are wasteful, or to water rights that are subject to reversion.

Use of Water Developed By Conservation

(1) Water developed by conservation practices must be used in a beneficial and reasonable manner. The type(s) of use for water developed by conservation must be specified as part of the water rights transfer application.

(2) Use of water developed by conservation practices must not cause injury to existing water rights.

(3) Use of water developed by conservation shall require approval by the Department including, but not limited to, sufficient water accounting procedures to reasonably demonstrate non-injury to existing water rights.

Transfer of Water Developed by Conservation

Water developed by conservation may be transferred, exchanged, sold, or leased to other users and/or changed in place and type of use provided existing water rights are not injured.

## REVERSION OF SURFACE WATER RIGHTS--EXEMPTION FOR FUTURE MUNICIPAL WATER NEEDS

In a Basin Management Area, the following shall be considered sufficient cause for exemption from the beneficial use requirement of ARS 45-141, and shall not be included as part of the five year period for reversion of a water right for non-use:

(1) where surface water rights are held by any municipality, county domestic water improvement district, private water company, or a public agency, to meet the reasonable future requirements for municipal water demands; or

(2) when non-use is due to underground storage of water for future application to municipal use.

## EFFLUENT

Any city, town or private water company which withdraws non-tributary groundwater pursuant to a right or permit within a Basin Management Area, and which is required to prove a 100 year assured water supply pursuant to an adopted management plan or provisions of this Code, shall be credited 100% of the annual quantity of effluent discharged to a river, stream or water course within the Basin Management Area against its annual withdrawals of non-tributary groundwater. The amount of non-tributary groundwater that has been returned to the river, stream or water course within the Basin Management Area as effluent shall be deemed a renewable source of water.

# IMPLEMENTATION OF ARIZONA'S NONPOINT SOURCE PROGRAM[1]

Kris Randall and Dan Salzler[2]

**ABSTRACT:** Nonpoint source pollution has been recognized as the primary cause of the nation's water quality problems. The 1986 Environmental Quality Act for Arizona established the Arizona Department of Environmental Quality and the Nonpoint Source Program (NPS). The goal for NPS management is "to increase effectiveness, efficiency, and public acceptance of the regulation of NPS water pollution." ADEQ's NPS program has gained national recognition in it's method of implementation and the results achieved so far to date. Four projects that are currently being implemented by ADEQ will be described. The projects are: 1) Best Management Practices for Regulated Agricultural Activities, 2) Riparian Area protection, 3) Oak Creek watershed project, and 4) Nonpoint Source Management Zones.

## INTRODUCTION

One critical water resource issue confronting not only Arizona but the entire United States is the issue of water quality. Nonpoint source pollution contributes over 65% of the total pollution load to US inland surface waters (USEPA, 1989). In a report on water pollution prepared by the U. S. General Accounting Office (1992), "ecological risks posed by nonpoint source pollution are substantially more serious than those posed by pollution from point sources, and the health risks are roughly comparable." The 1992 Water Quality Assessment for Arizona showed that of the 4,461 stream miles assessed, 75% have impairment to designated uses. The combination of turbidity, suspended solids, and siltation are the principal causes of stream impairment.

The approach to water quality issues in the past have often taken a "point source" approach through engineered techniques and regulations. Innovative approaches have been taken by the Arizona Department of Environmental Quality's Nonpoint Source Unit to deal with nonpoint source water quality problems. The methods used for implementation involve the public to a great extent. Four projects that are currently being implemented by the

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[1]Paper presented at the Sixth Annual Symposium of the Arizona Hydrological Society, Casa Grande, Arizona, September 23-24, 1993.

[2]Kris Randall is the Riparian/Wetland Coordinator, Nonpoint Source Unit of the Arizona Department of Environmental Quality, Phoenix, AZ. Dan Salzler is the Coordinator for the Oak Creek Watershed Project, Nonpoint Source Unit of the Arizona Department of Environmental Quality, Phoenix, AZ.

Nonpoint Source Unit are: 1) Best Management Practices for Regulated Agricultural Activities, 2) Riparian Area protection, 3) Oak Creek watershed project, and 4) Nonpoint Source Management Zones. Each of these projects will be discussed.

The goal of the Clean Water Act (CWA) is to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters." In 1972, the CWA addressed point sources as the principle contributors of pollution to the nation's waters. Point source discharges to the Nation's waters were defined as those impacts which generally come out of the end of a pipe or ditch. In 1987, the CWA was amended to recognize Nonpoint Source (NPS) pollution. NPS pollution as the name implies is anything that is not a point source or any impact to waters which do not come out of the end of a pipe.

## BEST MANAGEMENT PRACTICES FOR REGULATED AGRICULTURAL ACTIVITIES

In 1986, the Arizona State Legislature recognized water pollution as a major problem in Arizona and responded by passing the Environmental Quality Act (EQA). The EQA established the Arizona Department of Environmental Quality (ADEQ) and designated the agency for all purposes of the Clean Water Act (CWA) in Arizona. The EQA also mandated that a program to control Nonpoint Source discharges be adopted by rule (ARS §49-203).

The Arizona Nonpoint Source Water Quality Management Plan, as adopted by Arizona and approved by the Environmental Protection Agency, was developed on a category by category basis (ARS §49-241 and -246). Ten NPS categories were defined and are as follows: (1) Agriculture (i.e., application of Nitrogen fertilizers, aquaculture, grazing, concentrated feeding operations), (2) Silviculture (i.e., forestry, forest road construction), (3) Construction (i.e., highway and bridge construction, land development and military operations), (4) Urban Runoff (impacts from urban area surface runoff which are not NPDES discharges [National Pollution Discharge Elimination System]), (5) Resource Extraction (i.e., mining, sand and gravel operations), (6) Land Disposal (i.e., sludge, wastewater reuse, landfills and septic systems), (7) Hydrologic/Habitat Modification (i.e., channelization, dredging, streambank modification, flow regulation), (8) Other (i.e., natural occurrences such as sediment transport, highway maintenance and runoff, spills and storage tank leaks), (9) Unknown (this category are for those activities whose source is unknown), and (10) Recreation (i.e., swimming, fishing).

