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Introduction

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Research Program

Basic Information

Title:	Ponderosa pine water balance at Hart Prairie: Role of herbaceous transpiration
Project Number:	B-02
Start Date:	3/1/2000
End Date:	2/28/2001
Research Category:	Ground-water Flow and Transport
Focus Category:	Water Quantity, Ecology, Management and Planning
Descriptors:	Recharge, Evaportranspiration, fire management
Lead Institute:	Northern Arizona University
Principal Investigators:	Abe Springer, Tom Kolb

Publication

1. Amentt, M.A, A.E. Springer, T.E. Kolb, and L.D. DeWald, 2000. Restoration of a perched aquifer system through manipulation of transpiration at the watershed scale (abstract), 2000 annual meeting of the Geological Society of America, November 13-16, Reno, NV, v. 37, no. 7.
2. Springer, A.E. 2000. Restoring and conserving recharge for aquifers through forest management practices (abstract), 2000 annual meeting of the Geological Society of America, November 13-16, Reno, NV, v. 37, no. 7.
3. Springer, A., M. Amentt, L. DeWald, T. Kolb, and D. Fischer, 2000. Restoring riparian areas through landscape restoration: Influence of upland grazing, tree thinning, and fire on riparian ecosystems (abstract), Society for Ecological Restoration, International Symposium, Liverpool

England, September 4-7, 2000.

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A. Problem and Research Objectives

The problem we addressed is the lack of understanding of the role of plant transpiration in water balance at Hart Prairie, Arizona. Current proposals for watershed restoration in the Southwest are based on the assumption that tree thinning will reduce evapotranspiration and consequently increase runoff and ground-water recharge. However, high transpiration rates of herbaceous communities that often occur in forests dominated by ponderosa pines may reduce effects of tree thinning on runoff and recharge. Transpiration of these herbaceous communities has not been measured.

The main objective of our research was to measure seasonal water use by understory herbaceous communities in the ponderosa pine forest at the Hart Prairie Preserve. A second objective was to use this information to improve estimates of the local water budget. The third objective was to use the improved local water budget to predict the hydrological effects of different amounts of thinning of the ponderosa pine forest that occurs in the Hart Prairie watershed. Specifically, we are interested in whether thinning will increase the supply of water to the local aquifer, and thus enhance downstream spring and stream flows in the watershed.

Mark Briggs, in his book on "Riparian Ecosystem Recovery in Arid Lands" (1996), states the need for evaluating degraded riparian areas from a watershed perspective because of the critical upslope-downstream connections. He describes recovery strategies based solely on evaluation of the immediate degraded riparian site as incomplete because they often fail to correct the problem causing riparian ecosystem decline. We are developing such strategies to address conditions in ponderosa pine type watersheds upslope from riparian areas. In such an upslope watershed in Hart Prairie, Arizona, we are proposing to modify watershed conditions to increase and sustain water flows into the riparian community through prescribed burning and reducing the density of pines encroaching the wet meadow toward the riparian community. Successful completion of this objective might generate additional water and result in more complete restoration of the riparian community at Hart Prairie (DeWald and Springer, 1999).

Hart Prairie is a riparian area dominated by Bebb willow (*Salix bebbiana*) and mixed gramminoid communities. Aspen (*Populus tremuloides*), ponderosa pine (*Pinus ponderosa*) and limber pine (*Pinus flexilis*) are also present. The herbaceous understory is composed of bracken fern (*Pteridium aquilinum*), Kentucky blue grass (*Poa pratensis*), Arizona fescue (*Festuca arizonica*), mountain muhly (*Muhlenbergia montana*), other grasses, and various alpine flowers. Major historical disturbances to Hart Prairie include sheep and cattle grazing, and limited attempts at farming. Also, fire suppression efforts have eliminated the frequent, low-intensity fires that characterized the area prior to 1900.

The hydrogeology of Hart Prairie consists of small perched aquifers. Highly permeable alluvial and colluvial deposits derived from volcanic parent materials are common (Gavin 1998). Clay lenses in the alluvial and colluvial deposits cause these thin and discontinuous perched aquifers to form (Dewitt 1980). Recharge for these aquifers is directly related to the amount of precipitation in the form of snow and rain. Dry years will affect the storage capacity of the perched aquifer, so recharge must happen frequently (Dewitt 1980). Snowmelt is the primary source of recharge for Hart Prairie, but heavy monsoonal rainfall can also recharge some of the small perched aquifers in Hart Prairie.

B. **Methodology**

Our research was conducted in the Fern Mountain Botanical Area of the Coconino National Forest on the west side of San Francisco Mountain, near Flagstaff, Arizona. This site is currently being studied to determine the impacts of land-use management on the hydrologic system and regeneration of a Bebb willow-mixed grass riparian community. As part of an existing Arizona Water Protection Fund Grant, ponderosa pine encroaching onto the formerly open prairie is proposed to be thinned and later burned, possibly during 2001. The research described in this report was used to develop preferred alternatives for the Environmental Impact Statement being prepared for the project and to predict the response to the prescribed forest treatments. The "Decision Notice and Finding of No Significant Impact" was approved by the Coconino National Forest in April 2001 based partially on results from this study.

Field Methods

Precipitation was measured with a RainWise RGEL tipping bucket gage (+-1.2 mm) and data logger at the Arizona Snowbowl Ski Resort which adjoins Hart Prairie. The gage is at an elevation of 2,810 m, slightly higher than Hart Prairie. However, this location allowed the tipping bucket to be equipped with at heated blanket to melt winter precipitation to measure snow fall. Missing precipitation data were extrapolated from the nearby Pulliam Airport station collected by the National Weather Service.

We included two different herbaceous understory communities in the study. In the wetter areas and at lower elevations, the herbaceous community is dominated by bracken fern and several gramminoid species. Upslope and in drier areas, the understory is dominated by gramminoids with no ferns. A separate experiment was performed in each commuity type.

We estimated seasonal transpiration from the understory grass community by comparing soil moisture content between paired plots that differed in the presence of living understory vegetation. This approach has been used successfully to compare understory plant water use in the short-grass prairie in Colorado by Dodd *et al* (1998). A series of five blocks were randomly established in each community. Each block contained two circular (2 m diameter) plots, one for each treatment. The control treatment was not clipped throughout the growing season. All above-ground herbaceous vegetation in the other treatment was removed weekly by hand clipping and by using a weed whacker. Biomass of dead vegetation in the clipped plots was maintained at an amount similar to that in the unclipped plots to create similar shading of the soil in each plot type.

Soil water content was measured weekly in each plot from early spring when the grass started growing to late fall after the grass had senesced with an Environmental Sensors, Inc. MP-917, time-domain reflectometry instrument (+-0.03 %). Two pairs of thirty centimeter probes were inserted in the ground near the center of each plot to decrease the chance of any edge effects from adjoining vegetation. The two measurements were averaged to calcutate a mean for each plot.

Saturated soil hydraulic conductivity was measured at four different plots at the fern-grass site using a Guelph Model 2800K1 constant head permeameter. The field saturated hydraulic conductivity was calculated through the following equation

$$Kfs = [(0.0041)*(x)*(R2)]-[(0.0054)*(x)*(R1)]$$

where

x = the reservoir constant,
R1 = the steady state rate of fall at H1 (cm/sec), and
R2 = the steady state rate of fall at H2 (cm/sec).

Analysis Methods

We estimated water use by each herbaceous community type by comparing the difference in soil water content that developed between clipped and unclipped plots during distinct drying periods with no precipitation. Two such periods occurred in 2000 at Hart Prairie: late April to mid June, and late August to late September. The average difference in soil water content between clipped and unclipped plots present at the end of the dry period estimated total water use by the herbaceous community during the duration of the dry period. For periods with precipitation (mid June to late August), we used estimated daily transpiration rates from each dry period to estimate a range of herbaceous transpiration.

Volumetric soil water content was compared between clipped and unclipped treatments and among sample dates by repeated measures analysis of variance. SAS Jump Version 4 was used to perform statistical analysis on the data. The fern and gramminoid sites were analyzed separately.

Soil-moisture release characteristic curves have not been measured yet. Once the snow melts from the study area, samples will be augered and the curves measured at each of the ten blocks.

C. **Principal Findings and Significance**

Precipitation

Total precipitation between October 1999 and October 2000 was 367 mm (14.43 inches) (Figure 1). This amount is well below the average precipitation of 530 mm/year (20 in/year) in Flagstaff, Arizona which is 670 m (2,200 ft) lower in elevation. The majority of snowfall occurred between late February and March 2000. Even though the start of the monsoon was officially declared on June 19, 2000, most of the summer monsoon showers came between late July and August 2000 (Figure 1). The forest was so dry in June that there were restrictions on use of Forest Service lands, and we had to acquire a special research permit to conduct this research.

Seasonal Understory Water Use

Soil water content varied significantly ($p<0.05$) over sample dates and between clipped and unclipped plots in the gramminoid community (Figure 3). Plants in the gramminoid community used a total 0.18 cm/day during the pre-monsoon dry down period between April and mid June (Table 1, Figure 3). Their transpiration rate was higher during the post-monsoon dry down period between late August and late September (0.58 cm/day). Total water use during the monsoon period (mid June to late August) ranged between 13.4 and 49.8 cm, depending on whether low (April to mid June) or high (late August to late September) estimated daily rates were used (Figure 3, Table 1). Total water use by the gramminoid community ranged between 28.9 and 67.0 cm, depending on the assumptions used to estimate water use in the monsoonal period, and averaged 48.0 cm (Table 1).

Table 1. Net water use of the gramminoid communities over the 129 day growing season.

	Low (cm)	High (cm)	Mean (cm)	Length (days)	Rate (cm/day)
Pre-monsoon	4.20	5.20	4.70	26	0.18
Monsoon	13.4	49.8	31.7	83	0.38
Post-monsoon	11.3	12.0	11.7	20	0.58
Total	28.9	67.0	48.0	129	

Temporal trends in soil water content in the fern-gramminoid community were similar to trends in the gramminoid community (Figures 2 and 3). However, the difference in transpiration rate of 0.12 cm/day between pre-monsoon and post-monsoon periods was smaller for the fern-gramminoid community (0.24 cm/day and 0.36 cm/day) than the gramminoid community difference of 0.30 cm/day (0.18 cm/day and 0.58 cm/day). Total water use by the fern-gramminoid community ranged between 34.1 and 43.6 cm, depending on the assumptions used to estimate water use in the monsoonal period, and averaged 38.8 cm (Table 2).

Table 2. Net water use for the fern-gramminoid communities over the 132 day growing season.

	Low (cm)	High (cm)	Mean (cm)	Length (day)	Rate (cm/day)
Pre-monsoon	8.80	8.80	8.80	37	0.24
Monsoon	18.0	27.5	22.7	75	0.30
Post-monsoon	7.30	7.30	7.30	20	0.36
Total	34.1	43.6	38.8	132	

Guelph Permeameter

Saturated hydraulic conductivity was measured with the Guelph permeameter at four different plots at the fern-gramminoid community. Saturated hydraulic conductivity will be measured in the gramminoid community after snow melt in 2001. Saturated hydraulic conductivity values varied between 0.000828 and 0.0032 cm/sec (2.35 and 9.06 ft/day).

Local Water Budgets (growing season) and Predicted Effects of Thinning Burning

The Bebb willow community of 1,300 trees covers an area of 100 hectares and is calculated to have an average daily transpiration of 3 mm/day (Gavin 1998). Over a 132 day growing season, this would be approximately 40 cm of water. This compares to transpiration of about 48 cm for the gramminoid communities and about 39 cm for the fern-gramminoid communities. Average precipitation in Hart Prairie is about 60 cm/year. A separate research project in progress has quantified the amount of seasonal transpiration from the pine communities to be less than 1 cm (D. Fischer personal communication).

Although the increase in soil water and potentially aquifer recharge created by thinning and burning pine trees may be small, less than 1 cm (less than 2 % of annual precipitation), this increase is permanent because the trees are removed. Burning of understory vegetation may provide a large, temporary increase in soil water and potentially aquifer recharge. Transpiration by ferns and/or gramminoids may be reduced for a few weeks, or between 2 and 6 cm (3 to 10 % of annual precipitation), potentially providing increases of groundwater recharge. Unless burning of the understory vegetation is repeated on a regular basis, this increase in water would be restricted to the year of burning.

