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Introduction

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Prepared by the Arizona Water Resources Research Center, The University of Arizona, Tucson, Arizona 85721.

Research Program

Attenuation of Estrogenic Activity in Reclaimed Water and Stormwater During Impoindment in Natural Systems

Basic Information

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Principal Investigators:	Martin Milan Karpiscak, Robert Arnold, Wendell Ela, Charles Gerba, Martin Karpiscak, Kevin Lansey, David Quanrud

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1. Bjolseth, I.M. 2004. Fate of Estrogenic Activity during Wetland Treatment of Wastewater Effluent and Stormwater Runoff. Unpublished M.S. thesis. Department of Chemical and Environmental Engineering. The University of Arizona. Tucson, Arizona.
2. Bjolseth, I.M., Quanrud, D.M., Karpiscak, M.M., Ela, W.P., Lansey, K.E., and Arnold, R.G. 2003. Fate of Estrogenic Activity during Wetland Treatment of Wastewater Effluent and Stormwater Runoff. In: Proceedings, 11th Biannual Symposium on Groundwater Recharge, Phoenix, AZ, June 5-7, 2003.

A. Problem and Research Objectives:

The growing demand for water in Arizona and the semiarid southwestern United States prompts consideration of alternative water sources, including reclaimed water and stormwater runoff. On the other hand, caution regarding acceptable uses and use-dependent treatment requirements preceding water reuse is warranted, in part due to discoveries regarding the presence of endocrine disrupting compounds (EDCs) in domestic wastewater effluent. Among the EDCs measured in treated wastewater, estrogen, estrogen metabolites, and anthropogenic estrogen mimics are responsible for most observable ecological effects. Furthermore, there has been speculation regarding the effects of chronic human exposure to estrogenic compounds, such as elevated incidence of breast and prostate cancers and decline in sperm quality. There is a critical need to examine the fate of estrogenic compounds during wastewater treatment and the efficacy of effluent polishing techniques as methods for limiting estrogenic activity in reclaimed water.

Previous work in our laboratories at the University of Arizona indicates that local municipal wastewater contains ecologically significant levels of estrogenic activity. This activity is typically attenuated by 50-60 percent during secondary (biological) wastewater treatment at the Roger Road Wastewater Treatment (RRWWTP) (trickling filter) and the Ina Road Wastewater Pollution Control Facility (activated sludge). Locally available polishing techniques for improving effluent quality include wetlands treatment. However, the efficacy of constructed wetlands for removing estrogenic activity in treated effluent has not been established. This project was intended to provide a starting point for evaluation of constructed wetland technology as a treatment method for removing EDCs from wastewater effluent. A second objective was to examine the presence of estrogenic activity in stormwater runoff and to evaluate whether impoundment of runoff resulted in changes of estrogenic activity.

Related research. A variety of compounds with estrogenic properties are only partly removed during conventional wastewater treatment (Huang and Sedlak, 2000). Residual estrogens can produce changes in the overt sexual characteristics of exposed fish and elevated vitellogenin (an egg precursor protein) levels in exposed males (Folmar *et al*., 1996; Harries *et al*., 1996). Such observations have led to widespread speculation that exposure to estrogenic pollutants in the environment is responsible for recently observed increases in several types of human cancers and worldwide declining sperm levels in men. In fact, the effect of exposure to EDCs on human health is not known with certainty, and relevant epidemiological data is not likely to arise in the near future.

The endocrine system regulates numerous critical cellular activities by producing and controlling the concentrations of hormones. Cells respond to hormones at exceptionally low concentrations, commonly < 1 nM. Hormones are normally recognized at the cellular level through complexation reactions with intracellular or membrane-bound chemical receptors. Soluble hormone/receptor complexes bind to specific DNA sequences, stimulating gene expression. Estrogen, for example, is produced in mature ovarian follicles and transported through the bloodstream to elicit response in distant cells that produce estrogen receptors. The DNA binding regions for these compounds are called estrogen response elements (ERE; Figure 1). In this manner, estrogens, or perhaps estrogen-mimicking chemicals, regulate many aspects of sexual development and function, reproduction, etc. Estrogen agonists and antagonists both bind to the estrogen receptor. In the case of antagonists, the receptor complex is unable to initiate gene transcription.

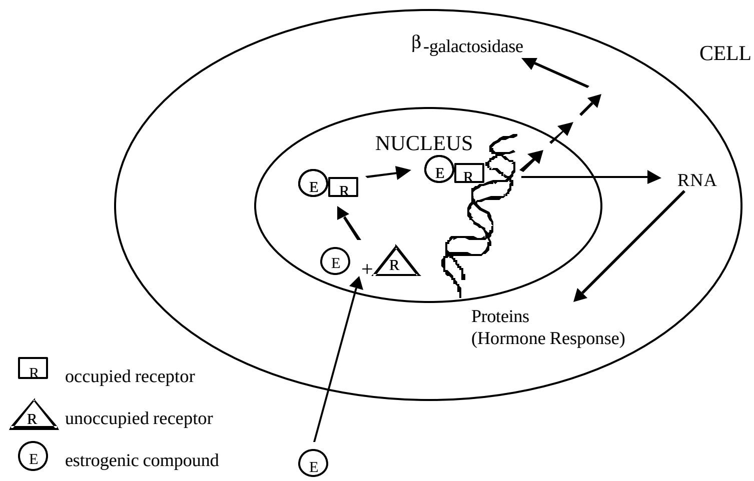

Figure 1. Basis of response to estrogens among regulated cells. Steps: (i) estrogen binds to estrogen receptor to produce estrogen/receptor complex; (ii) complex binds to specific DNA sequences (estrogen receptor elements) to initiate transcription/translation. The figure omits detailed aspects of estrogen response physiology.