The Arizona State Legislature mandated that the Department (ADEQ) develop regulatory programs to address nonpoint source pollution. The Arizona NPS Water Quality Management Program defines the program as being implemented through the programmatic components of planning, implementation by rule and by other means, and compliance activities.

One NPS category, Regulated Agricultural Activities as defined in ARS §49-201 is the application of nitrogen fertilizers and concentrated animal feeding operations (referred to as CAFOs). These activities are regulated through a general permit, issued to all owner/operators, which requires that Best Management Practices (BMPs) be implemented. Failure to implement BMPs could result in the loss of an operator's general permit. The operator who loses their general permit must apply for an individual permit, because all discharging activities must have an Aquifer Protection Permit (APP). The application process for an individual APP may require up to a year to acquire and may be quite expensive.

The Best Management Practices for Regulated Agriculture were developed by a governor-appointed Technical Advisory Committee comprised of producers and people with particular expertise. The BMPs are vested in rule, and are broad, goal-oriented statements that are applied statewide. Through the support of partnerships between agencies and private owner/operators the General Permit for Regulated Agricultural Activities has become a program based in education and voluntary compliance.

An example of one BMP for Concentrated Animal Feeding Operations is given in Table 1. Each BMP is supported by guidance practices. Unlike the BMPs, the guidance practices are not in rule and can be updated as technology improves. If it was determined that a change to the BMPs was needed, the change would require that the rule-making process be followed. This process can take anywhere from one to two years. The guidance practice manual is therefore a "living document" since it can be changed as the technology changes.

Table 1. Example of BMP in Rule

| **Concentrated Animal Feeding Operations**<br>(A.G. Rule No. R90-001) |
|---|
| 1. Harvest, stockpile and dispose of animal manure from concentrated animal feeding operations to minimize discharge of nitrogen pollutants by leaching and runoff. |

Arizona is the first and only state to have BMPs vested in rule. Many states are using Arizona as a model to develop their BMP programs. The key to Arizona's success has been to define BMPs as goal statements and not technological practices. Best Management Practices are defined in the EQA as:

> "those methods, measures or practices to prevent or reduce discharges and includes structural and nonstructural controls and operation and maintenance procedures. Best management practices may be applied before, during and after discharges to reduce

or eliminate the introduction of pollutants into receiving waters. Economic, institutional and technical factors shall be considered in developing the best management practices." (ARS 49-201)

Since BMPs are required to be implemented on a statewide basis, flexibility is essential to conform with facility variability. Using goal oriented BMPs suggested by site specific guidance practices achieves this flexibility. Technology is always changing and ways to control and limit nonpoint source pollution is constantly being updated. If BMP programs are vested in rule they must be flexible to be effective.

## RIPARIAN AREA PROTECTION

The NPS Program in Arizona is also developing BMPs for other categories of nonpoint source pollution. Regulating these activities will also be developed around the general permit concept. Since most Nonpoint Source categories have some impact to riparian areas, the BMPs for riparian areas will be developed for those activities which occur in these sensitive ecosystems. These BMPs will be incorporated into the particular management programs for the defined categories. In this respect, riparian area BMPs will be a component of the agriculture, the silviculture, and resource extraction programs.

Recommendations for riparian area protection are being developed through the Riparian Area Advisory Committee (RAAC). This committee was established by legislation passed in 1992. Included in the Riparian Area Protection Act is a directive given to three state agencies to prepare reports on various aspects of riparian areas. The Arizona Department of Environmental Quality will evaluate 12 activities that involve removing or depositing material, removing vegetation or otherwise obstructing, altering or destroying riparian areas. The Arizona Game and Fish Department is mapping, inventorying and classifying riparian areas on perennial streams. The Arizona Department of Water Resources is evaluating the effects of surface water diversions and groundwater pumping on riparian areas. These three reports will be utilized by the 34 member governor-appointed Riparian Area Advisory Committee in its development of recommendations for riparian area protection. These recommendations will be given in the form of a final report to be submitted to the governor and the legislature by December 1994. The RAAC meetings are public and if you would like to be notified of the upcoming meetings give me your name and I will include you on the mailing list.

The legislation that formed the RAAC did not provide for public involvement except through attendance of public meetings. A neutral facilitator has been contracted to assist the RAAC in developing consensus on the recommendations for a riparian area protection program. During the fall of 1993, the RAAC will hold open houses in five areas of the state to get public input on riparian issues. This should assist the consensus-building process.

## OAK CREEK WATERSHED PROJECT

This concept of consensus-building has been integral to the Oak Creek watershed project. Oak Creek Canyon is a unique place in Arizona. The surrounding Red Rocks of Sedona and the clean, cool waters of Oak Creek attract tourists from around the world and from all around Arizona. Approximately 300,000 people swim in the Slide Rock area and in the cool waters downstream, in the Grasshopper Point area. In addition, Oak Creek is home to campers, people who come to fish the cool waters and those who come to enjoy the natural beauty of the red rocks.

As an attraction to nearly one million visitors per year, Oak Creek, and the areas immediately surrounding the creek have a high potential for nonpoint source pollution contamination. Arizona State Parks, Arizona State Lands, Arizona Fish and Game, Coconino National Forest, the Cattlegrowers Association, Northern Arizona Audubon Society, Keep Sedona Beautiful, Arizona Department of Transportation, USGS, the Oak Creek Canyon Property Owners Association and many other organizations and agencies have special interests in the Canyon area. These interests may often be in contradiction to another organizations or agency's interest.

The concept of consensus-building is vital to the Oak Creek Watershed project. The objectives of this project, funded by the U.S. Environmental Protection Agency through the Clean Water Act Section 319(h) demonstration project, are twofold:

1. To determine the ambient water quality of Oak Creek and its major tributaries, and

2. To determine the effects of select Best Management Practices that have been implemented within the watershed on the water quality of Oak Creek.