Results of this study have prompted a new study of how fire of understory vegetation affects soil-water budgets. A new proposal has been submitted to repeat this herbaceous vegetation treatments with additional treatments of burning understory vegetation before and during the monsoon. It is anticipated that this study will be conducted in 2001 and 2002.

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Gavin, A.J., 1998. Hydrogeology and numerical simulation of a spring-dominated high-elevation riparian community, Hart Prairie, Arizona. Unpublished M.S. Thesis, Northern Arizona University, Flagstaff, Arizona, 177p.

Basic Information

Title:	Multiobjective Optimization of a Public Supply Wellfield using an Artificial Neural Network and Non-Linear Programming
Project Number:	B-03
Start Date:	3/1/2000
End Date:	2/28/2001
Research Category:	Water Quality
Focus Category:	Water Quality, Water Supply, Toxic Substances
Descriptors:	public wellfields, contaminants, unregulated contaminants, groundwater movement, hydrogeology
Lead Institute:	The University of Arizona
Principal Investigators:	Donald Davis, Ferenc Szidarovszky

Publication

A. Problem and Research Objectives:

Many public supply wellfields are located in urban areas where releases of contaminants into the subsurface are all too common. The resulting groundwater contaminant plumes are often captured by pumping wells, contaminating the drinking water supply, and constituting a potential risk to public health. Even though the Safe Drinking Water Act requires routine water quality monitoring of public supply wells, and, if detected above the maximum contaminant level(s), contaminant removal, the distributed drinking water may still contain potentially harmful compounds presently not regulated. In fact, while there are over 75,000 chemicals produced in the United States, only 80 are currently monitored for in drinking water.

Many compounds are not regulated simply because the effects on human health from exposure are not known. In 1997, The Environmental Defense Fund released a report alleging that there was a lack of publicly available data on the health effects of 2,700 US high production volume chemicals. Because many contaminant plumes consist of a myriad of compounds, many public supply systems are distributing water that, while meeting the requirements of the Safe Drinking Water Act, contain non-regulated contaminants at relatively high concentrations.

The area over which a pumping well captures it water, and potentially groundwater contamination, increases with increasing pumping rates. Because many water managers are faced with meeting high supply demands, particularly during hot months, many wells often pump at or near their maximum pump capacities. These high pumping rates produce capture zones that extend over large areas and can result in eventual pollution of the well.

The federally mandated Wellhead Protection Program requires States to delineate wellhead protection areas for all public supply wells. Often, these delineated areas are based upon a computed time of travel for contaminants to the wellhead, for times ranging from days to years. Potential and actual groundwater discharges that constitute a potential threat to the well may be regulated to minimize the chance of well contamination. However, this program does not adequately address existing contamination plumes that already pose a risk to the well(s), and whose pumping rate(s) may determine whether or not the contamination is captured. In cases like these, the water manager may want to implement a pumping policy that balances his supply objectives with the objective of minimizing the possibility of well contamination.

With these two conflicting objectives, the resulting water management problem reduces to a multiobjective and conflict resolution problem, where trade-offs among non-commensurable objectives must be identified. Because various stakeholders are involved, often each with difference preferences in the outcome, identifying the best compromise solution is essential for fostering an atmosphere of cooperative understanding and preserving public trust.

In this research, a new methodology was developed for identifying optimal operating pumping policies for a public supply wellfield that balances the conflicting objectives of maximizing supply and minimizing potential human health risks. The new methodology utilized a Computational Neural Network (CNN) to simulate the behavior of a real-world drinking water aquifer under variable pumping and climatic conditions. The results of this research demonstrate an efficient and accurate alternative to traditional groundwater management optimization methods. In addition, the CNN method provided the information necessary for conducting a formal and rigorous multiobjective and conflict resolution analyses of the water management problem. This enabled identification for an optimal pumping policy for balancing risk with supply in accordance with the preferences of the various stakeholders.

B. Methodology

The feasibility of training a CNN to learn the behavior of a numerical groundwater flow model under changing conditions was first explored using a hypothetical but realistic test case. Twelve distinct CNN's, each corresponding to a separate month, were individually trained to estimate the final monthly groundwater elevations at specific locations of interest in an aquifer, given some initial state of the system, monthly pumping rates, and the monthly areal recharge rate. The twelve monthly CNN's were then linked to predict the monthly time-evolution of the head field at locations of interest in response to changing pumping and areal recharge rates over an annual planning horizon. The resulting CNN architecture, a condensed linear approximation of the finite-difference groundwater flow equations, was embedded into a multiobjective linear programming problem, and non-dominated pumping policies, in the form of a Pareto frontier, were identified. The Pareto frontier is the trade-off curve that depicts water supply (total well pumpage) versus total risk (predicted hydraulic gradients at select locations along the contaminant plume boundary). This Pareto frontier served as the basis for both multiobjective and conflict resolution methodologies.

Following development and testing, the method was then applied to the Parkway Wellfield, located in Toms River, New Jersey. The wellfield consists of six high-capacity public supply wells that draw their water from the regional unconfined aquifer. Two of the supply wells were contaminated from a groundwater contaminant plume that originated from a neighboring Superfund site. The two contaminated wells are being used primarily to capture and remove contaminated groundwater. Because of a suspected cancer cluster, the treated water is distributed for consumption only under drought conditions. The four remaining non-contaminated supply wells, also in close proximity to the groundwater contaminant plume, are at risk to contamination if pumped at sufficiently high rates.

The supply requirements of the community must be balanced with the potential health risks associated with the contaminated groundwater. Various stakeholders within the community have different interests in the outcome, and their preferences must be consolidated to arrive at an acceptable compromise solution. The stakeholders are the

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Water Company, the public who consume the water, and the chemical company whose waste contaminated the aquifer.

The New Jersey Geological Survey developed a multi-layer groundwater model to simulate the regional unconfined aquifer and pumping effects at the Parkway wellfield. As in the hypothetical case, this model was used to develop a linked CNN to estimate the effects of pumping on the groundwater system at locations of interest. The linked CNN was embedded within a multiobjective model and linear programming was used to identify the Pareto frontier, again representing the set of non-dominated set of solutions between risk and supply.

As in the hypothetical case, this frontier served as the basis for both multiobjective and conflict resolution methodologies. For the three stakeholders, weight preferences (relative weighted importance to both risk and supply) were assigned by experts familiar with the case. In addition, power factors or the relative strength of each stakeholder in the decision-making process were also assigned. The weight preferences and power factors were then used in conjunction with the multiobjective and decision-making methodologies to identify the best compromise wellfield-management solution.

C. Principal Findings and Significance

In this research, it was found that the developed CNN methodology, in combination with multiobjective and conflict resolution methods, could be used for identifying the best pumping strategy under the conflicting objectives of maximizing water supply while minimizing potential human health risk.

A number of findings of significance came out of this research. The first is that the construction of a CNN, which, after sufficient training, could serve as a highly accurate approximation to the finite-difference flow model, while having significantly fewer variables and a less complicated structure. These features facilitate embedding the CNN architecture as part of the constraint set into any optimization model.

The second is the development of a multiobjective decision support system in which a compromise solution was found between the conflicting objectives of water supply and potential health risks. Distance-based methods served as the multiobjective tool and the trained CNN served as the physical model. Distance-based methods have flexibility in selecting the type of distance and the particular weights. Using the developed methodology, a complete description of the compromise solution could be obtained, while incorporating the conflicting preference orders of the different stakeholders or interest groups into the model.

The third is the development of a decision support system based upon conflict resolution methodology. The most important conflict resolution methods compute either an optimal solution of a composite objective or find the solution of a certain non-linear equation. As with the multiobjective case, the constraint set consisted predominantly of the CNN equations.

Most importantly, however, this research demonstrated the theoretical possibility of training a CNN directly from field data, and directly optimizing management of the system without having to rely upon a numerical groundwater simulator. This could result in significant savings in both time and money, while possibly increasing the accuracy of the optimization efforts. In fact, subsequent work has demonstrated that a computational neural network can be trained to estimate aquifer water levels in response to variable pumping and climatic conditions significantly better than a well-calibrated numerical groundwater flow model. A paper presenting these results is currently being prepared for submission to Water Resources Research.

In conclusion, the CNN methodology and decision support systems were applied to a complicated and real-world groundwater management problem in Toms River, New Jersey. Numerical simulation of the optimal pumping policy identified by the CNN approach verified that the solution achieves an acceptable compromise between the conflicting preferences of the stakeholders. Representatives of the NJGS believe this approach and the results may serve as the basis for their decision-making process.

Basic Information

Title:	Decision Support System for River System Management Under Hydroclimatic Variability
Project Number:	G-98
Start Date:	3/1/2000
End Date:	2/28/2001
Research Category:	Climate and Hydrologic Processes
Focus Category:	Management and Planning, Water Supply, Surface Water
Descriptors:	river basin management, climate variability, arid climates, evaporation, evapotransporation, hydrology, hydrogeology, soil physics, unsatruated flow
Lead Institute:	The University of Arizona
Principal Investigators:	Juan Valdes, Kevin Lansey

Publication

1. Ahmed I., K. E. Lansey, H. Shin, and J. B. Valdes, 2001, "Optimal control of multi-reservoir systems under hydroclimatic uncertainty: benefit function analysis and real-time Implementation," to be submitted for publication in Water Resources Research, AGU.
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A. Problem and Research Objectives

Management of large river/reservoir systems is typically very conservative as a result of the broad impact of decisions and failures. A significant cause of this conservatism is the uncertainty of future inflows. Since major decisions have a long period of influence, operators oftentimes base decisions on streamflows that are less than the average flow in order to provide a safety factor during operations. As a consequence, decisions may be far from the optimal policy, if perfect forecasts were available, and result in spillages that do not contribute to meeting project objectives.

This project focused on developing a decision support system (DSS) to assist decision makers improve reservoir and river basin management by adapting to varying climate conditions.

The DSS includes components to produce forecasts and analyze the impact of an operation policy under different sets of forecasts either by simulation or by developing an optimal operation policy. The forecasting models predict flows on the order of one year in advance. A critical issue in water management in the western US is the influence of the El Niño-Southern Oscillation (ENSO) and other climatic precursors. The interannual and intraannual hydroclimatic variability resulting from the ENSO is seen to varying degrees in different western states. It has been shown to have a particularly profound impact on the northwest. Analysis of data from Arizona also shows that significant variations occur during years when ENSO impacts the local climate. Thus, the forecasting tools combined to account for the ENSO influence while maintaining forecast quality for one-year forecasts on a monthly time step.

B. Methodology

Management of large water resources projects is strongly influenced by long-term weather conditions and hydroclimatic variation. More accurate streamflow forecasts will result in better operational planning. Reservoir operation decisions, in particular, can take advantage of improved forecasts, by allocating storage and releases in anticipation of likely events. For example, in the fall of 1997 the Salt River Project, recognizing the strongly developing ENSO, began supplying users from their surface water reservoirs rather than from groundwater sources. The decision was based on the likelihood of high flows but was not based on quantitative forecasts. The risk involved potentially not re-filling the reservoir this spring. Their decision was successful with higher than average snowfall that will brought reservoirs to acceptable levels. The result is a long-term gain in overall aquifer storage and on the order of a million dollars in reduced pumping costs. Additional lead-time and more accurate forecasts of the influence of ENSO could further improve their operation policies on an annual basis.

This project, in part, focused on methodologies for improving hydrologic forecasts. However, it is critically important that beneficial products of advanced research are passed to the practicing community. Therefore, this proposal is centered about the development of a decision support system (DSS) to assist system managers in situations, like the one noted above, and improving their operational planning. Three primary objectives were pursued in the development and application of the DSS. They are to:

1) Develop an improved methodology for making streamflow forecasts for the western US considering the influences of ENSO and other climatic precursors like Pacific Decadal Oscillation (PDO);
2) Examine the influence of forecasts on reservoir system management; and
3) Provide an operator friendly interface for comparing operational plans and determining optimal policies, based on the improved forecasts.