Due to the difficulty and expense of measuring steroid hormones in complex aqueous-phase matrices at relevant (ng/L) levels, there have been relatively few measurements from which environmental fate and transport can be determined. From the recent USGS survey of United States streams (Kolpin *et al.*, 2002), it is apparent that natural and synthetic estrogens survive conventional wastewater treatment, at least in part. A number of *in vitro* bioassays have been devised to screen chemicals for estrogenic effects. In a few instances, those same tests have been used to measure estrogenicity in complex mixtures of chemicals including domestic wastewater and wastewater effluent (Tanaka *et al.*, 2001; Holbrook *et al*., 2002; Turney *et al.*, in press). Such studies have begun to yield evidence regarding the probable fate of estrogenic compounds during conventional wastewater treatment. Previous efforts by our research group to account for changes in aqueous-phase estrogenic activity during wastewater treatment and subsequent polishing steps have led to the following summary observations (Conroy *et al*. (submitted), Turney *et al.* (in press), Quanrud *et al.* (2002a), and Quanrud *et al.* (2002b)):

i. *From 40 to 70% of the soluble, aqueous-phase estrogenic activity in raw domestic wastewater is removed during secondary wastewater treatment.* Fractional removals depend somewhat on the efficiency of organic conversion during biochemical treatment steps.

ii. *Effluent polishing via soil-aquifer treatment (percolation and temporary underground storage) can reduce estrogenic activity by an order of magnitude.* Local soil characteristics impact this result. Most reduction in estrogenic activity occurs in the top few feet of basin soils. Turney *et al*. (in press) measured estrogenic activity in secondary effluent from the Roger Road Wastewater Treatment Plant before and after percolation through about 120 feet of unconsolidated sediments at the Sweetwater Recharge Facilities. Results indicate that >95% of the residual estrogenic activity in treated wastewater is removed after percolation to the local unconfined aquifer. The dominant removal mechanism, at least over time scales of days to weeks, is thought to be adsorption to sediments.

iii. *Estrogenic activity in secondary effluent is attenuated by >65% after transport along a 23-mile reach of the Santa Cruz River near Tucson, Arizona.* In effluent-dependent Santa Cruz River, in which there was no dilution or groundwater/surface water exchange over the reach sampled, estrogenic activity was significantly attenuated over a transport distance of 23 miles. The estimated travel time was on the order of a day. Processes responsible for downstream water quality improvements are poorly understood but may involve photodegradation reactions or sorption onto streambed sediments.

Project objectives. We examined the fate of estrogenic activity in wastewater effluent, backwash water, and stormwater runoff during passage through two local surface water service impoundments (described below). The central hypothesis was that wetland treatment and impoundment of wastewater/runoff would lower the levels of estrogenic activity present in these waters. It was hypothesized that attenuation of estrogenic activity occurs during wetland treatment via a combination of mechanisms including biodegradation, sorption, and photodegradation reactions.

B. Methodology:

Field sites

Two local field sites in the City of Tucson, Arizona, were utilized in this research: the Sweetwater Wetlands and the Tucson (Ajo) Detention Basin (TADB), also known as the Kino Wetlands. The Sweetwater Wetlands is a part of the Sweetwater Recharge Facilities (SRF) (Figure 2), located west of Interstate 10 near Prince Road. The SRF is owned and operated by the City of Tucson. The wetland component is comprised of 1.8 acres (0.7 ha) of settling basins, a stream system and 15 acres (6.1 ha) of wetland cells (Figure 3). The dominant vegetation in the settling basins and wetland cells includes several different species of bulrush and cattail. The Sweetwater Wetlands receive a mixture of secondary effluent from the RRWTP and backwash water from the City of Tucson Reclaimed Water Plant. The facility has been in operation since 1997. The research team has access to the SRF via an ongoing research project studying water quality changes (including fate of estrogenic activity) during soil aquifer treatment.

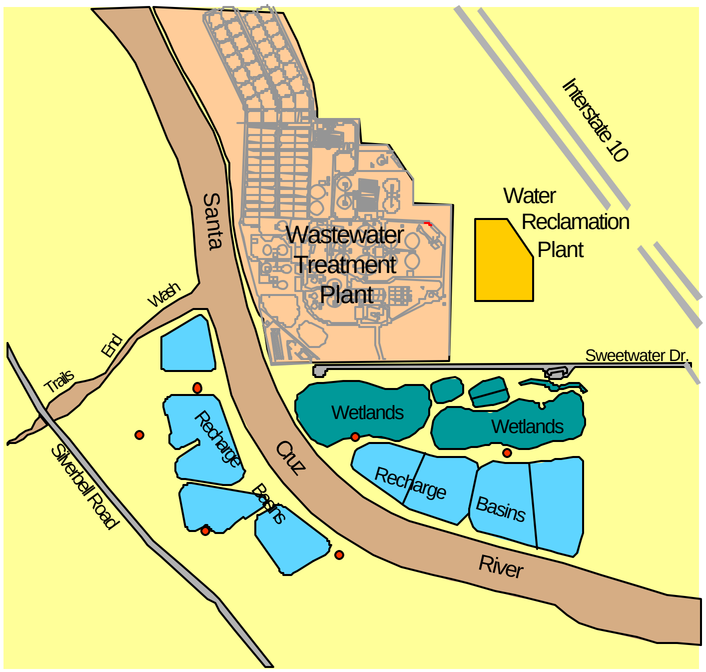

Figure 2. Site map for the Sweetwater Recharge Facilities, Tucson, Arizona.