Measuring the effectiveness of applied Best Management Practices is a relatively easy task. It does not require consensus, nor cooperation from any member organization, agency or individual within the watershed. Only the application of good science. However, paramount to the success of the project is the development of Best Management Practices (or BMPs) and the acceptance of these practices to the individuals, organizations and agencies that conduct business within the watershed.

To accomplish this aspect of the BMP program requires successful consensus-building efforts that often require years to develop. These individuals who represent the citizens of Oak Creek Canyon watershed and the organizations and agencies that conduct operations within the watershed have come together as an Advisory Committee. This Advisory Committee will assist in the identification of nonpoint source pollution sources as well as the Best Management Practices that will serve to minimize the effects of nonpoint source pollution. Many of the individuals who come to the table to discuss Best Management

Practices have been professionally at-odds for a number of years. Consensus has brought them together to develop a single goal-oriented Work Plan.

The Work Plan that has been prepared for the Oak Creek National Monitoring Plan represents the determined spirit of those individuals within the watershed to correct any natural or human-induced contaminants that may be impairing the water quality of Oak Creek and to preserve and protect the unique waters of Oak Creek.

## NONPOINT SOURCE MANAGEMENT ZONES

Arizona's Nonpoint Source program is very aggressive and involved in statewide nonpoint source issues. Efforts are being made to implement Arizona's the Nonpoint Source Program on a watershed by watershed approach through Nonpoint Source Management Zones. The Management Zones proposed for the state are the Verde, Bullhead City/Lake Havasu City,and the Showlow/Winslow Zones (Figure 1). These Zones will be started as resources become available. Currently one zone management plan is being developed for an area that has multiple watersheds. It is called the Safford/Duncan Management Zone.

The Management Zones are being implemented in areas which are 1) located in targeted priority watersheds that have perennial waters, 2) identified in the 1988 State Assessment Report and subsequent 305(b) reports as being subjected to multiple nonpoint source category impacts, and 3) amendable to management through cooperative multiple agency/entity programs and public supported pollution prevention programs.

The Management Zones are an integrated and holistic multi-program approach which will take place in phases.

- Information compilation
- Development of watershed-specific BMP implementation plans through coordinated resource management, planning and advisory groups
- Execute BMP implementation plans, including program/activity coordination
- On-going monitoring
- Encouragement of NPS demonstration projects

The Management Zone concept has been well received by EPA Region IX. Implementation of programs in these Zones along with the other innovative approaches the Nonpoint Source Unit have taken require a great deal of coordination and cooperation. It is anticipated that the partnership's developed between the agency, principle land management agencies and the public will ensure for more effective protection for the water resources of the State of Arizona.

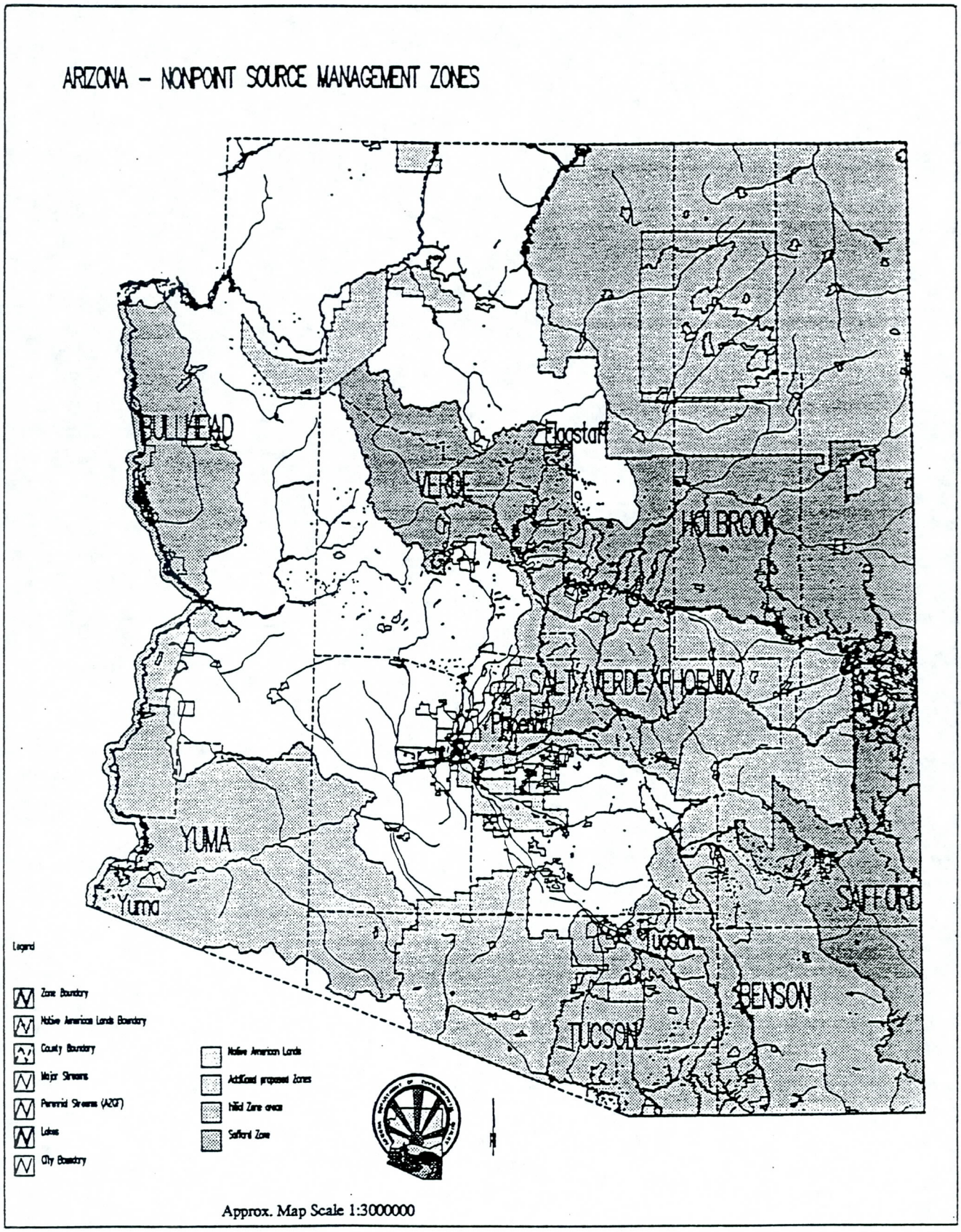


Figure 1. Arizona Management Zones

## REFERENCES

Arizona Department of Environmental Quality, 1992. Arizona Water Quality Assessment, Clean Water Act Section 305(b) Report.