As noted, forecasts of likely future events can be invaluable in planning under uncertainty. The work in this aspect of the project was to develop a data fusion system that incorporates 1) forecasted ENSO; 2) other variables including snow water equivalents; 3) persistence-based forecasts; and 3) up-to-date observations. The resulting operational model produces streamflow forecasts and error bounds on the forecasts.

The influence of forecasts and their uncertainty on river system management was studied on three systems. The first is the Salt River Project on the Salt and Verde rivers in Arizona. This system is operated primarily for water supply for the Phoenix metropolitan area. The Santa Ynez River system of Central California is the second system examined in this work. It includes three water supply reservoirs and provides water for agriculture and steel head trout fisheries. This reservoir system is of a regional/local scale on the order of 2000 km^2 drainage area. It is typical of inland valleys in the central and southern coast regions of California whose water resources are vulnerable to climate fluctuations, and, specifically, to droughts and El Niño related phenomena. The third system is the Lewis River in the Pacific Northwest. These systems are in different climate regions and are operated for different purposes as such the utility of forecasts and the uncertainty of the forecasts may vary. Data has been collected on each system including reservoir capacities, historical streamflow, and operation policies.

Using these systems as a basis, a series of questions were considered through simulations. The questions include:

1) How should management decisions be changed during ENSO influenced years versus non-ENSO years?
2) How are management decisions affected by differing system characteristics, climatic conditions and objectives under ENSO influenced years?
3) How will the time increment of forecasts (e.g. months or seasons) affect uncertainty and management decisions?
4) How will the initiating period of forecasts affect management decisions?

Streamflow Forecasting

To address these questions, the tradeoff between forecast error in future streamflows as measured by the root mean square error and will lead to evaluating the increase in return from a reservoir system as compared to the present operation scheme.

Salt-Verde River Basin

To begin that analysis, the impact of ENSO on the Salt-Verde streamflows was investigated. Following Ropelewski's (1986, 1987) classification of El Niño and La Niña years, the annual flow observations for the Salt-Verde basins were subdivided into two groups, either El Niño and non-El Niño or La Niña and non-La Niña. The Mann-Whitney (Mechoso et al., 1992) test was applied to examine the statistical significance of the differences between the two groups. The null hypothesis of no statistical significant difference between El Niño/La Niña and non-El Niño/La Niña years was rejected in all tests at a 5 % significance level.

A box-plot analysis was then carried out on the seasonal streamflows, Palmer Drought Severity Index (PDSI), and precipitation of the Salt-Verde basins. This work intended to analyze the possible shift of response in the exceedence probability distributions of these hydroclimatic variables during the cold, normal, and warm Sea Surface Temperature (SST) phases of the Niño 3 area in the Equatorial Pacific. From this analysis it was found that the ENSO signal has slight effects on Salt-Verde basins streamflow, precipitation, and PDSI.

The area of analysis of sea surface temperatures was extended to the entire Pacific and spatial correlations for several lags were estimated between SSTs and the Salt-Verde streamflows, using CLIMLAB2000 (International Research Institute for Climate Prediction, 1999). Two regions of high correlation were found; one in the Northwestern Pacific and the other in the Southern Pacific near Australia. Regional SSTs averaged over these two zones were included in the set of predictors of streamflow.

Stepwise multiple linear regression analysis was then applied to develop streamflow-forecasting models. The independent variables can be classified into three groups. Those include 1) the global climatic indices such as Southern Oscillation Index (SOI), PDO, SST on Niño1+2, Niño3, Niño3.4, Niño4, and the selected regions mentioned above, and the 400mb heights for 14 regions, 2) local hydrologic variables such as precipitation, winter snow water equivalent, and 3) the previous streamflows. Both monthly and seasonal climatic indices were used to develop a mathematical model for streamflow forecasts for different levels of seasonal aggregation (12), from annual to monthly. Each season has different starting month, but each end in September. As was expected, regression equations based on monthly indices give better results. For the validation of the forecast model, a cross-validation technique was applied for models with selected independent variables. Both the calibration and validation procedures were programmed in MATLAB code.

Artificial Neural Networks (ANNs) was also applied as an alternative procedure for developing a streamflow forecasting model. Since ANNs are good estimators for non-linear systems like hydroclimatic systems, ANNs are a logical choice for streamflow forecasting. LLSSIM, an ANN software developed by Hsu et al (1995) and NEVPROP developed at the University of Nevada (1996) were used for the analysis. To avoid the problems of over-fitting that are frequent in ANN-based models, a simple 3-layered (input, output and 1 hidden layer) network was considered and the number of input nodes and hidden nodes were limited at most 3 and 3, respectively. For the forecasts of spring streamflow, ANN with 3 input nodes and 2 hidden nodes showed much better R^2 of as high as 0.82 in calibration. Validation results were similar to those from stepwise regression but ANN were poor estimators compared to multiple linear regression.

Finally seasonal forecasts were disaggregated into monthly streamflows. Valencia and Schaake's multivariate disaggregation technique (1973) was and applied because the streamflow data from the Salt-Verde River showed high correlation between two sites.

Pacific Decadal Oscillation effect

Previous forecast work on the Northwestern US demonstrated the relationship of Southern Oscillation Index (SOI) to streamflows in the region. Building upon this understanding, the influence of the Pacific Decadal Oscillation (PDO) on streamflow was investigated. First, the effect of PDO on the streamflow-SOI relationship was evaluated, in terms of runoff volume and its distribution. Since PDO was found to be important in the streamflow-SOI relationship, a procedure was developed to produce seasonal volume streamflow forecasts with up to a one-year lead-time and to disaggregate the volume forecasts to provide monthly flows.

Using three river basins in western Oregon and Washington (the Sandy, Rogue, and Skykomish Rivers) for which adequate data were available, the amount of streamflow occurring in the November through June period was related to the SOI (Koch and Fisher, 2000). As with previous studies, the relationship was variable in magnitude and in time and not statistically significant for the Rogue River, the southern-most basin in the study. However, further analysis revealed that the seasonal streamflow-SOI relationship varies depending on the phase of the PDO. A split sample analysis performed using streamflow data for these three river basins revealed that the phase of the PDO conditions the response of these rivers to the ENSO as measured by the SOI. During the cool (low) phase of the PDO, the correlation of the SOI and streamflow in all basins is much higher than during the corresponding warm (high) phase of the PDO. The consistency of the findings across the study basins suggests a consistent relationship in at least the Washington and Oregon Cascades watersheds and potentially throughout the Pacific Northwest

An evaluation of composite monthly hydrographs at all three locations, based on both the PDO and ENSO phases, suggested that there are also clear differences in the annual amount and distribution of flow depending on both the SOI and the PDO. For all of the basins, the highest annual flow was observed for La Niña (positive SOI) events occurring when the PDO was in the low phase. For these conditions, a significant increase in the proportion of runoff occurred early in the season resulting primarily from rainfall. Some differences were noted in the monthly hydrographs when composites were constructed only for low and high PDO phases, indicating differences in the timing of runoff response between these two conditions. No systematic differences were noted for composites constructed for El Niño and La Niña periods.

An analysis of seasonal flow and its distribution within the year was also conducted for the Salt River basin in Arizona. The results were consistent (but inverse) with those observed in the Pacific Northwest. The streamflow-SOI relationship was strongest (but negative) during the cool PDO phase and there was no statistically significant relationship between streamflow and SOI during the warm phase. In addition, when composites were constructed based on PDO, differences in the monthly hydrographs were more consistent than those observed in western Oregon and Washington. The peak flow month was consistently shifted depending on PDO phase, with an earlier peak occurring during cool phase PDO, regardless of whether an El Niño and La Niña occurred.

A New Forecasting Procedure

Using these results, a forecasting procedure was developed. The starting point for this procedure is current method for developing seasonal streamflow forecasts developed and regularly applied by the NRCS. The process for forecasting is as follows:

1. Seasonal forecast models are developed for low and high PDO periods using the NRCS procedure resulting in a statistical model of the streamflow volume for each for each forecast period.
2. Forecast volumes for the selected forecast period, including the random component, are simulated from the model with the number of simulations from each model determined by the probability of being in a low or high PDO period, based on the most recent value of the PDO
3. Each forecast volume is disaggregated based on the appropriate disaggregation model, also selected based on a low or high PDO.
4. The resulting monthly flows can be used in a reservoir simulation or optimization model

The new model was verified by cross validation and by a forecast model developed on all the data without consideration of the PDO. The mixing of the split seasonal volume forecasts resulted in more accurate mean forecasts with more consistent estimates of variability. Further, the mixing of the split forecasts better estimated the flows in the upper terciles, however improvements in lower tercile estimates are inconclusive. The control or all data equations underestimated the high flows during the cool PDO phase and overestimated the flows during the warm PDO phase. While the mixed split forecasts were still slightly biased, the new model produced results that were significantly better than the control.

The mixed split forecasts were further evaluated and they were able to produce consistent mean monthly forecasts with less variability in the early forecast periods, with the exception of the October-September forecast, which only made use of the historical mean and standard deviation for the warm PDO phase forecast. The results suggest that not only can seasonal streamflow volume forecasts be extended reliably back to the October-September volume, but further that the disaggregation of those forecasts into monthly values can be accomplished to provide additional information to water supply management.

The method was applied to forecast monthly streamflow for the Sandy River for water year 2000 as a verification of the split forecast method. Only the November volume is outside the 50% confidence limits. Further, many of the volumes are very near the median forecast.

Although it has been shown that mixing disaggregated volume forecasts based on the PDO improves the skill of seasonal streamflow forecasting, the process of splitting the historical data by the phases of the PDO and fitting forecast equations for both phases is data intensive. Many forecast sites will not have data over a long enough period of record to adequately fit forecast equations for both phases of the PDO. Even though some forecast sites will not support the new forecast methods described here, integration of the PDO and disaggregation into statistical streamflow forecasting will benefit water supply management in the future.

Reservoir Management

Two important factors in reservoir management problems are the prediction of value of storage (in particular expected value of water in storage at the end of a planning period) and inflows. Together with information on the state of the reservoir, these factors constitute the information needed necessary by decision-makers to determine the release decision. Deterministic optimization models are based on deriving a release policy that optimizes a given objective. Such approaches do not account for the fact that the release, that is a function of random inflow thus a random variable itself, may have a distribution with different variance measure based on the available forecasts. Stochastic optimization methods have been developed but do not easily accommodate updating of forecasts in time, are difficult to implement in real-time and do not consider temporal or spatial correlation between inflows. The presented methods overcome this primary difficulties and were incorporated in a user friendly Decision Support System to provide users easy access to important information to assist in their decision making process.

Benefit function analysis and real-time implementation

While much effort has been placed in developing an efficient method to incorporate the uncertainty in inflows and their spatial and temporal correlations in reservoir operations, very few approaches (e.g., Dynamic Programming) use the benefit (Cost-to-Go) in a real-time implementation. Here, the parameter iteration method (Gal, 1979; Zhang et al., 1991) is used to approximate the value of the benefit function (or the Cost-to-Go). This approach allows temporal and spatial correlations in streamflows to be directly considered in the decision process.

The nonlinear programming temporal decomposition approach developed in this project (Ahmed et al, 2001) accounts the value of water at the end of the operating horizon as a *boundary condition.* However a windowing approach is applied so that a fixed first period decision is made but future decisions may vary based upon the likelihood of the event occurring. Future decisions are then updated, as information becomes available (either as actual flows or as improved forecasts). Lagrangian Duality (Nash and Sofer, 1996) is applied to find these real-time operating policies and is applicable for deterministic and probabilistic forecasts.

The model is applied on the Salt River Project multi-reservoir system in Arizona with power production objective. Results demonstrate show the influence of forecast length and statistical parameters on the system output and decisions.

Mean-variance model for reservoir operations

Since operators often desire to minimize the uncertainty in their decisions, the variance of the objective (expected return) can be used to measure the robustness of an operating (release) policy. A mathematically sound mean-variance formulation is implemented in real time that considers spatial and temporal correlation in streamflows (Ahmed and Lansey, 2001a). The foundation of the formulation is rooted in stochastic portfolio optimization scheme of Markowitz (1959). The variance-constrained problem is solved by a series of relaxations. In essence, this is the *penalty function approach* in which constrained problems are solved using penalized relaxations (Nash and Sofer, 1996) and a multiplier-based penalty approach. Details of the mathematical derivations and solution techniques are discussed and applications presented in the above reference and Ahmed (2001).