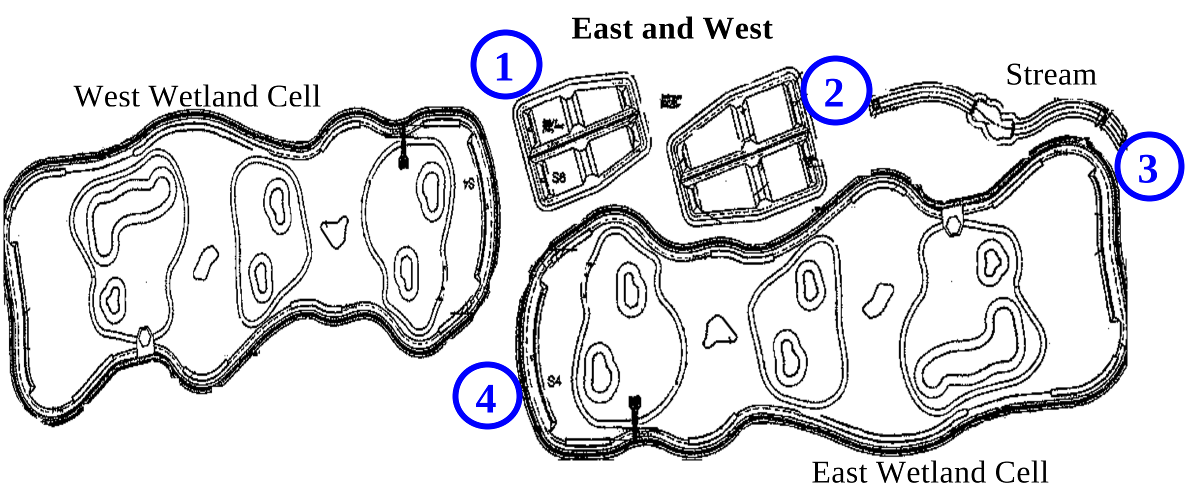

Figure 3. Sweetwater free-water-surface wetland cells. Samples were obtained from (1) the inlet to the settling basins, (2) the outlet of the settling basins, (3) the outlet of the stream, and (4) the outlet of the wetland.

The TADB project (Figure 4) is a constructed stream and marsh system located in the south-central portion of the City of Tucson just north of Ajo Way and west of County Club Road. The project was completed in 2002 and is operated by the Pima County Department of Transportation and Flood Control District. The wetland system is designed to receive, treat, and detain urban stormwater runoff. The facility consists of four stream components that feed into three marshes (total area of 8.4 acres) and a 7-acre pond. The marshes are approximately one half emergent vegetation and one half open water.

The riparian system received its first stormwater flows in September 2002. The stormwater is detained in the large pond and is pumped to the inlets of the streams to maintain the riparian system. The operational scheme of this system allows examination of the effect of extended detention time on attenuation of estrogenic activity in stormwater. The research team received permission from Chris Bartos, Pima County Kino Sports Complex, to conduct the research at this site.

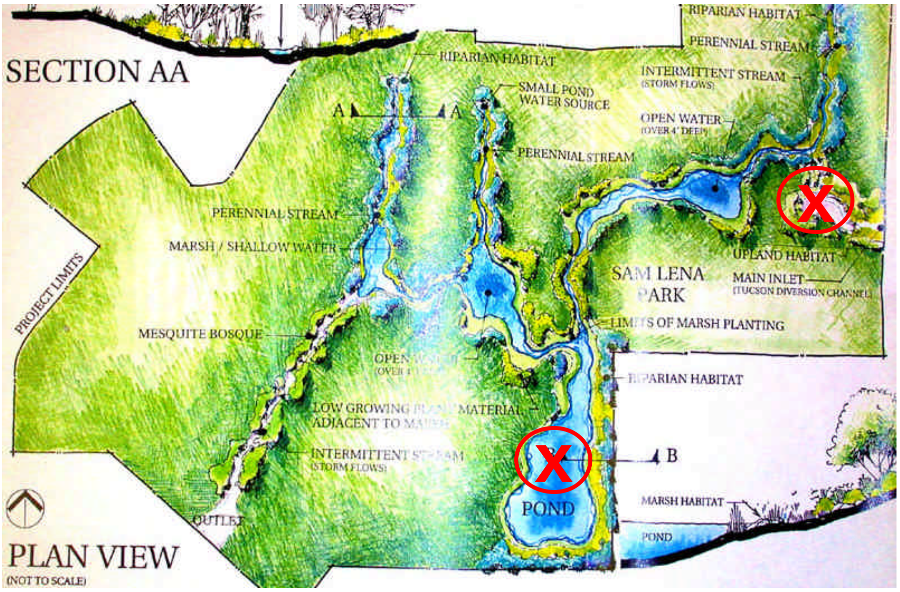

Figure 4. Site map of the Tucson Ajo Detention Basin. Samples were obtained at the marked locations: near the inlet to the system and at the big pond.