Arizona Environmental Quality Act, 1992. Arizona Revised Statutes, Title 49.

US Environmental Protection Agency, 1989. Nonpoint Sources: Agenda for the Future. WH-556. USEPA, Office of Water, Washington, DC, November, 1989.

# Part VII

# ABSTRACTS

## WHO SAID "PUMP & TREAT DOESN'T WORK"? A LOOK AT THE EPA AND ORNL REPORTS

Mock, Peter. Senior Hydrologist, CH2M Hill. Tempe, AZ.

A popular recent assertion in the environmental field is that "Pump and Treat Doesn't Work." The reported basis for this claim has been either the EPA or ORNL reports. Review of the EPA and ORNL reports indicates that they provide valuable insights into the practical end of aquifer restoration for volatile organic compounds (VOCs). It appears that no one has yet restored an aquifer to agency cleanup goals. It is important to define the terms pump & treat, restoration, and containment before observing if something is or is not working. Distinctive behaviors of concentrations during pump and treat remedial action have been documented which can be reasonably explained with known physical processes. The data needed to reliably evaluate these processes are the same types of data collected during site investigations. The physical measures of aquifer restoration may be new, but are straightforward in application. With an understanding of how "well" our site is cleaning up, it is then incumbent on us to consider the balance of protecting human health and heretofore uncontaminated groundwater resources with the capital, operations, maintenance, and monitoring costs of remedial action. Given these technical and policy observations, the framework for reasonable expectations for pump & treat can be built by companies, agencies, and the public.

## CHALLENGES AND OPPORTUNITIES IN REMEDIATING GROUNDWATER CONTAMINATION

Graf, Charles G. Arizona Department of Environmental Quality.

Many groundwater contamination problems in Arizona are proving or will prove exceedingly difficult to solve. Numerous technical and non-technical obstacles hinder cleanup of these problems. Some technical obstacles include sheer size of some problems, unknown extent of other problems, highly variable hydrogeological conditions, presence of contaminants in non-aqueous phases, short-circuiting of pollutants into deeper zones through unused wells, and inherently long cleanup times. Non-technical obstacles include lack of identifiable responsible parties (RPs), too many Rps, uncooperative Rps, ambiguity about cleanup standards, multiple or conflicting cleanup programs, and difficulty in finding beneficial end uses for treated groundwater.

These obstacles point the way to new opportunities. However, we must first discard entrenched notions and appreciate that (1) poor quality groundwater is an untapped resource and (2) conjunctive management of groundwater quality <u>and</u> quantity is key to speeding up groundwater remediation. In this vision, groundwater cleanups could be planned to optimally combine elements of source area containment, pumpage (by both Rps and third parties), treatment, transport, and better matching of water quality to end use. Such a comprehensive approach will require flexibility in melding -aspects of water quality, water

rights, and water conservation programs. Incentives will likely have to be instituted to encourage this comprehensive approach.

## HYDROPHYSICAL LOGGING AT WQARF SITE; PAYSON, ARIZONA

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Hydrophysical logging was recently employed as part of a hydrogeological investigation of groundwater contamination at a State Superfund (WQARF) site, in Payson, Arizona. Hydrophysical logging is a new aquifer and groundwater characterization technique which provides high resolution identification of water bearing intervals, the contaminant concentration of selected intervals and the vertical distribution of hydraulic conductivity on the intermediate scale surrounding the wellbore.

The hydrophysical logging technique is based on a time series profiling of induced electrical conductivity changes in the wellbore fluid column. Hydrophysical logging contemporaneously identifies the location of water bearing intervals, the interval specific inflow rate during pumping or non-pumping conditions, and in-situ hydrochemistry (fluid electrical conductivity, temperature, Ph and oxidation-reduction potential) of the formation waters associated with each producing interval. In addition, by employing a downhole discrete point fluid sampler during hydrophysical logging, the technique provides an evaluation of the interval specific contaminant concentrations for each sampled producing interval.

The Arizona Department of Environmental Quality applied the hydrophysical logging technique at a site at the town of Payson, Arizona, where 2 future production wells have confirmed PCE contamination. Due to the spatial heterogeneity of the hydrogeologic regime (weathered and fractured granite), characterization of the vertical distribution of both hydraulic conductivity and contamination is a particularly challenging task.

The hydrophysical logging results indicated a reasonable high density of water bearing intervals in each well. Although the vertical distribution of the water bearing fractures varied considerably between the two wells, in general, these fractures were located within the upper 160 feet of each well. The rate of inflow of these water bearing intervals ranged from 0.5 to 49 gpm, while pumping at about 100 gpm. Flow was dominated in both wells by three or four fractures located within 60 to 110 feet below land surface. The vertical distribution of inorganic water quality parameters and PCE contamination indicated that water types were reasonably similar throughout each welllbore. However, the wells did exhibit different overall water quality compared to each other. Ambient flow evaluation indicated minor downward flow (about 2 gpm) within the interval of 60 to 100 feet in one well and no apparent ambient flow in the other well.

ADEQ intends to use the results provided by hydrophysical logging in designing an efficient and cost-effective remedial system. Results of the hydrophysical logging have verified the feasibility of groundwater extraction as a remedial action. However, the initial plan to re-inject treated water to the fractured granite should be reevaluated. The weathered granite interval from 0 to 60 feet below ground surface is cased off in both production wells and could not be evaluated by hydrophysical logging. Additional drilling followed by vertical permeability and hydrochemical characterization of this interval must be conducted before any remedial action can be initiated.