To implement the mean-variance formulation, the uncertain *benefit* (expected value of water) at the end of the operating horizon is quantified using the parameter iteration method (Zhang et al., 1991). From a multivariate regression analysis the correlations between the parameters of the benefit function of an assumed form is obtained and introduced in the variance structure for the last period in a *windowed* operating horizon. The model is applied on the Salt River Project multi-reservoir system in Arizona using a power production objective.

Decision Support System for multi-reservoir system operation: Implementation, Workability and Applications

To provide user access to the methods developed, the mathematical routines for forecasts and optimization are incorporated in a user-friendly decision support system for multi-reservoir management under hydroclimatic uncertainties (Ahmed and Lansey, 2001b). The DSS was developed to operate multi-reservoir systems under hydroclimatic uncertainty using a Visual Basic Shell with *point-and-click* approach to provide system information. This interface is used to select the reservoir system configuration and guide the user to set up or update the database and generate a reservoir operation policy. The system accesses a database to locate the necessary data and utilizes a repertoire of mathematical and/or statistical models to provide and present the desired information at the user's terminal. The DSS incorporates four basic models: Synthetic Streamflow Generation Model, Forecast Model, Reservoir Simulation Model, and Optimization Model. Each model refers to relevant database and necessary sub-models. Reservoir simulation provides the users an ability to analyze alternative operation policies and compute the resulting responses of the systems. One would expect that permutation of the optimal policy to be examined to examine the sensitivity of the solution to changes in inflow. All optimization methods described above were imbedded in the DSS.

Optimal design and operational model for the Santa Ynez river basin reservoir system

A reservoir design and operation model for the Santa Ynez river basin of southern California has been developed. Inputs to the model are reservoir rainfall, reservoir evaporation, runoff accretions between reservoirs, water diversions and required fishery releases, reservoir area vs. storage functions, cost data for reservoir construction. The user must specify reservoir-storage and release constraints as well as choose between alternative objective functions. The model was designed for easy implementation based on Excel data files and solver for optimization problems. The combination design/operation problem is difficult to solve, as it requires multiple operation problems to be solved for alternative reservoir capacities. The simple approach here overcomes that difficulty.

C. Principal Findings and Significance

Current methods for seasonal water supply forecasting were expanded and potentially improved significantly in this project. These improvements came from several components of the work.

An analysis of the effects of the Pacific Decadal Oscillation (PDO) on the relationship between streamflow and ENSO as measured using the SOI revealed that the streamflow-SOI relationship was modulated by PDO and with a stronger (weaker) than average relationship when the PDO was in the cool (warm) phase. Since SOI is the primary long-lead predictor of streamflow, its utility depends on the PDO. This behavior was observed in both the Pacific Northwest and the Southwest. This insight expands our current understanding of the relationship of regional climate and hydrology to large-scale behavior in the atmosphere and oceans. The observation on the effect of PDO on streamflow led to the modification of the existing forecast procedures used by NRCS to incorporate this information and provide a better indication of forecast uncertainty: less during low PDO and more during high PDO periods. Working directly with NRCS forecasters on this project has assured that these techniques will be incorporated in to the procedures.

A further addition to the forecasting procedure was the disaggregation of seasonal streamflow volume (ranging from a year to several months) into monthly volumes for use in reservoir operation models. Here again, the PDO was used based on the observation that a different average pattern of flow occurred during the two different phases of the PDO. Thus a different set of disaggregation model parameters was identified and applied for each period.

In summary, the potential exists for this work to contribute to improvements in water supply forecasting. During low PDO periods, the utility of the SOI as a variable in forecasting improves markedly for all cases evaluated. This result implies that there is the possibility to forecast not just streamflow resulting from snow accumulation and melt but also the portion of the hydrograph due to rain, thus expanding the forecast capability. On the other had, the SOI is apparently not useful in forecasting when the PDO is in the high phase. In both cases, that is for low and high PDO, a better estimate of the uncertainty of forecasts would result based on this information. Finally, an understanding of differences in the monthly distribution of seasonal flow is useful for the operation of reservoirs, and potentially for other purposes. This work is being used as the basis for the development of conditional disaggregation models, that is models that will distribute the seasonal flows throughout the season as monthly flows. If the typical distribution were different for low vs. high PDO, a different model would be required.

The overall objective behind the development of the optimization schemes was to incorporate hydroclimatic uncertainty in streamflow prediction and study its influence on our multi-reservoir systems. The optimization algorithms developed can consider the two important factors in reservoir management problems: the prediction on *benefits* and *streamflows*. For a 20- year simulation on the Salt River Project multi-reservoir system, the parameter iteration method successfully converged to optimal parameter values for an assumed benefit function (Zhang et al., 1991). This lead to a series of successful runs in real-time with perfect forecast generated from multiple-regression analysis. The real-time algorithm takes into account the remaining benefit of water at the end of the operating horizon, and enables the DSS user to perform *windowed* runs with different forecast length to better assess the monthly expected return when several streamflow scenarios (due to uncertainty) play important role in decision-making. The Decision Support System developed is a computer-based information system that will help multi-reservoir managers, in general, to make decisions by accessing relevant physical data in an *easily understandable* form.

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Basic Information

Title:	Using Ground Penetrating Radar to Estimate Recharge from the Rillito Creek
Project Number:	B-04
Start Date:	3/1/2000
End Date:	2/28/2001
Research Category:	Ground-water Flow and Transport
Focus Category:	Management and Planning, Water Supply, None
Descriptors:	infiltration rates, drainage, soil properties
Lead Institute:	The University of Arizona
Principal Investigators:	Paul Andrew Ferre

Publication

1. Quijada, Brandon; Warren Thiptus; Paul Ferré, 2001, "Can Ground Penetrating Radar Be Used to Quantify Recharge in Rillito Creek?", Undergraduate Research Grant Forum, University of Arizona Honors College, February 7.
2. Thiptus, Warren; Brandon Quijada; Paul Ferré, 2001, "Can Ground Penetrating Radar Be Used to Quantify Recharge in Rillito Creek?", El Dia del Agua, Department of Hydrology and Water Resources, University of Arizona, April 4.

A. Problem and Research Objectives

The objective of this research was to determine whether ground penetrating radar (GPR) could be used to make nondestructive measurements of infiltration rates into the bed of Rillito Creek following natural flow events. GPR measures the two-way travel time of electromagnetic waves from the ground surface to a reflective target (e.g. a metal pipe) in the subsurface. This travel time increases with increasing saturation of the sediments above the target, potentially allowing for measurement of the amount of water stored in the subsurface. Measurements of the change in water storage with time can indicate the rate of drainage following a surface flow event. This can then be related to the hydraulic properties of the soil that control infiltration rates.

B. Methodology

The research was conducted in four steps. The first three steps were completed in an effort to optimize signal quality. The final step was completed to attempt to explain the observed results.

Step 1: Establishing GPR targets. An ideal GPR target consists of a metallic pipe of at least 30 cm in diameter buried between 1.5 and 3 meters below ground surface. A survey of buried utilities was conducted for the entire reach of Rillito Creek. Most buried utilities were found to be either too small in diameter or too shallow to act as GPR targets. However, preliminary surveys were conducted over a series of buried pipes located near Dodge Boulevard to preclude their use. Survey results showed that these pipes did not provide useful GPR targets. Based on historical records we also located a water conduit near Craycroft Boulevard that was installed and used by Mormon settlers. While this target could be identified at select locations in the creekbed, it was not continuous enough to allow for reliable infiltration measurements. Given the inability of GPR to reliably identify existing buried targets, two metal pipes were buried in the creekbed to improve our surveying efforts. Each pipe was 0.75 m in diameter. A trench was dug near Dodge Boulevard with a backhoe. One pipe was buried in the trench at a depth of 1.5 meters and the second pipe was buried at a depth of 2.5 meters. The trench was backfilled with streambed materials.

Step 2: Optimizing GPR collection parameters. The bed of Rillito Creek proved to be a difficult environment for collecting useful GPR data. Therefore, the majority of the efforts expended on this project were spent optimizing the GPR collection parameters to improve GPR signals. The buried pipes were used as targets during these optimization activities. The primary control on signal quality was the choice of an appropriate antenna frequency. We tested 25, 100, and 200 MHz antennae. The 200 MHz antennae were found to give sufficient depth of investigation while maximizing near-surface detail. In addition to antenna selection, the following system parameters were optimized: transmitter voltage, signal stacking, step size, and antenna separation.

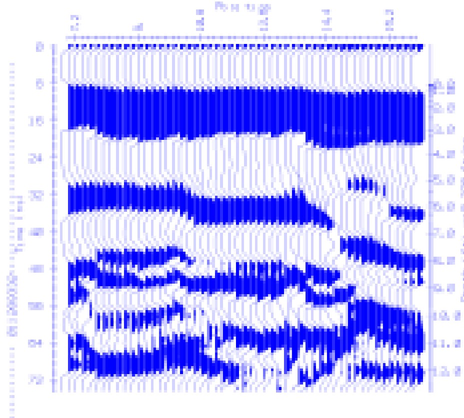

Figure 1: Data collected with a 100MHz Antenna.

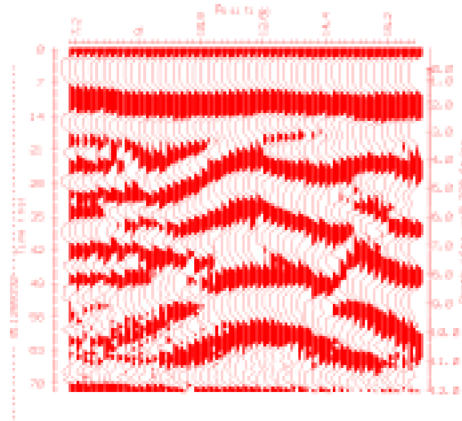

Figure 2: Data collected with a 200MHz Antenna.

Figure 1 and 2 show how each of these parameters can be optimized to improve signal quality. Notice the parabolic reflectors visible in the center of Figure 2 that are not evident in the traces collected with 100 MHz antennae. Our optimized system used a 1000V transmitter with 128 times stacking, a step size of 0.1 feet and 200 MHz antennae separated by a distance of 2 feet.

Step 3: Data Collection and Interpretation. GPR surveys conducted over the buried pipes did not show the parabolic reflections characteristic of these targets (Figure 3). It is hypothesized that the extreme variation in grain size, ranging from silt to very large boulders, led to excessive scattering of returning signals, obscuring any useable reflections. However, examination of the GPR records shows apparent flat lying reflectors, which may be associated with changes in subsurface geology or water content. Additional efforts focused on examining the change in travel time to these flat-lying reflectors. However, there was no consistent observed change in travel times to these targets following a flow event.

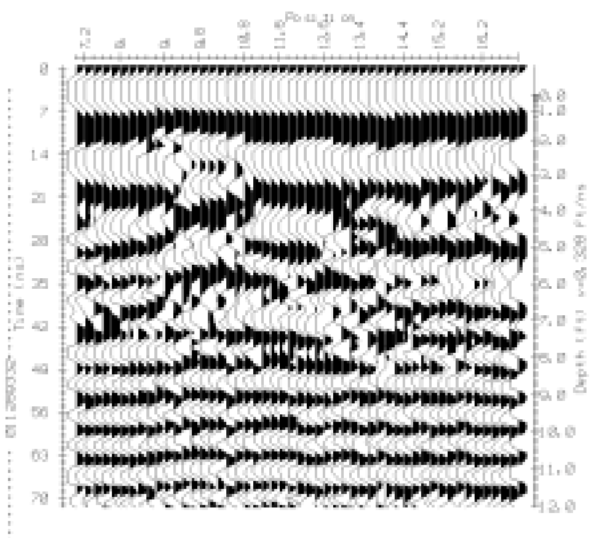

Figure 3: Inconclusive transect.