Figure 5. The 7-acre pond at the Tucson Ajo Detention Basin. View is looking to the south; photo was taken January 17, 2003. Tucson Electric Park is in the background.

Work was conducted over a 14-month period. Three sets of samples were collected from the Sweetwater wetlands; at the TADB, nine sets of samples were obtained during this study. Sampling locations at the Sweetwater wetlands (Figure 3) included the two influent water sources (backwash water, secondary effluent); the inlet and outlet of the east settling basin; and the inlet and outlet of the east free-water-surface wetland cell. At the TADB, stormwater runoff samples were collected at the inlet to the facility and at the 7-acre pond. The sampling schedule at the TADB was designed to take advantage of new runoff derived from local storm activity in 2003. We adjusted the sampling program to permit evaluation of the fate of estrogenic activity in stormwater runoff during impoundment in the 7-acre pond.

Methods for quantifying estrogenic activity *in vitro* include competition binding, reporter gene expression, and cell proliferation assays. These assays (Table 1) differ in terms of effort and demand for technical skill and their sensitivities to aqueous phase 17β-estradiol (E2, natural female estrogen hormone). In this project, samples were analyzed using the competition binding and reporter gene assays to evaluate estrogenic activity in waters from the two constructed wetland/impoundment sites.

Table 1. Comparison of *in vitro* assays for chemical estrogenicity based on sensitivities and effort. Sensitivity data are the lowest concentrations of 17β-estradiol that produce an estrogenic response.

Bioassay	Representative Sensitivity (ng/L)	(nM)	Time Required (days)	Reference
1. *In Vitro* competition Binding assay	500	~2.0	1	Bolger *et al.,* 1998
2. *In Vitro* Gene Expression (reporter-gene assay)	100	0.5	1-3	Routledge and Sumpter, 1996 Coldham *et al.,* 1997
3. *In Vitro* Cell Proliferation assay	~3	0.01	5-7	Soto *et al.*, 1995

Competition Binding Assay. The competition receptor-binding assay is relatively fast and straightforward. The receptor-binding assay used here follows procedures established for the Estrogen Receptor-β Competitor Assay (Bolger *et al*., 1998). In this method, estrogenic activity is measured by displacement of a fluorescent ligand bound to human estrogen receptor (hER-β). Compounds capable of binding to the receptor (e.g., 17β-estradiol) displace the fluorescent estrogen. Displacement is detected by fluorescence polarization. Method detection limits for 17β-estradiol are ~10^{-9} M. A drawback of this type of assay is that receptor-binding assays do not differentiate between endocrine system agonists (estrogen mimics) and antagonists (those that block endocrine system response).

Fluorescence polarization was measured with a Beacon 2000 variable temperature fluorescence polarization system (PanVera, Model P2300) using an excitation wavelength of 360nm and a fluorescence detection wavelength of 530nm at 25°C. The instrument provides a numerical indication of the degree of light polarization at the fluorescent wavelength. The fluorescence polarization method is fully described in Turney *et al.* (in press). The IC_{50} for 17β-estradiol varied between 8.3×19^{-9} – 1.1×10^{-8} M (2.26 – 2.99 µg/L) (Figure 6). The "IC_{50} sample" was derived experimentally (the volume fraction that produced 50% ES2 displacement), and the concentration factor (200x) resulted from the C18 extraction procedure.

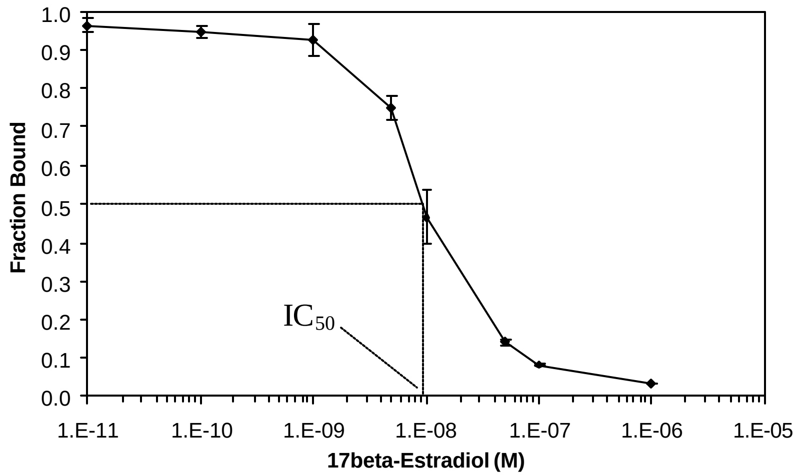

Figure 6. Competition binding assay response for 17β-estradiol.