## COMPARISON OF CURRENT AND ALTERNATIVE METHODS FOR MEASURING VOLATILE ORGANIC COMPOUNDS IN SOILS

Heywood, Judy, Michele Kennard, Gloria Koroghlanian, and Faye Troisi. Arizona Department of Environmental Quality, Phoenix, AZ.

Volatile organic compounds (VOCs) are among the most common contaminants present in groundwater in Arizona and throughout the United States. Frequently however, laboratory analyses result in no detectable concentrations of VOCs in soil samples collected from sites with significant groundwater contamination and where field measurements of organic vapors would indicate contamination exists. The Arizona Department of Environmental Quality (ADEQ) has suspected that there were serious limitations to measuring VOCs in soils in Arizona. Recently, experiments have quantified the scope of the problem confirming that current sample handling and storage practices result in high losses of VOCs prior to laboratory analysis regardless of soil type. With the development of ADEQ's Groundwater Protection Guidance Levels, the importance of accurate measurements of VOC concentrations in soil becomes critical. Already, other states are beginning to require soil sample collection and preservation methods that differ from currently accepted practice. ADEQ is evaluating alternative methods for future program implementation.

## SCOTTSDALE'S EXPERIENCE AS A VOLUNTEER USER OF REMEDIATED GROUNDWATER

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In 1981, VOCs were detected in groundwater beneath Scottsdale. In 1983, the Indian Bend Wash North Superfund Site was designed by the U.S. EPA. After thirteen years of investigation, negotiation, planning and construction, actual cleanup activities are scheduled to begin in 1994. The City of Scottsdale, while not a potentially responsible party ("PRP") for the first 11 years, volunteered early on to be part of the cleanup effort. The City worked closely with EPA and the PRPs, and agreed to be the end user of treated water from a central treatment plant. The role of end user has some advantages for the City, but also

brings along with it many limitations on the City's water supply operations and subjects the City to being treated legally like a PRP, including being subject to stipulated monetary penalties. City officials have mixed feelings about the Superfund process and the wisdom of volunteering to be the end user of treated groundwater as part of a Superfund cleanup project. This paper will discuss the City's experience to date in this process.

## ASSURED WATER SUPPLY RULES UPDATE

Jacobs, Katherine. Director, Tucson Active Management Area. Arizona Department of Water Resources.

The Arizona Department of Water Resources (Department) is presently in the process of developing the final draft of the Assured Water Supply (AWS) Rules. These rules affect all lands to be subdivided within Active Management Areas (AMAs). The 1980 Groundwater Management Act requires that prior to approval of subdivision plats, there must be a finding that sufficient water supplies of adequate quality are available to serve the proposed use for 100 years. The water supply must also be consistent with the management plan and the management goal for the AMA. Since the management goals for the AMAs involve limiting the use of overdrafted or mined groundwater, the AWS Rules are expected to result in a major transition to utilization of renewable water supplies.

The Department has been involved in drafting AWS Rules for almost ten years. However, the most recent effort began about two years ago, with development of a concept paper on "Consistency with the Management Goal." Draft Rules were released in October of 1992, followed by an extensive public participation and comment period. To date, 21 public meetings have been held to solicit input. In addition, an extensive study of the economic impacts of the draft rules has been prepared with the assistance of a consultant. The results of this study have also been released to the public for review.

The legislative framework within which the AWS Rules are being drafted has changed substantially in each of the last four legislative sessions, with new augmentation agencies and replenishment districts appearing each year. In addition, limits on groundwater transfers were enacted, in response to concerns that these rules would drive water users within AMAs to deplete the water supplies of rural Arizona.

After nearly two years of intensive public participation, the Department will soon enter the formal rule adoption process. A draft of the rules is now well underway, which is expected to proceed to the Governor's Regulatory Review Council in the near future. This paper discusses the major issues that are being addressed in the redrafting process.

## POOR QUALITY GROUNDWATER: ASSURED WATER SUPPLY IMPACTS AND REQUIREMENTS FOR USE

Davis, Bruce. Chief Operations Division, Arizona Department of Water Resources, Operations Division. 15 S. 15th St., Phoenix, AZ.

A.R.S. §45-516 allows for the withdrawal of poor quality groundwater within an Active Management Area and was originally developed to allow for withdrawals of brackish water or water high in salinity. The statute requires a beneficial use of the water and the permit can only be issued for non-irrigation purposes. Remedial actions have created the need for flexibility in the administration of the Poor Quality Groundwater Withdrawal Permit in order for withdrawal and removal of contaminants to proceed legally. This flexibility, necessary to allow the remedial action to proceed, has created a number of legal and policy issues for the Department of Water Resources to consider, including how poor quality groundwater will be considered in developing assured water supplies. The Department is proposing incentives for the use of poor quality groundwater in the Assured Water Supply rules.

## TREADING THE REGULATORY AND TECHNICAL MAZE TOWARDS A GROUNDWATER CLEAN-UP

Boyer, John L. Senior Environmental Consultant, Arizona Public Service Company, Phoenix, AZ.

The choices are not always clear when deciding on the appropriate method to clean up a petroleum spill from an above ground tank or an underground pipeline. Choosing a clean-up method that is rational, technically feasible and legally correct is difficult at best. This talk will describe how one clean-up has progressed and where changes and clarification of the regulatory system could facilitate the process and protect the environment.

Two separate diesel spills at the Arizona Public Service Company, West Phoenix Power Plant in the late 1980's. The site is located in the West Van Burean WQARF area. The spills are currently being remediated using a BioVenting system. A number of remedial methods were investigated and shown to be infeasible due to technical or regulatory reasons. The current system should allow clean-up over a reasonable time frame while avoiding discharges that require additional treatment.

## THE EFFECT OF PULP MILL WASTEWATER IRRIGATION ON SOIL SALINITY

Tecle, Aregai, M.R. Wagner, and C.C. Avery. Northern Arizona University. Flagstaff, AZ.