Step 4: Explanation of GPR Results. Given the inability of GPR to detect changes in near surface water content, we designed a monitoring network to measure the water content at discrete depths using buried TDR probes. Whereas GPR measurements require that an operator walk in the streambed, buried TDR probes can measure the water content continuously without an operator. Therefore, while TDR can capture the water content drainage immediately following cessation of flow, GPR measurements typically began 6 to 18 hours following cessation. This delay was due to the time lag between notification of cessation and mobilization of the field crew. In addition, safety considerations limit the minimum time following flow when the creekbed can be accessed. Figure 4 shows the water content as a function of time immediately following a flow event. The results indicate that the upper 1.5 meters of sediment had dried completely within 0.5 days. This extremely rapid drainage adequately explains the inability of GPR to identify water content changes; drainage was likely nearly complete before the surveys began.

C.

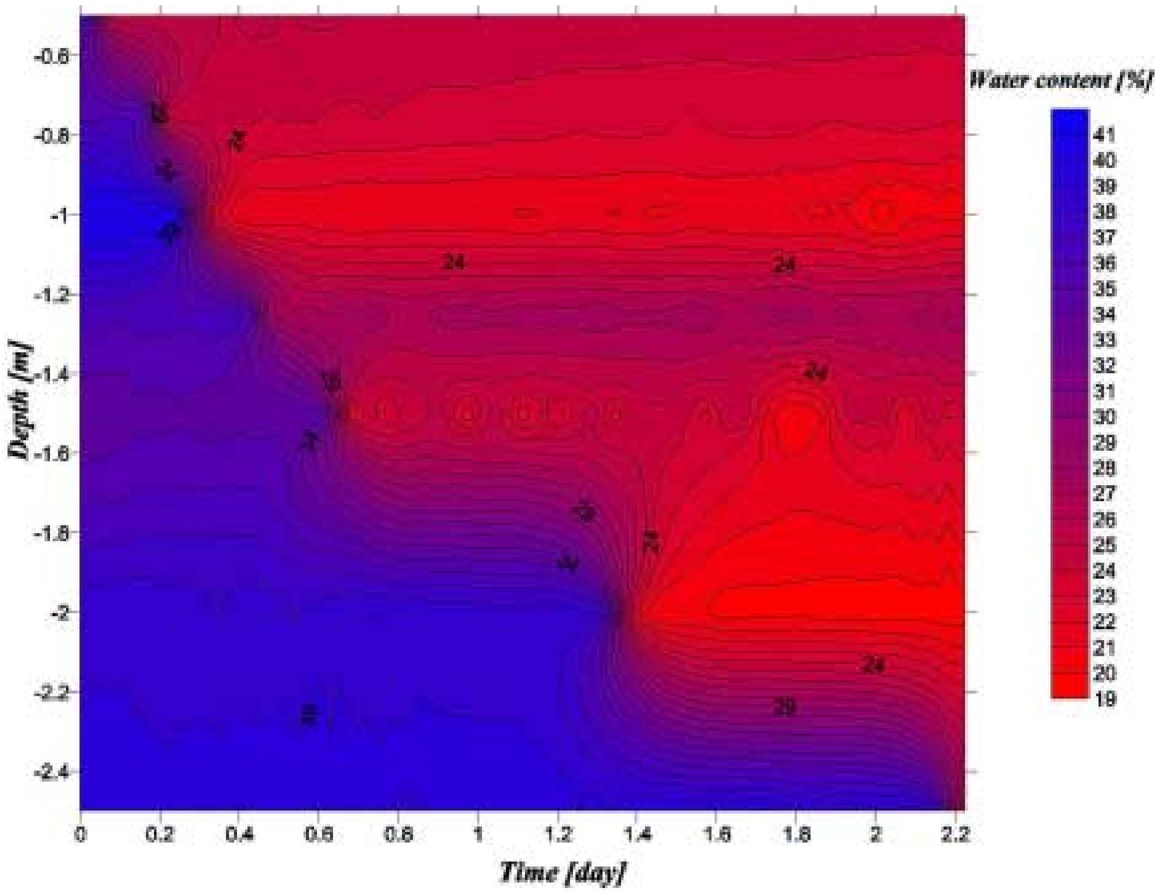

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Figure 4: TDR data collected after a surface flow event.

Findings and Significance

Although we were unable to monitor drainage in Rillito Creek using GPR, the study did produce several useful results. The rapid rate of drainage of the subsurface sediments measured with TDR was unexpected. This finding suggests that evaporative loss following flow events is minimal, facilitating the direct use of infiltration measurements to estimate recharge beneath the streambed. The limitations to using GPR in ephemeral streambeds posed by the presence of large boulders were also unexpected. Given that these materials are not identifiable from standard drilling and boring activities, it is recommended that shallow trenching be conducted at sites of potential GPR monitoring to allow for visual inspection of the particle size distribution. Finally, the ability of GPR to locate the buried water conduit demonstrates the promise of this technology for archaeological investigations. However, the same cautions listed above should be applied to identify which environments will be amenable to GPR surveying.

Basic Information

Title:	Field Studies of Virus Transport Through Unsaturated Alluvium and Fractured Rock
Project Number:	B-05
Start Date:	3/1/2000
End Date:	2/28/2001
Research Category:	Ground-water Flow and Transport
Focus Category:	Water Quality, Groundwater, Hydrology
Descriptors:	groundwater, virus, virus transport, groundwater chemistry, unsaturated flow, wastewater irrigation, groundwate recharge
Lead Institute:	The University of Arizona
Principal Investigators:	Mark Brusseau, Charles Gerba

Publication

A. Problem and Research Objectives:

Enteric virus contamination of groundwater used for potable water is of increasing concern (U.S.E.P.A., 2000). This concern has fomented interest in the transport and fate behavior of viruses in the subsurface environment. Accordingly, several bacteriophage transport studies have been conducted under well characterized conditions (see recent review by Schijven and Hassanizadeh 2000). Because of the hazards and costs associated with human viruses, the bacteriophage PRD-1 is often employed as an analogue to viruses of concern to human health (Gerba, 1984; Bales et al. 1993). The results of this previous work indicate that aquifer physical/chemical properties (e.g. permeability, aquifer heterogeneity, pH, temperature, total dissolved solids, and dissolved organic matter) influence the transport and fate of virus. Within the aquifer environment the factors controlling virus transport are attachment to and detachment from the porous medium surfaces, growth and inactivation, filtration, sedimentation, advection, and dispersion.

This study was initiated with the objective of isolating the influence of groundwater chemistry on the transport and fate of viruses under field conditions. The sewage plume at the Cape Cod site is higher in pH, ionic strength, and dissolved organic matter than the uncontaminated groundwater at the site. Experiments were conducted in both sewage-contaminated and uncontaminated zones to examine the impact of water chemistry on virus transport. The experiments were conducted at a larger scale than previous studies to provide additional information regarding transport behavior.

B. Methodology:

Site Description

Surficial strata at the site is associated with the last Pleistocene glacial retreat, which occurred approximately 14,000 years ago. Deposited in the top 9 to 15 meters is a section of outwash material consisting of well-sorted medium to coarse sand with some gravel (Leblanc, 1984). In the northern portion of the area, the sand and gravel overlie fine sand and silt lenses. To the south, the outwash material appears above fine sand, silt, and a dense sandy till. The till contains lenses composed of silt and clay, and others of sand and gravel. These unconsolidated sediments reside atop a crystalline graniodiorite bedrock which generally slopes from west to east through the region.

The site has a shallow aquifer of thickness varying between 90 and 100 meters, the top of which is 3 to 7 meters below land surface in the study area (Leblanc et al. 1991). The horizontal hydraulic conductivity in the sand and gravel zone is estimated to be from 60 to 120 meters per day (Leblanc, 1984, Garabedian, 1988). The fine sand and sandy till is postulated to be one-tenth as conductive as the sand and gravel (Leblanc, 1984). The water table is unconfined and slopes south to southwest at about 1.5 meter/km (Garbedian, 1988). The groundwater flows horizontally with a velocity in the range of 0.2 to 0.7 m/day in the sand and gravel. The porosity is reported to be between 0.2 and 0.4 (Leblanc, 1984).

Portions of the aquifer are heavily contaminated by sewage disposal from Otis ANGB. The sewage effluent emanates from sewage infiltration beds up-gradient of the experimental station. In 1979, the contamination plume was 0.8 to 1.1 kilometers wide, 3 meters thick, and more than 3.4 km long (Leblanc, 1984). The body moves with the ambient groundwater flow in a south to southwest direction. It is overlain by 15 meters of uncontaminated water originating primarily from infiltration of local precipitation. Elevated levels of dissolved solids, boron, chloride, sodium, phosphorous, ammonium, nitrate, and detergents characterize the plume (Leblanc, 1984). In some locations, volatile organic compounds are also in the plume (Thurman et al., 1984). There background concentration of the bacteriophage used in this study, PRD-1, was below detection limits of 0.25 pfu/ml and the bromide was below 0.2 mg/L.

The site is instrumented with an array of multi-level sampling wells. Sampling ports protrude out the side of each well in an up-gradient direction at approximately 25 cm intervals. The sampling lines are polyethylene tubes with 0.47 cm inside diameter and 0.64 cm outside diameter and the wells are PVC casing with a 3.17 cm diameter (Leblanc et al., 1991). A more complete description of the site is found in Leblanc et al. (1991).

Experimental Design

Groundwater samples were collected from all sample ports prior to the tests. Bromide and PRD-1 were both below their respective quantifiable detection limits (PRD-1 detection level < 0.25 PFU/ml, and bromide 0.15 mg/L). Analysis of the vertical profile of pH, electrical conductivity, and temperature in well 6-16A showed variation in water chemistry between the sewage-contaminated and uncontaminated zones (see Figure 1). In contrast, similarities in the bromide transport results for this study at the two experimental depths show that the study zone has a relatively uniform distribution of hydraulic properties. This condition enables the isolation of the relative influence of groundwater pH, ionic strength, and dissolved organic matter on the bacteriophage fate and transport.

For the first study (deep-plume experiment), approximately 600 liters was withdrawn by a peristaltic pump with norprene tubing from two ports in well 6-16 and from two in well 6-16A (see Figure 2). The depths of the ports are 10.46 and 10.72 meters above mean sea-level (see Figure 2). The bacteriophage PRD-1 and potassium bromide were mixed into groundwater withdrawn from the injection location. The solution was injected through the same ports from which the groundwater was extracted. Sixty-seven grams of potassium bromide salt was dissolved into the water equating to a Br^- ion concentration of 75 mg/L. A solution containing the bacteriophage PRD-1 served as the viral tracer. The water at the time of injection had an electrical conductivity of 530 µ-siemens/cm, pH of 6.14, a temperature of 15°C, a bromide concentration of 75 mg/L, and a concentration of 10^{11} PRD-1 plaque forming units per ml (pfu/ml). This temperature is slightly above the natural groundwater temperature at the injection location (14.5^{o}C) (see Figure 1). Injection of the 600 liters into the four injection ports was completed in approximately 162 minutes.

For the second study (shallow-plume experiment), approximately 300 liters of groundwater was withdrawn from one port each from wells 6-16 and 6-16A at 12.75 meters above mean sea-level (see Figure 2). It was spiked with the potassium bromide salt, and PRD-1 bacteriophage from the same source as used for the first experiment. These led to concentrations of 75mg/L Br^- and $2.6x10^{14}$ PFU/ml PRD-1 at the time of injection. After cooling with blue ice, the injectate had a conductivity of 335 µ-siemens/cm, pH of 5.5, and a temperature of 10.6^{o}C.

Samples from the injection wells after completion of injection showed that the aquifer had mitigated the lower temperature of the injected solution to equal the natural level of 13°C. The solution was injected into the same ports from which the groundwater was extracted, and was completed in approximately 140 minutes.

Bromide concentration was measured in the field using both a bromide-specific electrode and an electrical conductivity detector. Samples for bacteriophage analysis were sent to off-site laboratories at the University of Arizona. To reduce potential for cross-contamination, sampling ports were flushed prior to sampling. For the first four days, 250 ml was extracted prior to sample collection. This amount is approximately three times the volume of water for the deepest port sampled (9.7m below sea-level). However, based on initial results, the flush volume was reduced to 100 ml to reduce the volume extracted for each sampling round.