Yeast Estrogen Screen (YES) Assay. The estrogen-inducible expression system used in this study is comparable to the method described in Routledge and Sumpter (1996) to study endocrine disruption by municipal wastewater and effluent-impacted surface waters in the United Kingdom. The method responds to compounds capable of passing through the yeast cell envelope and binding to hER-β. The complex binds to the ERE in the recombinant yeast strain, per above. In this approach, estrogenic activity is measured via expression of *lacZ* fused to a human estrogen response element sequence in *Saccharomyces cerevisiae*. Consequent β-galactosidase activity is measured colorimetrically based on conversion of chlorophenol red β-D-galactopyranoside to a red product. Although the assay has been used extensively to measure estrogenicity among synthetic compounds (Routledge and Sumpter 1996, Harris *et al.* 1997, Beresford *et al.* 2000), its application for measurement of estrogenicity in complex matrices has been more limited (Holbrook *et al*., 2002).

Whole-water samples were collected in muffled glass bottles, immediately filtered (0.45 um, Millipore) upon return to the laboratory, and stored at 4°C until further processing. Hydrophobic organics in whole-water samples were concentrated by extraction onto Empore C-18 disks (3M) and elution in ethanol. The alcohol solution was evaporated to dryness and the nonvolatile residuals were resuspended in water or buffer to achieve nominal concentration factors of 100-300 or greater. Sample concentrates were analyzed for estrogenic activity using one or more of the *in vitro* assays described above. Results were expressed as an equivalent concentration of 17β-estradiol, after accounting for the concentration factor used.

C. Principal Findings and Significance:

The working hypothesis in this study was that impoundment of secondary effluent or stormwater runoff in wetlands would lower the concentrations of organics responsible for estrogenic activity. Hypothesis testing involved sampling and analysis at the Sweetwater Wetlands (secondary effluent) and the Tucson Ajo Detention Basin (stormwater runoff).

Estrogenic activity in wastewater effluent (Sweetwater Wetlands)

The water entering the inlet of the settling basin at the Sweetwater Wetlands consists of a mixture of backwash water from the City of Tucson's Reclaimed Water Plant and secondary effluent from the Roger Road Wastewater Treatment Plant. The mixing ratio during all three sampling events in this study was 3:1 (secondary:backwash). Estrogenic activity was not detected in the backwash water itself (Table 3), however, binding assay results for samples taken at the inlet to the settling basin, consisting of the secondary/backwash mixture, consistently exhibited higher levels of estrogenic activity than secondary effluent alone (Table 3, Figure 7). It was hypothesized that this seemingly anomalous result was due to the presence of anti-estrogenic activity in the backwash water. The presence of anti-estrogenic activity in backwash water is a topic for additional study.

Table 3. Summary of estrogenic activities at Sweetwater Wetlands sampling points. Data shown represent equivalent E2 equivalent concentrations (nM).

Sample Date and Location	Binding Assay	YES Assay
February 5, 2003		
Filter backwash water	Non detect	-
Secondary effluent	1.8	-
Into settling basin	2.5	-
Out of settling basin	Non detect	-
Into east wetland cell	4.5	-
Out of wetland	1.1	-
August 29, 2003		
Filter backwash water	Non detect	Non detect
Secondary effluent	7.5	1.6×10^{-1}
Into settling basin	20.0	9.1×10^{-2}
Out of settling basin	3.0	1.3×10^{-2}
Into east wetland cell	7.5	2.5×10^{-1}
Out of wetland	1.8	Non detect
February 5, 2004		
Filter backwash water	-	Non detect
Secondary effluent	-	3.8×10^{-2}
Into settling basin	-	1.6×10^{-2}
Out of settling basin	-	4.7×10^{-3}
Into east wetland cell	-	1.3×10^{-1}
Out of wetland	-	2.0×10^{-3}

In all three sampling events (Table 3), estrogenic activity decreased substantially (by about 50 percent) during passage of the secondary/backwash mixture through the settling basin but then increased substantially again through the connecting stream (Figure 7). This result was consistently observed in both assays (Table 3). The reasons for an increase in estrogenic activity after passage through the stream segment are unknown and are an appropriate subject for additional study. Estrogenic activity then consistently decreased during the six-day residence time in the East free-water-surface wetland cell. There was no apparent seasonal variability in removal efficiency of estrogenic activity during wetland treatment. These results were observed using both assay methods.

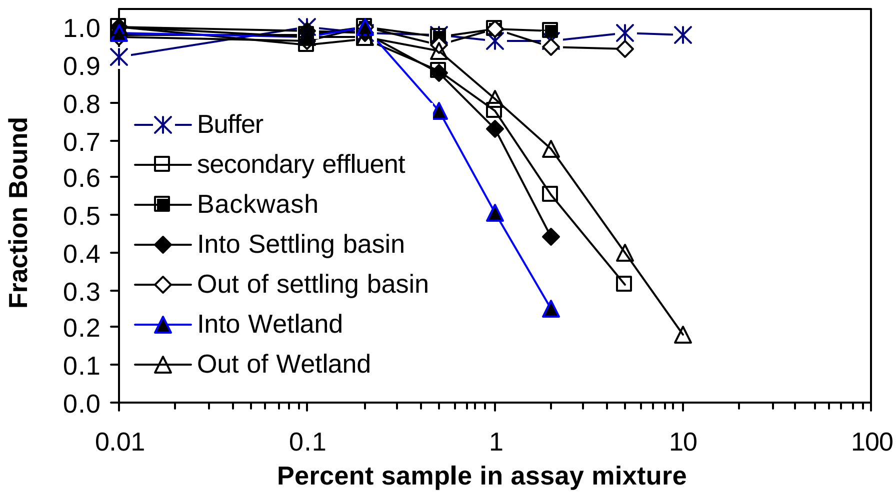

Figure 7. Competitive binding assay measurements of estrogenic activity among water samples derived from Sweetwater surface wetland sampling points collected on February 5, 2003. Ordinate values are the fraction of a fluorescent marker that is bound to hER-β. Estrogenic compounds, as defined by this assay, are those that can displace the marker compound.