This paper assesses the impact of paper pulp mill effluent upon soil salinity. The project was initiated in order to safely and cost-effectively reuse a large volume of wastewater produced by the Stone Container paper pulp mill plant near Snowflake, AZ. Reuse of wastewater through biomass irrigation was considered to be a promising methodology to meet this objective. An experiment was designed to test the feasibility of this procedure. The experiment included land preparation, design and construction of an irrigation system which includes land leveling, development of irrigation canals and ditches, and designing appropriate irrigation scheduling and data acquisition systems. The latter includes installation and use of appropriate instrumentation, and sampling schemes. All together about 80 acres of experimental fields were prepared and planted with more than 170 different varieties of trees. The first 18 acres of the experimental fields were initiated in 1991 while the other 60 acres were set up in 1992. In order to determine the impact of the wastewater irrigation upon the soil, a complete soil chemical and physical analysis was made at first. Then, rootzone soil water and irrigation wastewater samples were taken at varying intervals from the different fields in order to determine the changes in soil characteristics with time and space. On the basis of two-year data, it is found that changes in soil chemical characteristics vary significantly with time and space. Also there seems to be some accumulation of salt in the soil, even though the level of accumulation decreased during the cold season when the fields were not irrigated with the wastewater. Analysis of soil samples from a long-abandoned wastewater-irrigated field show that the increase in soil salinity does not reach critical levels for plant growth and soil hazard.

## MONITORING STRATEGIES TO DETECT AND PREVENT RIPARIAN DEGRADATION FROM GROUNDWATER WITHDRAWAL

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Groundwater declines resulting from groundwater pumping and surface water diversions have impacted riparian ecosystems of the desert Southwest for centuries. Recently, there has been a resurgence of interest in this issue in light of growing appreciation and awareness of dwindling riparian resources. Vegetation types that have been most impacted by groundwater pumping and surface water diversion include Fremont cottonwood-Goodding willow forests, mesquite forests, cienegas (marshlands), and other plant communities associated with low elevation desert rivers. Many riparian areas have been irreversibly altered. For example, groundwater at sites along the Gila River has declined from a few feet to several hundred feet below the floodplain surface, and vegetation has converted from riparian forest to desert scrub. Many other desert riparian zones are in early stages of degradation, but can be restored if proper management is taken to prevent

impending groundwater declines. This paper will recount the status of our knowledge on vegetation-groundwater relationships, and will discuss the scientific basis for the design of riparian monitoring strategies and stress-detection programs.

## INSTREAM FLOW MAINTENANCE BY THE US FOREST SERVICE IN ARIZONA

Roy Jemison, Research Hydrologist, Rocky Mountain Forest and Range Experiment Station, Flagstaff, AZ.

Many of Arizona's riparian ecosystems are being affected by declining flow regimes on lands managed by the US Forest Service. The Forest Service has a mandate to manage these natural resources for multiple uses, which include maintenance of riparian areas. Therefore, determination and maintenance of adequate instream flows are essential. This presentation will highlight activities by the US Forest Service in Arizona that address instream flows.

## SANTA CRUZ RIVER: BINATIONAL ISSUES

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The future of the Santa Cruz River depends on close coordination between the U.S. and Mexico, but federal-level water management has been unwieldy and often unresponsive to local needs. New solutions are proposed which focus on locally-driven cross-border cooperation to keep the river alive and flowing for the benefit of both countries.

## EFFECTS OF RESERVOIR DRAWDOWN ON RESUSPENSION OF DELTAIC SEDIMENTS IN LAKE POWELL

Vernieu, Bill, Bureau of Reclamation, Glen Canyon Environmental Studies, Flagstaff, AZ.

Lake Powell, located in Utah and Arizona, is a major component of the Colorado River Storage Project formed by Glen Canyon Dam on the Colorado River. Due to prolonged drought conditions in the Upper Colorado River basin, Lake Powell's water surface elevation has declined steadily since 1988 to a current level approximately 27 m below a high level of 1130 m, resulting in a 60% reduction in reservoir capacity.

Associated with this drawdown has been the exposure and resuspension of over 100 channel kilometers of deltaic deposits in the major tributary arms of the reservoir. This

resuspension process is thought to be a significant source of nutrient and trace element loading to the reservoir due to the breakdown of organic material and deltaic sediments which have remained undisturbed since their deposition during higher lake levels. Changes in reservoir volume and the fate inflow density currents within the reservoir may affect the significance of this process.

While Reclamation has maintained a long term water quality monitoring program on Lake Powell since 1965, there has been little focus on productivity. Increases in indicators of productivity are now being observed in what has been an oligotrophic reservoir throughout its relatively short existence. However, the lack of baseline information makes quantitative productivity comparisons difficult.

(Note: The following extended abstract was presented at the Fifth Annual Symposium of the Arizona Hydrological Society in Sedona, Arizona, on September 10-11, 1992, but was inadvertently omitted from the Proceedings.)

# ISOTOPIC CONTENT AND WATER CHEMISTRY OF GROUND WATER THAT SUPPLIES SPRINGS IN THE VERDE HEADWATERS, YAVAPAI COUNTY, ARIZONA[1]

Laurie Wirt[2]

An understanding of the interaction between ground water and surface water is critical in developing management strategies to protect sensitive riparian areas. Stable-isotope and chemical data can yield information about the origin and geochemical evolution of natural waters. This approach was applied to a study of the relation between two aquifers in Big Chino Valley and the upper Verde River in north-central Arizona (fig. 1). The 35-mile reach of the upper Verde River included in this study is from the point where perennial flow in the river first begins (below Sullivan Lake near the town of Paulden) to just below the mouth of Sycamore Creek at the U.S. Geological Survey streamflow-gaging station near Clarkdale (09504000). This reach has a small but reliable base flow derived from ground water and supports a diverse riparian community. The primary objective was to identify the source(s) of ground water to several springs that supply base flow to the Verde River in the study area. A second objective was to determine whether the quantity of discharge in this reach of the river had changed significantly since the last seepage run was conducted in 1977. In the summer of 1991, 11 ground-water, 13 streamflow, and 4 spring samples were collected in Big Chino Valley and along the upper Verde River (fig.1). Discharge was measured at 10 sites in addition to the 2 gages near Paulden and near Clarkdale. Samples were analyzed for dissolved chemical constituents and for stable-isotope ratios of oxygen ($^{18}O/^{16}O$), hydrogen (D/H), and carbon ($^{13}C/^{12}C$).