The sampling procedure for PRD-1 involved pouring 20 ml of groundwater into polystyrene vials containing approximately 10 milligrams of beef extract powder to preserve the bacteriophage. To further preserve viability, the vials were chilled to 4°C. Bromide concentration, conductivity, and temperature were determined using another 50 ml. Also, 250 ml samples were intermittently drawn for analysis of microspheres. In total, at most 560 ml was extracted per sample for the first 4 days of the study and 370 ml afterward. Preserved PRD-1 samples were shipped overnight to the University of Arizona and were analyzed within two days of receipt.

PRD-1 Concentration Analysis

The bacteriophage PRD-1 is an icosahedral (twenty triangular faces) lipid containing bacteriophage with an average diameter of 62 nm (Olsen et al., 1974). The lipid-containing protein cover of PRD-1 promotes hydrophobic behavior (Bales et al., 1993). Additionally, the protein coat contains amino and carboxyl groups that can lead to electrostatic sorption. For PRD-1, the point of zero net surface charge or isoelectric point was found by Dowd et al. (1998) to be a pH of 4.2. PRD-1 was judged by Blanc et al. (1996) to be more suitable than another widely used enteric virus analog tracer, MS-2, for determining the persistence of pathogenic viruses.

Bacteriophage concentration was determined by plaque counting techniques previously described by Bales et al. (1991). Because of low potential for aggregation, each PFU represents a discrete viral particle (Sharpe, 1965). Most precise counting results are for plates with 30 to 150 plaques ±20% (ASTM, 1991). Because of only limited knowledge of potential bacteriophage concentration, normally three analyses were done covering 3 to 4 orders of magnitude of concentration.

In order to examine the accuracy of the analysis methods, multiple plaque assaying of field samples were performed. Five field samples with a range of concentrations were assayed 25 times each. No dilutions were made of these samples. The five average concentration were 5.2, 30.4, 98.7, 294.2 and 450.2. The respective coefficients of variation were 0.30, 0.14, 0.06, 0.14 and 0.18. These results show that the most confident determination of PRD-1 concentrations are achieved with assays whose PRD-1 plaque counts were near 100.

Of the field samples, the vast majority were assayed once at a particular concentration. Ten percent of the field samples were analyzed twice. A measure of analytical accuracy can be made by evaluating three subsets of 25 each from the samples that were analyzed twice. The subsets were chosen where the average of the 25 samples were close to the counts 5.2, 30.4 and 98.7 from the previous plaque-assay reliability study. The averages of the three subsets of field samples are 5.2, 30.1 and 99.1. The average coefficients of variation of the duplicates subsets are 0.26, 0.12, and 0.06. These levels of variation compare favorably with the results where individual samples were analyzed 25 times each.

The inactivation rate of the bacteriophage PRD-1 in groundwater from the site was investigated under controlled conditions in the laboratory. Following the method of Yahya et al. (1993), 45 ml samples of groundwater from the same ports as those used for injection of the viral plumes were collected in polypropylene tubes and spiked with 5ml of solution containing the PRD-1 to a concentration near 10^8 pfu/ml. These samples were then kept in a constant temperature water bath of 13°C, which is approximately midway between the temperatures of the shallow and deep injection (see Figure 1). The concentration of PRD-1 in the vials was periodically measured over the next 75 days. The concentration was determined twice at two different dilutions.

The concentration of active viral particles (pfu/ml) declined over time for both solutions. A log-linear regression of the results best approximated the decrease in the observed aqueous concentration of PRD-1 in both the shallow and deep groundwater samples. The fits for the exponential model are 0.900 and 0.960, respectively, for the shallow uncontaminated and the deep sewage-contaminated groundwater. The slope of the regressions indicate that the inactivation of virus in the groundwater in the shallow and deep experiments would decrease viral concentration by an order of magnitude every 554 and 565 hours, respectfully.

Data Analysis

The time at which viruses reach a point can be estimated through analysis of the frontal portion of the virus breakthrough curve. Local aquifer physical properties can be determined from the transport of a non-reactive tracer. Bacteriophage in this sand and gravel aquifer will be exposed to similar flow conditions, but their movement is also influenced by chemical interactions within the aquifer. By comparing bromide and PRD-1 propagation patterns, the influence of physical and chemical properties on PRD-1 transport may be evaluated.

The movement of the virus and bromide groundwater plumes was determined from the trends in the calculated temporal moments of the breakthrough curves of these tracers at the monitoring points down-gradient of injection. In this analysis forward-difference versions of the temporal moment analysis equations were used. Specifically, trends in the zeroth temporal moment (t_o) integrates the area under the breakthrough curve, which reflects the mass of tracer traveling through the vicinity of the sampling port.

Velocity calculations were made through comparing the average time of arrival or time of the peak observed concentration for all ports at a single depth with complete breakthrough curves with the distance from the midpoint of injection for those observation points. The velocity is computed as the inverse slope from linear regression analysis of the time versus distance data. Overall retardation factors for the bacteriophage tracer were calculated by layer. This was accomplished through dividing the computed bromide velocity by that of the virus velocity. Secondary retardation analysis was performed through determining the existence of any trends with distance from observation in the ratio of the virus to the bromide average arrival time.

C. Principle Findings and Significance:

Results indicate that during the two field experiments the vast majority of the bacteriophage were either lost due to inactivation or “irreversibly” lost from the fluid phase due to retention by the aquifer solids, and hence were not transported in viable form via groundwater during the time period of this study. The shallow and deep experiments vary in the amount of viral mass transported to the first downgradient sampler. For the deep experiment performed in the contaminated groundwater, the viral mass decreased to $10^{-4.5}$% relative to the observed bromide mass between the injection well and first down-gradient sampler (1.15 m). For the same distance, the loss for the shallow plume was much greater with the ratio of bromide to viral mass decreasing to $10^{-10.1}$%. The higher initial loss in the shallow plume is likely due to the lower levels of organic matter and dissolved anions and to a lesser extent the lower pH (5.7 versus 6.1) of that groundwater. Decreases in each of these factors favors greater electrostatic exchange of negatively charged viruses to the positively charged ferric oxyhydroxides and clay minerals which coat portions of the soil grains. Sorption in this manner is predominantly irreversible during short time spans unless groundwater chemistry is altered.

The results showed that the viral plume in the contaminated groundwater required a much larger volume of aquifer than the uncontaminated region of the same aquifer to reduce similar numbers (10^{-7}% C/C_o) of mobile virus. As shown in a smaller-scale study by Ryan et al. 1999, this could be attributed to the fewer sites on the positively charged ferric oxyhydroxides and clay mineral soil coatings being available for the negatively charged virus to electrostatically exchange due to competition for those sites by organic matter, phosphate, and other anions.

After the initial high rate of loss in viral mobile mass seen in the first 4.4 m of transport through the sewage contaminated groundwater and in the first 1 m of the uncontaminated groundwater, the remaining viral mobile mass levels decreased at far slower rates. These mobile virus traveled at nearly the same rate as bromide, and experienced rates of concentration decline consistent with hydraulic dilution effects. The velocity of unattached PRD-1 is within ±30% of the Br^- velocities. Most of the differences in calculated travel times result from more extensive tailing of the PRD-1. The tailing in the breakthrough curves is most likely due to rate-limited desorption of previously adsorbed bacteriophage. The results of this study indicate that a small, but infectious fraction of viable virus particles can persist and travel significant distances in sedimentary aquifers, despite differences in water chemistry.

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Figure 1 pH, Temperature, and Electircal Conductivity Vertical Profile from Injection Well 6-16A Prior to Test

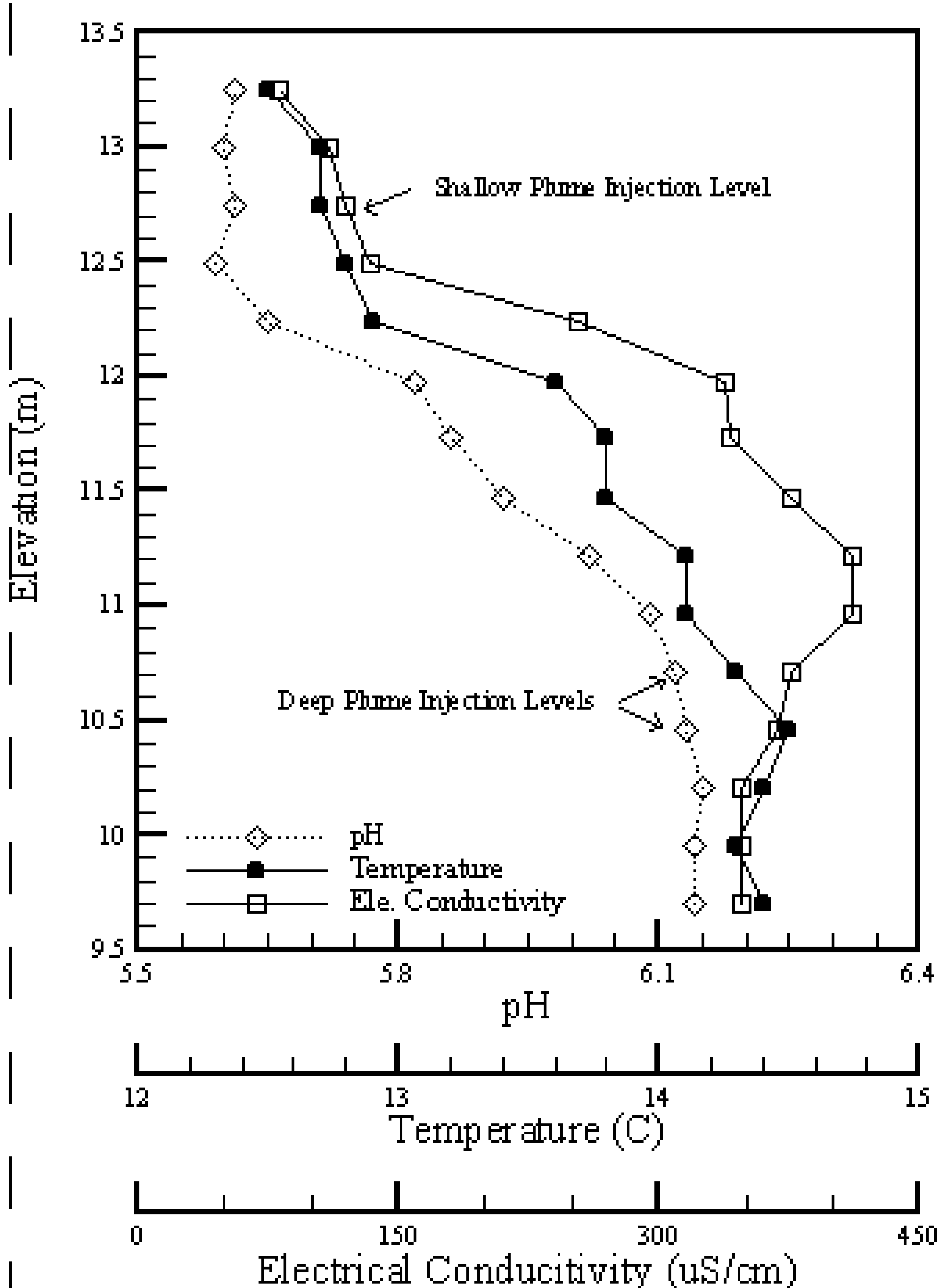
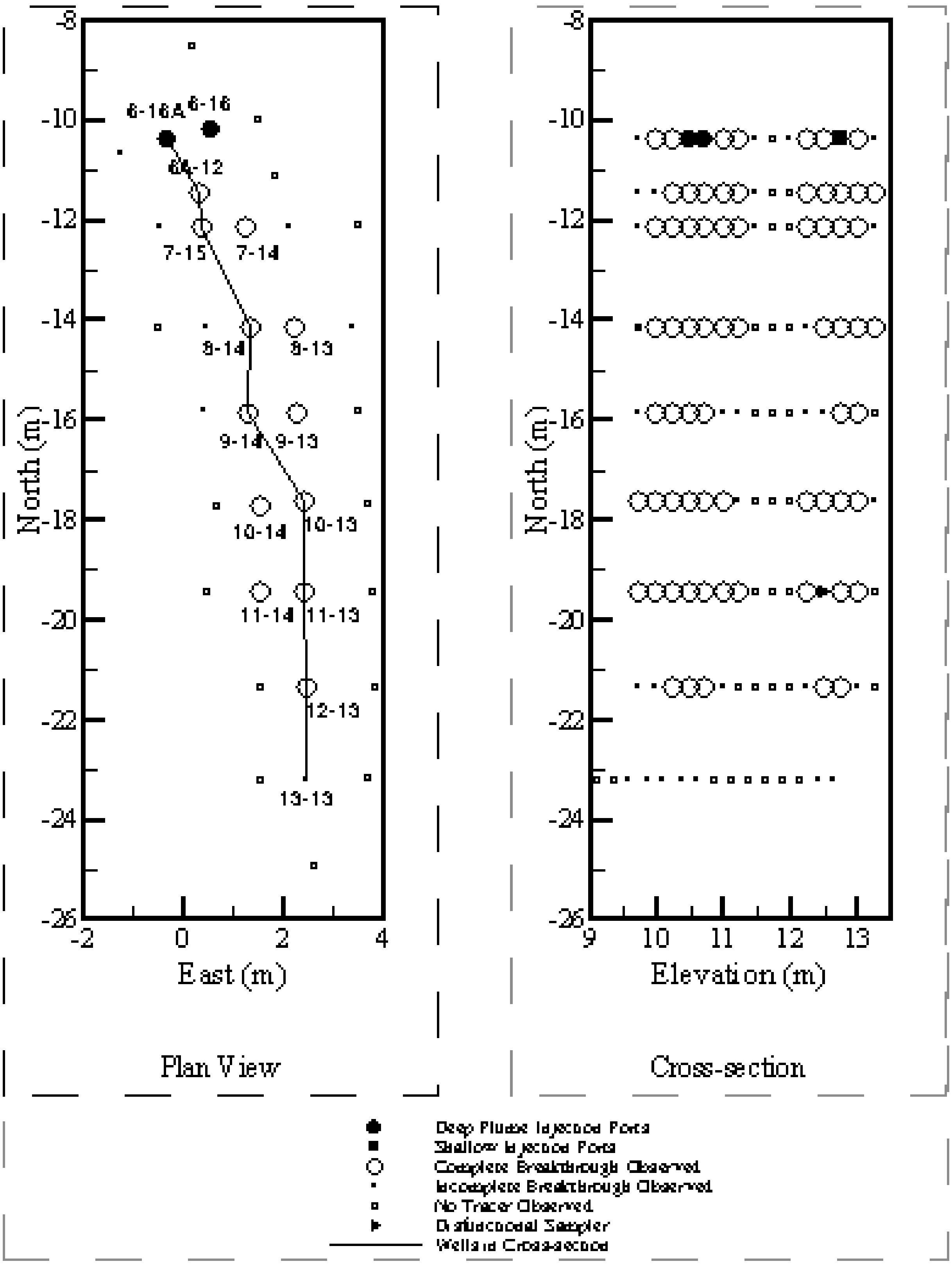