Samples obtained during August 2003 and February 2004 from the Sweetwater Wetlands were examined for estrogenic activity using both the competitive binding (Figure 7) assay and the YES assay (Figure 8). Results from the two assays were in reasonable qualitative agreement and showed that the stream effluent (wetland influent) was more estrogenic than the stream influent and also that wetland treatment is a reasonable polishing procedure for removing residual estrogenic compounds from secondary effluent. However, the huge drop in estrogenic activity across the wetlands (> 80% reduction; indicated by the YES assay) was unexpected. The measured estrogenic activity (in terms of 17β-estradiol equivalent concentration) was significantly higher in the binding assay than in the YES assay. We believe that the low response of the YES assay to wetlands effluent was due to a combination of the presence of anti-estrogenic activity (antagonists) along with removal of estrogenic compounds (agonists) during wetland treatment.

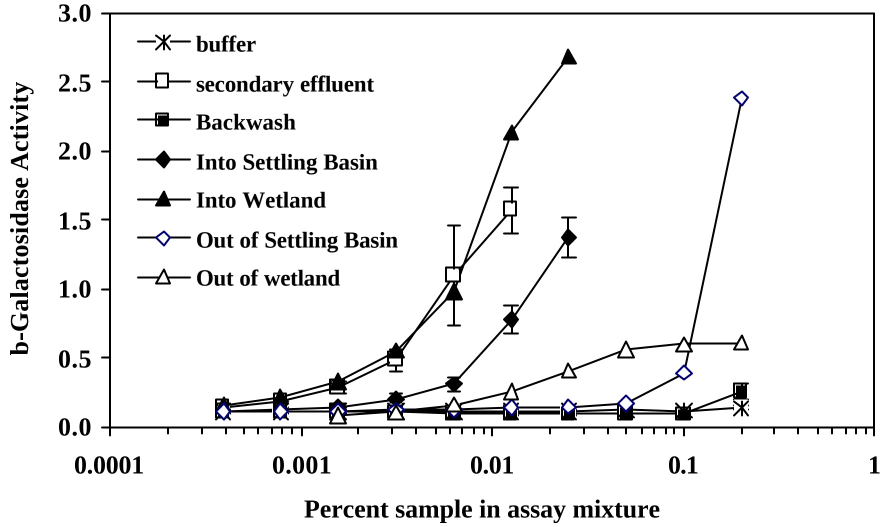

Figure 8. YES assay measurements of estrogenic activity among water samples from the Sweetwater surface wetlands collected on August 29, 2003. The presence of estrogenic compounds in the concentrated samples stimulates synthesis of β-galactosidase in the strain of yeast employed. β-galactosidase activity is then measured based on light absorbance at 570 nm.

Estrogenic activity in urban stormwater runoff (Tucson Ajo Detention Basin)

This aspect of the study was designed to create perspective relative to levels of estrogenic substances in wastewater effluent and urban stormwater runoff. We compared estrogenic activity in stormwater runoff to that of secondary effluent before and after treatment at the Sweetwater Wetlands. We also examined hypotheses regarding first flush effects and the effect of stormwater storage on estrogenic activity at the TADB.

A total of nine sampling events were performed at the TADB during this study; results from measurements for estrogenic activity from the inlet and the 7-acre (big) pond are provided in Table 4. Measurements were obtained using the competitive binding and reporter gene bioassays.

Estrogenic activity was consistently detected in samples from the TADB when using the binding assay and the magnitude of response was 10-25% of that seen in wetland samples of wastewater origin (Table 4 and Figure 9). Results from the reporter gene assay were equivocal in this regard; estrogenic activity was detected in only one set of stormwater runoff samples (collected on 03-30-04) from the TADB.

In order to address the discrepancy in results among the two assay techniques, a modified reporter gene assay was used to look for the presence of anti-estrogenic activity in stormwater runoff. The presence of compounds with anti-estrogenic activity (antagonists) would lower the response in the YES assay and increase the response in the binding assay. The YES (reporter gene assay) only responds to compounds with estrogenic activity (agonists) where as the binding assay responds to all compounds capable of binding to the human estrogen receptor (agonists plus antagonists). The investigators have previously used the modified YES assay to examine the fate of anti-estrogens in wastewater effluent during soil aquifer treatment (Conroy *et al*., submitted).

Table 4. Estrogenic activity in stormwater samples collected at the Ajo Detention Basin in Tucson during 2003-2004. Samples represent estrogenic activity in either the 7-ac pond itself or in stormwater runoff that was influent to the pond on the date shown. Estrogenic activity is reported as the equivalent 17β-estradiol concentration (nM).