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1 Paper presented at the Fifth Annual Symposium of the Arizona Hydrological Society, Sedona, Arizona, September 10-11, 1992.

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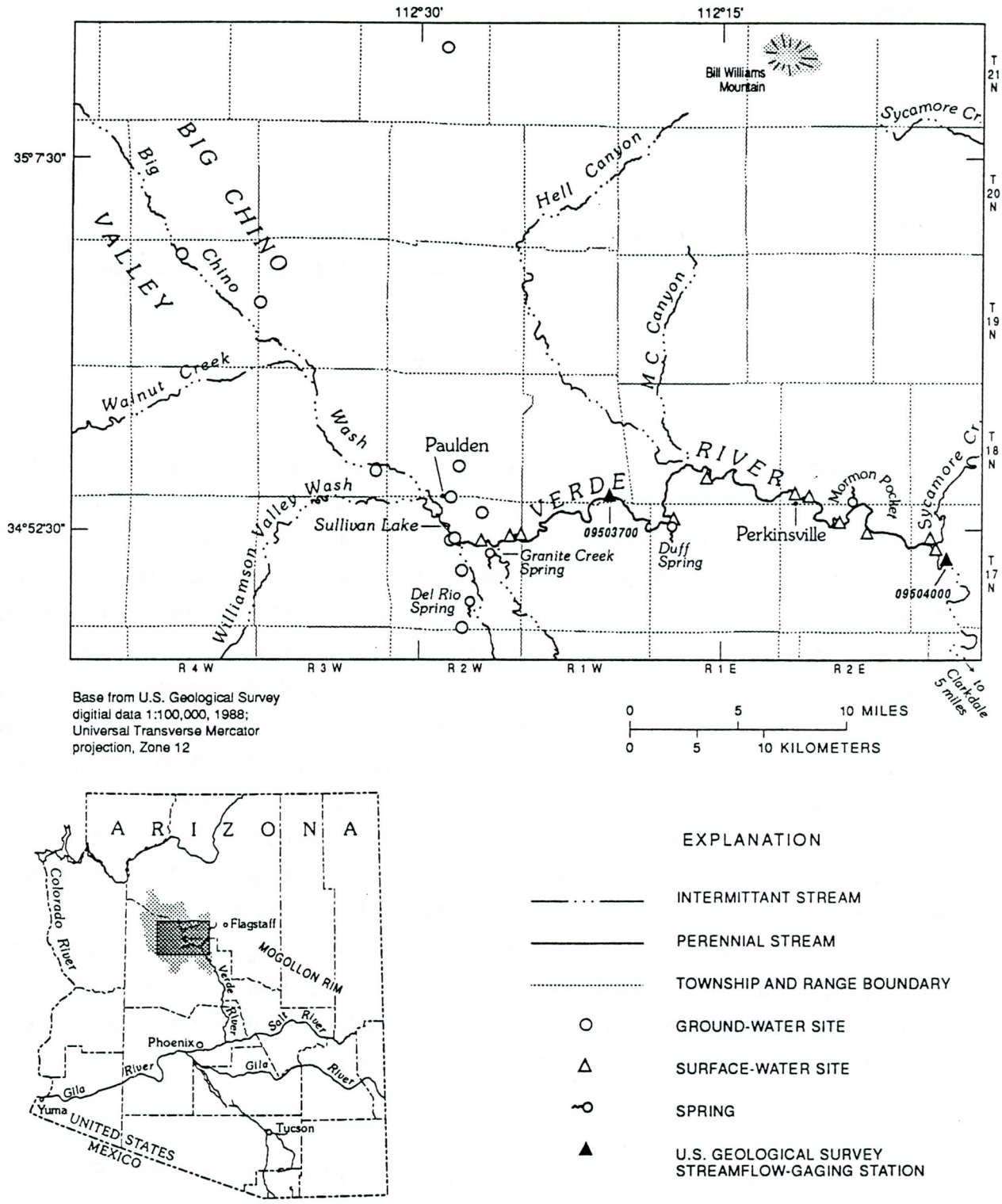


Figure 1.—Ground-water, surface-water, and spring sampling locations in the Big Chino Valley and the upper Verde River area, north-central Arizona.

The major water-bearing unit in Big Chino Valley is basalt that underlies alluvium in the center of the valley and is exposed in the uplands and valley margins. Well logs indicate that the basalt varies in thickness and is absent in some areas. The basalt is underlain by limestone. Concentrations of certain elements were distinct for ground water in contact with specific rock types. Concentrations of Si and Sr exceeded 70 mg/L and 700 mg/L, respectively, in samples from wells open to basalt. In comparison, samples from wells that are open to the underlying limestone have a water chemistry similar to that of samples from wells open to basalt but are elevated in specific conductance, Na, F, As, B, Li, Cu, and temperature. Ground water discharging to seeps in the streambed of the Verde River at the U.S. Geological Survey streamflow-gaging station near Paulden (09503700) has a water chemistry intermediate between that of the basalt and the limestone aquifers in Big Chino Valley.