Figure 2 Location of Sample Ports Utilized in the Experiments



Information Transfer Program

The Water Resources Research Center at the University of Arizona engaged in three categories of activities, throughout the reporting period. First, the Center carried out general activities to educate the public about water issues in the state. These activities include, organizing conferences and workshops, writing reports, compiling directories, community presentations, designing exhibits, and publishing newsletters. Second, the Center has an ambitious and productive water education program for classroom teachers and educators, which reaches over 600 teachers annually and thousands of K-12 students, through Project WET. Third, the Center has pursued regional water conservation efforts through the Water Conservation Alliance of Southern Arizona (Water CASA) which, since its inception in 1997, has been recognized as both a leader and innovator in the conservation field.

Basic Information

Title:	Arizona Water Resource Newsletter
Start Date:	3/1/2000
End Date:	4/30/2000
Descriptors:	Water Management, Central Arizona Project, Groundwater Management Act.
Lead Institute:	The University of Arizona
Principal Investigators:	Joseph Gelt

Publication

12 page newsletter presenting general news, events and issues analysis for Arizona water community. The lead article is “20 Years of the Groundwater Management Act: form secret negotiations to public policy.” A second lead article is, “Feds, State Work Out Central Arizona Project. (CAP) Cost Settlement: other issues await settlement before final approval.”

Basic Information

Title:	Arizona Water Resources Newsletter
Start Date:	5/1/2000
End Date:	6/30/2000
Descriptors:	Historical Water Records, Arcata Marsh
Lead Institute:	The University of Arizona
Principal Investigators:	Joseph Gelt

Publication

12 page newsletter presenting general news, events and issues analysis for Arizona water community. Lead article is “Arizona’s Care of Historical Water Records Shortsighted”.

Basic Information

Title:	Arizona Water Resource Newsletter
Start Date:	7/1/2000
End Date:	8/31/2000
Descriptors:	Settling Central Arizona Project, Pharmaceuticals in Water
Lead Institute:	The University of Arizona
Principal Investigators:	Joseph Gelt

Publication

12 page newsletter presenting general news, events and issues analysis for Arizona water community. Lead article is, “Pharmaceuticals in our Water Supplies: are “drugged waters” a water quality threat?” A second lead article is, “Halted Environmental Impact Statement (EIS) is Latest Incident in Ongoing Saga of Central Arizona Project Negotiations.”

Basic Information

Title:	Arizona Water Resource Newsletter
Start Date:	9/1/2000
End Date:	10/31/2000
Descriptors:	GeoPowering the West, Endocrine Disrupters.
Lead Institute:	The University of Arizona
Principal Investigators:	Joseph Gelt

Publication

12 page newsletter presenting general news, events and issues analysis for Arizona water community. Lead article is, “Endocrine Disrupters in Water: What are EDs? What risks do they pose?” A second cover article is, “Arizona Has Untapped Geothermal Potential.”

Basic Information

Title:	Arizona Water Resources Newsletter
Start Date:	11/1/2000
End Date:	12/31/2000
Descriptors:	Aquaculture, Subsidence Damages Private Property
Lead Institute:	The University of Arizona
Principal Investigators:	Joseph Gelt

Publication

12 page newsletter presenting general news, events and issues analysis for Arizona water community. Lead article is, “What Recourse is Available When Subsidence Damages Private Property?”. A second lead article is, “Aquaculture, a Global and State Growth Industry: farming the waters for varied payoffs.”

Basic Information

Title:	Arizona Water Resource Newsletter
Start Date:	1/1/2001
End Date:	2/28/2001
Descriptors:	Power Plants
Lead Institute:	The University of Arizona
Principal Investigators:	Joseph Gelt

Publication

12 page newsletter presenting general news, events and issues analysis for Arizona water community. Lead article is, “Power Plants in Arizona – an Emerging Industry, a New Water User: is review underway to ensure wise water use?”

Basic Information

Title:	Arizona Water Resource Newsletter
Start Date:	3/1/2001
End Date:	4/30/2001
Descriptors:	Urban Ecology, New Arizona Power Plants
Lead Institute:	The University of Arizona
Principal Investigators:	Joseph Gelt

Publication

12 page newsletter presenting general news, events and issues analysis for Arizona water community. Lead article is, "New Arizona Power Plants Pose Water Questions, Raise Issues." Second lead article is "Urban Ecology, Nature in an Urban Setting."

Basic Information

Title:	Water Resources Research Center
Start Date:	3/1/2000
End Date:	2/28/2001
Descriptors:	water conservation, water issues, graywater, water quality, water management
Lead Institute:	The University of Arizona
Principal Investigators:	Peter J. Wierenga, Terry Sprouse, Val Little, Kerry Schwartz, Barbara Tellman, Joe Gelt

Publication

1. Henderson, Jim, Gary Woodard, 2000, Functioning of Aging Low-Consumption Toilets, Water Resources Research Center, University of Arizona, Tucson, Arizona, 25 pp.
2. Tellman, Barbara, 2001, Water Conservation in Pima County: Sonoran Desert Conservation Plan, Water Resources Research Center, University of Arizona, 20pp.

WATER RESOURCES RESEARCH CENTER

Groundwater Management Conference

In May 2000, The Water Resources Research Center organized a statewide conference to commemorate the twentieth anniversary of Arizona's Groundwater Management Act, landmark groundwater legislation. The subject matter included a history of the law, accomplishments over the past twenty years in implementing the law, and identification of issues still in need of resolution. The conference was sponsored by many agencies and industries, most notably by the Arizona Department of Water Resources which not only contributed funds, but sent approximately 150 employees and members of advisory committees to the meeting. The Governor opened the conference with an announcement of formation of a Water Management Commission which will examine needed changes in the law. Approximately 350 people attended the conference, including representatives of statewide and local water agencies, water providers, industry, university faculty and nonprofit groups.

Report on Watercourses

WRRC staff produced a report in spring 2000 for Pima County entitled An Overview of Pima County's Watersheds and Watercourses. This report was coauthored by two local consulting firms who did mapping of floodplains as part of the study. It is one in a series of reports in preparation for Pima County's Sonoran Desert Conservation Plan, a county-wide plan designed to satisfy requirements of the Federal Endangered Species Act and to protect sensitive areas and habitats. This report dealt with the physical features of the watersheds and watercourses.

Water Conservation Report

WRRC staff produced another report in March 2001 for Pima County that described past and present water conservation efforts and the laws dealing with water conservation. This, too, was written for the Sonoran Desert Conservation Plan and will in the summer of 2001 result in revised ordinances in Pima County.

Invasive Exotic Species

WRRC staff completed editing of a book on invasive exotic species in the Sonoran Region, to be published by the University of Arizona Press in 2002. Significant portions of the book deal with invasive species issues in riparian areas and wetlands. The book covers both flora and fauna.

Pima Invasive Species Council

WRRC staff assisted with formation of the Pima Invasive Species Council which is an attempt to bring government agencies and nonprofit groups together to work on invasive species issues in southern Arizona and to cooperate with groups working in others parts of the state.

Aquatic Exotic Species Workshop

WRRC staff also assisted Pima County with a workshop held in February for professionals in riparian and wetland management on Aquatic Exotic Species in Pima County. Topics included bullfrogs, crayfish, invasive plants, and a variety of management strategies.

Water Information Directories

WRRC staff surveyed all Arizona water agencies and nonprofit groups dealing with water, as well as water researchers at the three state universities to produce an updated version of her previous two directories Where to Find Free (or almost Free) Information about Water in Arizona and Where to Find Water Expertise at Arizona Universities. These are now combined into one volume which will be published in June 2001 and distributed to libraries, government agencies, schools, the media, and the general public.

Ecological and Historical Exhibit

WRRC staff helped design a historical, ecological exhibit for the Mesa Southwest Museum entitled, "The Santa Cruz River". The exhibit also was exhibited in Tucson as well as other locations around the state.

Community speakers

Water center staff continued its visibility with the community by providing 20 presentations to various organizations around the state, discussing water issues confronting communities and the state. Staff also communicates with local newspapers, such as the "Arizona Daily Star" to provide information to reporters on water-related issues.

2001 Water Conference

Preparations were made for the 2001 Water Conference to be held in November. The theme of this year's conference will to examine the recommendations of the Governor's Water Commission, which will result in changes to the 1980 Groundwater Management Act.

Water Map Poster

Revisions are being made to update the popular Water Map Poster that the Center first published in 1994. Copies of the map, which was very popular with schoolteachers, state and federal agencies, as well as the general public, have been distributed and is now out of print. The map will use revised and updated text, map, graphics, and photographs. As the previous one, the new map will present complex subject matter in a format suitable for the general public.

Arizona Water Issues Report

A report is being prepared which describes key water issues in the state of Arizona. These issues include effluent use, riparian areas and shallow groundwater, U.S.-Mexican border issues, climate variability, the groundwater-surface water connection, water supply and population growth, and challenges inside and outside state Active Management Areas.