Sampling Location and date	E2 Equivalent Conc. (nM) (binding assay)	E2 Equivalent Conc. (nM) (YES assay)
Influent (02-13-03)	3.8	-
Big pond (02-13-03)	0.75	-
Influent (02-26-03)	Non detect	-
Big pond (02-26-03)	1.3	-
Influent (06-13-03)	-	Non detect
Big Pond (06-13-03)	-	Non detect
Influent (08-13-03)	0.75	Non detect
Big pond (08-13-03)	0.45	Non detect
Influent (10-02-03)	0.45	Non detect
Big pond (10-02-03)	1.1	Non detect
Influent (10-23-03)	0.40	Non detect
Big pond (10-23-03)	0.43	Non detect
Influent (11-14-03)	0.38	Non detect
Big pond (11-14-03)	0.38	Non detect
Influent (02-19-04)	-	Non detect
Big pond (02-19-04)	-	Non detect
Influent (03-30-04)	-	1.0×10^{-1}
Big pond (03-30-04)	-	1.0×10^{-1}

Anti-estrogenic activity was detected in the stormwater runoff entering the TADB (Figure 9). In the modified YES assay, the presence of anti-estrogenic compounds in the stormwater runoff results in a depression of the upward (right hand) limb of the positive control (EE2) curve. The amount of depression increased with increasing addition of runoff concentrate (Figure 9). This result is in contrast to the agonist response seen for "fresh" secondary effluent obtained from the Roger Road Wastewater Treatment Facility (Figure 10) in which there is an additive response to the left hand portion of the EE2 positive control curve. The presence of anti-estrogenic activity in stormwater runoff is consistent with observed results in which estrogenic activity was detected using the binding assay and not detected using the reporter gene assay.

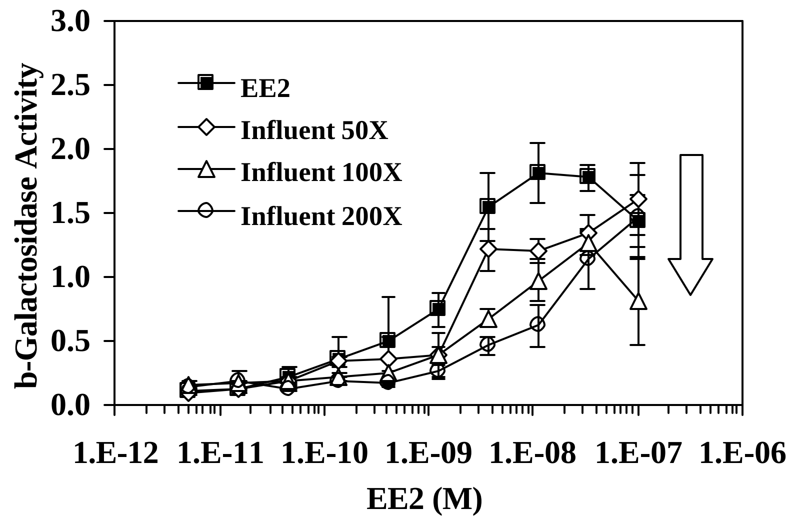

Figure 9. Anti estrogenic activity (antagonism) detected in rainfall runoff entering the TADB facility. Anti-estrogenic activity is indicated by the downward deflection (arrow) of the right hand side of the EE2 + Influent curves. The amount of antagonism increases with increasing additions of stormwater runoff concentrate added to the EE2 positive control.

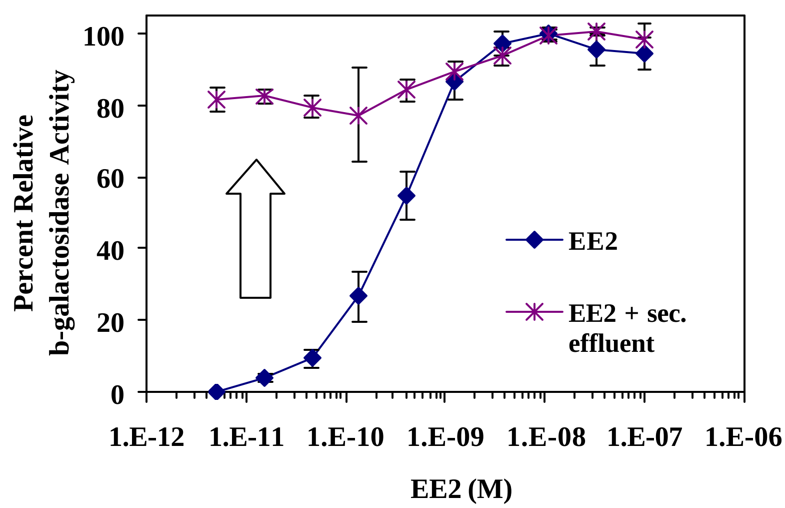

Figure 10. Estrogenic activity (agonism) detected in fresh secondary effluent from the Roger Road Wastewater Treatment Plant. Agonism is indicated by the upward deflection (arrow) of the left hand side of the EE2 + sec. effluent curve.

Data gathered during this study also support the preliminary conclusion that estrogenic activity in stormwater runoff is attenuated over time during detention in the 7-acre pond at the TADB. On more than one occasion, the pond water exhibited a lower level of estrogenic activity than new influent stormwater runoff when samples were collected shortly after storm events. For example, on February

26 and August 13 in 2003, estrogenic activity was higher in the influent stormwater than in the detained water in the big pond. Both sample events were conducted within 24 hours after a >0.50 inch rainfall event in the area. This preliminary observation supports the hypothesis that estrogenic activity is attenuated over time during impoundment. Mechanisms responsible for attenuation of estrogenic activity may include photodegradation, volatilization, and sorption to sediments. Elucidation of attenuation mechanisms is another topic for additional study.