Stable-isotope data were used to distinguish parts of the river that are supplied by ground-water contributions from different source areas and rock types. $\delta^{18}O$ and $\delta D$ values of -10.0 and -71.5‰ from streamflow at the gage near Paulden are similar to those for ground-water samples from wells in both rock types in Big Chino Valley. The $\delta^{13}C$ content, however, indicates that ground water has been in contact with different rock types. Samples from wells and springs originating in the limestone bedrock are enriched in $\delta^{13}C$ relative to the ground-water samples from wells and springs in basalt. Ground-water samples originating in limestone contain about -6.5 $\delta^{13}C$ PDB, whereas ground-water samples from wells in basalt contain about -11.8 $\delta^{13}C$. The $\delta^{13}C$ content is an indication of the degree of exchange that occurs between bicarbonate in the ground water and in the limestone. The Verde gorge cuts below the major basalt unit into limestone immediately downstream from Sullivan Lake, where perennial flow begins. As water from the basalt aquifer drains downgradient through the underlying limestone, it is diluted by isotopically heavier $\delta^{13}C$ before emerging to the surface as flow in the Verde River. The $\delta^{13}C$ content of streamflow in the headwaters area above the gage near Paulden is about -5.4 ‰.

Two small springs, Granite Creek Spring and Duff Spring, emerge from small drainages on the south side of the river in the first 6 miles of perennial flow. In comparison to streamflow near these sites, the two $\delta^{18}O$ values of -9.2‰ and the $\delta D$ values of -66.5 and -67.0‰ for the spring samples are enriched by about +0.8 and +5.0‰, respectively. $\delta^{13}C$ values of -8.2 and -11.0 are +3 to +5‰ heavier. The $\delta^{13}C$ content indicates that the two springs are ground water that has not had significant contact with limestone. The two springs contribute a combined

discharge of about 1 $ft^3/s$ to the Verde River and do not significantly affect the isotopic content of water in the main channel.

In comparison with streamflow samples upstream from Perkinsville, springs that supply base flow downstream from Perkinsville at Morman Pocket and Sycamore Creek have isotopically lighter values. Samples from a spring at Mormon Pocket and Sycamore Creek have $\delta^{18}O$, $\delta D$, and $\delta^{13}C$ values of -11.65, -80.5, and -7.2 ‰, respectively. As evidenced by values depleted by -1.65 ‰ in $\delta^{18}O$ and -10.5 ‰ in $\delta D$ from streamflow upstream, ground-water contributions at Mormon Pocket and Sycamore Creek probably are derived from aquifers that receive recharge from higher altitudes to the north. Sycamore Creek drains the southeast flank of Bill Williams Mountain which forms the Mogollon Rim in this part of Arizona. Base flow past the gage near Clarkdale is isotopically intermediate between samples from springs above Perkinsville and springs below Perkinsville.

Discharge measurements made during a low-flow seepage run July 2-4, 1991, of the Verde River from the gage near Paulden to the gage near Clarkdale agree with measurements made during a seepage run in 1977 at nine matched locations. This agreement is an indication that ground-water contributions in the study area have not changed significantly in the last 14 years. Both seepage runs were during low-flow conditions. Base flow increased from 0 to 20 cubic feet per second ($ft^3/s$) in the first 3 miles of perennial flow below Sullivan Lake. This increase in flow was derived mainly from seeps through the streambed. Downstream, the discharge increased several cubic feet per second from small seeps near Perkinsville. Below Perkinsville at Mormon Pocket, discharge increased to 48 $ft^3/s$ from seeps through the streambed and several springs along the north bank. The base flow from Sycamore Creek (12 $ft^3/s$) and underflow through the streambed near the mouth contributed an additional 29 $ft^3/s$, for a total of 77 $ft^3/s$ at the gage near Clarkdale.

# Other Speakers

The following speakers at the Sixth Annual Symposium did not submit written papers or abstracts for publication in these proceedings.

**Luncheon Speakers**

The Changing Face of Western Water Policy
*Ms. Rita Pearson, Director, Arizona Department of Water Resources, Phoenix, AZ*

Water, Water Everywhere, But Not a Drop to Drink
*Bill Wiley, Deputy Director, Arizona Department of Environmental Quality, 3033 North Central Avenue, 3rd Floor, Phoenix, AZ 85012.*

**Session Speakers**

CAP Today
*Grant Ward, Central Arizona Water Conservation District, Phoenix, AZ.*

CAP Terminal Storage
*Dennis Rule, Tucson Water, Tucson, AZ.*

CAWCD Recharge Projects and Plans
*Cliff Neal, Central Arizona Water Conservation District, Phoenix, AZ.*

Water Resources Issues in the Tohono O'Odam Nation
*David Frank, Attorney General, Tohono O'Odam Nation, P.O. Box 1202, Sells, AZ 85634*

Water Rights Issues in the San Carlos Apache Tribe
*Joe Sparks, Sparks and Siler, First Street, Scottsdale, AZ 85251*

Water Resources Issues in the Colorado River Indian Tribes
*Gary Hansen, Director, Water Resources, Colorado River Indian Tribes*

Design of Constructed Wetlands
*Peter Livingston, CH2M Hill, 5210 E. Williams Circle, Suite 550, Tucson, AZ 85711*

Strategic Value of Environmental Risk Assessments
*Linda Henry, Corporate Toxicologist, Brown and Caldwell, Consultants, 3480 Buskirk Ave., Pleasant Hill, CA 94523-4342*

The Science of Human Health Risk Assessment
*Steven Pike, Chief Executive Officer, EnviroMD, 3443 East Fort Lowell Rd., Tucson, AZ 85716*

The Arizona Comparative Environmental Risk Project
*Pamela Beilke, Group Manager, SHEP, Hughes Missile Systems Co., Tucson, AZ.*

Status of ACERP Technical Committee - Human Health
*Steven Pike, Chief Executive Officer, EnviroMD, 3443 East Fort Lowell Rd., Tucson, AZ 85716*

Status of ACERP Technical Committees - Ecosystems
*Katherine Roxlo, Manager of Environmental Services, Brown & Caldwell Consultants, Phoenix, AZ.*

Status of ACERP Technical Committees - Quality of Life
*Martha Rozelle, Director of Public Involv. Serv., Dames & Moore, Phoenix, AZ.*

The Role of Science and the Public in Setting Environmental Policy
*Pat Mariella, ACERP Project Director, Arizona Department of Environmental Quality, 3033 N. Central Ave., Phoenix, AZ 85012*