WATER EDUCATION PROGRAMS

The WRRC Education Program Coordinator is the state representative for the National Project WET (Water Education for Teachers) program. As such, the WRRC Education Program Coordinator is responsible for promoting an understanding of water and water-related issues statewide. Project WET activities provide an opportunity for people of all ages in all places to better understand the water resource issues facing their community and the world.

WRRC has an ambitious and productive water education program for classroom teachers and educators. WRRC coordinates a network of 30 trained facilitators that lead teacher training workshops for over 600 teachers per year and reach thousands of K – 12 students. This program reaches classroom teachers in public and private schools, youth groups leaders, tribal governments, environmental education centers (including gardens), community colleges and state universities.

The Education Program Coordinator for WRRC supervises an Environmental Educator whose job is to teach and promote the Project Learning Tree (PLT), natural resources-based program. Three student assistants also report to the Education Program Coordinator.

Project WET (Water Education for Teachers)

Teachers and educators trained this year in Project WET workshops numbered 632 with the capacity to reach a minimum of 18,000 students about water resources. As a result of an interagency agreement grant, sixteen-hour teacher training workshops are conducted for City of Phoenix Schools including 24 School Districts. At the University of Arizona and Northern Arizona University, day-long water education classes for Pre-service Teachers have been established. In addition, WRRC staff have facilitated workshops through Cooperative Extension specialists, the Science Coordinators and/or the Staff Development Coordinators for many School Districts in Arizona, Arizona State Parks, and the Natural Resource Conservation District Education Centers.

Considerable coordination efforts were involved in the successful 2-day workshop held in cooperation with the NAU Institute for Tribal Environmental Professionals (ITEP) and the Cooperative Extension Office in Shiprock on the Navajo Reservation. Water Education training workshops have been coordinated for the Arizona Sonora Desert Museum and Tohono Chul Park docents incorporating hands-on groundwater flow model training with in-depth discussion of local water issues.

National Water Education Day – Water Festival

As the State Project WET coordinator, the WRRC Education Program Coordinator is responsible for planning, organizing and implementing an annual Water Festival for National Water Education Day. The Arizona water festival is one of the simultaneous water festivals being held in all 50 states. In this and other efforts, WRRC staff stay connected to the education community as well as the water community.

The Water Festival celebrating National Water Education Day held last fall benefited from the involvement and cooperation of the Tucson Regional Water Council, the U.S. Bureau of Reclamation, Tucson Water, the Arizona Sonora Desert Museum, Central Arizona Project, Arizona Department of Water Resources, the Community of Civano, Americorps, State Parks, U.S. EPA, Pima Center for Conservation Education (NRCD), and Vail School District Elementary Schools. An extraordinary educational opportunity was offered to 400 4th and 5th grade students and their teachers.

Tucson Interactive Water Education Exhibit

The Tucson Interactive Water Education Exhibit was created to offer schools state of the art information on water in the Tucson AMA. The exhibit was set up at elementary schools so that librarians and teachers could lead students through the exhibit over the course of a week or two. The color-coded sections of the Tucson Interactive Water Education Exhibit included:

I. Water in the Desert
II. Water Cycle
III. Sources of Water
IV. Water Uses
V. Water for the Future
VI. Water History

Since April 2000, the Tucson Interactive Water Education Exhibit has been hosted in four different school districts and been toured by more than 4000 students this year. Teachers and librarians have completed evaluation forms and the response has been overwhelmingly positive. In addition, 1500 visitors of all ages to the Mineral Discovery Center and Old Tucson Studios toured the Interactive Water Education Exhibit during the summer months.

Groundwater Flow Model Demonstrations

As a resource for teachers seeking water resources education information, the WRRC Education Program Coordinator trainw teachers to use water oriented teaching tools. The groundwater flow models are an incredibly good tool for teaching about groundwater and aquifers. Groundwater flow model demonstrations are conducted with visiting scientists, government employees, and educators of all kinds. Groundwater presentations conducted with WRRC flow models reached 1,675 students and 550 adults this year. Groundwater flow models are maintained by WRRC staff for use by teachers and for use at training workshops.

Arizona-specific Educator Resources distributed by the WRRC include:

$ **Conserve Water Educators Guide**
 - *Educator Training and On-Site Presentations available*

$ **Arizona WET K-8 Guide with Student Activities**
 - *Educator Training available.*

$ **Arizona WET K-6 Nonpoint Source Water Pollution Curriculum**
 - *Educator Training available.*

$ **Arizona WET Grade 9-12 Curriculum On Nonpoint Source Water Pollution**
 - *Educator Training available.*

$ **Groundwater Flow Models**
 - *Educator Training and*
 - *Available on a loan basis*

$ **EnviroScape Water Pollution Awareness Model**
 - *Educator Training and*
 - *Available on a loan basis*

$ ***Liquid Treasure* Water History Trunks**
 - *Available on a loan basis*

Coordination of Educational Assessment

In addition, the WRRC Education Program Coordinator organized and coordinated a statewide ***Water Resources Education Assessment*** effort for University of Arizona, Cooperative Extension.

WATER CASA

The Water Conservation Alliance of Southern Arizona (Water CASA) was formed three years ago to provide a means for member water providers to augment their individual conservation programs and to improve the region's overall water conservation efforts. To date, Water CASA's membership includes Metro Water District, Avra Water Co-op, Community Water Company of Green Valley, Flowing Wells Irrigation District, Pima County Wastewater Management and the U.S. Bureau of Reclamation. This alliance has rapidly become a productive organization effectively using economies of scale, and by providing a strong, unified voice on water conservation issues regionally.

<u>Welcome Packets</u>

Water CASA continues to provide its members with a variety of brochures and information pieces that are distributed in Welcome Packets for new water customers. Water CASA developed and continues to update the literature in the packets. Members distribute more than 300 packets a month to their new customers and also to customers who request conservation information. We are now beginning to track water use patterns related to the packets and to thereby analyze the effectiveness of the Welcome Packet program. *(See the Water CASA web site under publications for a complete set of Welcome Packet materials.)*

<u>Conservation Devices</u>

Bulk orders of conservation devices continue to be made for, and divided among, the members of Water CASA. This is a good example of Water CASA's effectiveness in the use of economy of scale. We are able to purchase conservation devices at the lowest possible price with our bulk ordering. In addition, the US Bureau of Reclamation supports this program with $10,000 toward the purchase of the showerheads and aerators. These conservation devices are included in Welcome Packets for new customers moving into older homes and are also available to water customers on request. Field staff who respond to customer questions or complaints also hand out devices, which has proved to be an effective customer service.

<u>Graywater Project</u>

Water CASA has identified residential graywater reuse as having huge conservation potential. The Alliance applied for and was awarded an ADWR conservation assistance grant in 1998 to look at actual "wildcat" graywater systems throughout Pima County. The just completed study has determined that approximately 13 percent of single family residences are making use of one or more sources of their graywater Health risk associated with actual graywater systems and have been found to be within acceptable limits. We are currently involved with support of the Arizona Department of Environmental Quality's efforts to simplify the rules for residential graywater reuse and to create rules based upon performance standards. *(See the Water CASA web site under research for the complete Residential Graywater Study.)*

<u>Ordinances</u>

At the request of Pima County, Water CASA has drafted and submitted to the county, ten potential water conservation ordinances. Those ordinances are awaiting adoption within the County's Sonoran Desert Conservation Plan. Pima County's adoption of our suggested water ordinances will strengthen conservation efforts not only in Water CASA members service areas but will benefit the entire county as well.

Safe Yield Dialogue

Water CASA has consistently promoted development of a dialogue within the region and throughout the State to look at overall effective water management. Partially as a result of our efforts, the Arizona Department of Water Resources (ADWR) has established task forces in each AMA to examine safe-yield and funnel recommendations to the Statewide Water Management Commission recently appointed by the Governor. Water CASA Manager, Val Little, continues to serve as co-chair of the Conservation subcommittee and is a member of the TAMA Safe Yield Task Force. Water CASA Board Member, Alan Forrest, has been selected to serve on the Statewide Technical Advisory Committee for the Water Management Commission.

Groundwater Management Act Anniversary Conference

Water CASA was a sponsor of this statewide meeting, held on the occasion of the 20th anniversary of the Groundwater Management Act. Water CASA Manager, Val Little represented the Tucson Active Management Area (AMA) in a presentation to the joint Groundwater Users Advisory Council (GUAC) meeting held in conjunction with the Conference.

Conservation Assistance Fund

ADWR has funds available for conservation assistance grants, which in previous years have been spread among more than 20 projects. Water CASA has consistently advocated for not more than three to five conservation projects to be selected for their overall, quantifiable benefit to the region. Our goal is the most efficient use of the dwindling monies available. Water CASA has taken leadership in advocacy for the regional and statewide multimedia program 'Water Use It Wisely' as a primary target for funding. Water CASA withdrew both of its Conservation Assistance Fund proposals to be consistent with our advocacy.

News Articles & Press Releases

Press releases and news articles are drafted for use by the regional media throughout the year. These items are either used as is by local newspapers, been adapted as features by the print media or have been used in Water CASA member newsletters to customers.

Demonstration Gardens

Water CASA has a goal to develop public, low-water-using demonstration gardens in the service area of each member. A public installation of the Metro Water Demonstration Garden was held in the fall of 1999 for phase one and this spring of 2000 for phase two. We were able to get Rainbird to fund the irrigation supplies necessary for the garden installation. The installation event provided an opportunity for Metro Water Customers to observe the installation of a drip irrigation system installation and the proper techniques for desert plantings and plant maintenance. A demonstration garden for Avra Water Co-op has been designed, an irrigation plan is being developed and is scheduled for installation this fall.

Individual Member Services

Water CASA continues to assist members with development of Reasonable Conservation Measures negotiated with ADWR, to assist with negotiates of stipulation and consent decrees, and to provide auditing services through our partnership with the Low 4 Program.

Governor's Pride Award

Water CASA was nominated for and received the first ever Governor's Pride in Arizona Award for Water Conservation. We were lauded for our innovative approaches to water conservation, and impressive results in a rather brief period of time. "The program's goal of involving water companies with community members impressed the judges and earned the organization the award." The award committee also commended Water CASA for being instrumental in drafting water conservation ordinances for Pima County, studying graywater reuse in the Tucson area and promoting low-water-using landscapes.

The Bureau of Reclamation Recognizes Water CASA's Partnering and Innovation

In recognition of its outstanding efforts in water conservation activities, the Water Conservation Alliance of Southern Arizona (Water CASA) was selected by the Bureau of Reclamation as the recipient of the 2000 Commissioner's Water Conservation Award .

Each year, the commissioner of the Bureau of Reclamation acknowledges exceptional efforts in the field of water conservation with the presentation of five awards throughout Reclamation's seventeen western states. In 2001, the commissioner recognized the efforts of Water CASA. Since its creation in 1997, the alliance has defined itself as both a leader and innovator in the conservation field. The Bureau stated that Water CASA served as an example of how shared resources enables members to benefit from group purchasing power, expertise, and professional support staff. Water CASA was identified as the type of proactive force that shows what can be accomplished when partnering takes place.

Understanding that water conservation is a key ingredient in the recipe for meeting the water supply needs of a growing West, the Bureau applauded Water CASA's efforts in water conservation education, demonstration, and implementation. Additionally, the Bureau commended Water CASA as a leader in the area of research, through the development and implementation of studies, including graywater research which lead to the modification of state permitting criteria, and the current dual metering study which will provide invaluable information concerning indoor verses outdoor water usage over time.

USGS Summer Intern Program

Student Support

Student Support					
Category	**Section 104 Base Grant**	**Section 104 RCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	8	0	0	0	8
Masters	1	0	0	0	1
Ph.D.	4	0	0	0	4
Post-Doc.	0	0	0	0	0
Total	13	0	0	0	13

Notable Awards and Achievements

Bureau of Reclamation Award

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Patent Application

The University of Arizona, in connection with the results from Project B-3, filed for a patent on the methodology developed in this research. Specifically, the patent is for application of the developed computational neural network/optimization methodology to management of subsurface fluid flow, including water, natural, gas, and petroleum.

Best Paper

Best Paper at the 2000 Western Snow Conference for Koch and Fisher (2000). Project G-98.

Publications from Prior Projects