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Selection of High Performance Microalgae fro Bioremediation of Nitrate-Contaminated Groundwater

Basic Information

Title:	Selection of High Performance Microalgae fro Bioremediation of Nitrate-Contaminated Groundwater
Project Number:	2003AZ15B
Start Date:	3/31/2003
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Focus Category:	Nitrate Contamination, Groundwater, Treatment
Descriptors:	GW, NC, TRT
Principal Investigators:	Qiang Hu, Milton Sommerfeld

Publication

1. Natalie Case, Milton Sommerfeld, and Qiang Hu, 2004, A Search For High Performance Microalgae To Remediate Nitrate-Contaminated Groundwater: Concept And Preliminary Results. 48th Annual Meeting of the Arizona-Nevada Academy of Sciences, April 10, 2004, Midwestern University, Glendale, Arizona (Poster).
2. Mike Bellefeuille, Qiang Hu, and Milton Sommerfeld, 2004, Removal Of Nitrate From Agriculture Runoff Using The Green Alga Scenedesmus sp. 48th Annual Meeting of the Arizona-Nevada Academy of Sciences, April 10, 2004, Midwestern University, Glendale, Arizona (Poster).
3. Natalie Case. Screening and characterization of high-performance microalgae for bioremediation of nitrate-contaminated waters. M.S. Dissertation (in process) School of Life Sciences, Arizona State University, Tempe, Arizona.
4. Mike Bellefeuille. Microalgae-based nitrate bioremediation: from laboratory to pilot scale. B.S. Dissertation (in process). School of Life Sciences, Arizona State University, Tempe, Arizona.

A. Problem and Research Objectives:

Clean and safe water is a precious and vulnerable resource. In Arizona, more than 40% of drinking water comes from groundwater. Over 1,000 wells across the State exceed the maximum contaminant level of 10 mg L^{-1} for nitrogen as nitrate in drinking water set by the US EPA. Major pollutant sources in Arizona include agricultural activities, wastes from industries, leaking underground storage tanks, septic tanks, landfills, mining and wastewater treatment plants. Many of the groundwater quality problems are located in the Phoenix and Tucson metropolitan areas, but groundwater quality problems are found in all of Arizona's 10 watersheds. Particularly, large portions of aquifers within the Salt River Valley, including areas in Glendale, Mesa, Chandler and Phoenix, contain groundwater with nitrate concentrations high enough to render the water unfit for potable use. In addition, high nitrate levels occur in Marana, St. David, Quartzsite, Bullhead City, Lake Havasu City and other areas. Septic tank discharges are common nitrate sources in rural areas of Arizona and have contaminated drinking water wells. Quartzsite, Bullhead City and Lake Havasu City are just a few locations with documented nitrate problems from septic tanks (*ADEQ's FY '02 Groundwater Assessment*).

High levels of nitrate in groundwater pose a serious health risk for some of Arizona's residents. It can be fatal to infants when nitrate is reduced to nitrite, and the latter combines with hemoglobin in the blood to form methemoglobinaemia and leads to a condition known as "blue baby syndrome" (Gangolli et al. 1994). Reduction of nitrate to nitrite can also be a risk to adults deficient in glucose-phosphate dehydrogenase. Moreover, nitrite can react with secondary amines or amides in water or food to form *N*-nitroso compounds that are potential animal carcinogens (Shank 1975; Pontius 1993). Long-term consumption of drinking water containing nitrate concentrations of $\geq$ 18 mg L^{-1} was reported to increase the risk of non-Hodgkin's lymphoma (Ward et al. 1996).

Nitrate removal from groundwater may be accomplished by microbial-based nitrification and denitrification, or chemically and physically-based technologies (such as ion exchange, reverse osmosis, electrodialysis and catalytic denitrification) (Kapoor and Viraraghavan 1997). However, these treatment processes are often difficult and expensive. They require input of external energy sources (e.g., electricity, organic carbon) and/or chemical additives, and generate concentrated waste-streams that then must be disposed. Shortage of surface water supplies coupled with a rapid increase in population places constant pressure on Arizona's cities and water supply utilities to treat and use available groundwater. Development of innovative, environmentally friendly and cost-effective sustainable technologies for treating nitrate-contaminated groundwater is becoming increasingly urgent.

Groundwater nitrate removal by engineered microalgal systems is an advanced concept. Microalgae require mostly simple mineral nutrients, such as nitrogen, phosphorous and inorganic carbon for growth and reproduction. By utilizing sunlight, microalgae convert, through photosynthesis, nitrate into organic compounds (such as proteins). Microalgae can exhibit growth rates that are an order of magnitude higher than other plants due to their extraordinarily efficient light and nutrient utilization. By taking advantage of various designs of engineered microalgal photobioreactors and high density algal culture techniques, large quantities of groundwater can be stripped of nitrate within a short period of time (Hu et al. 1996; 1998).

The long-term goal of the proposed research was to develop an advanced microalgal system for sustainable large-scale nitrate removal from nutrient-contaminated groundwater. The major objectives of this research grant proposal were to isolate high-performance algal species and to evaluate their nitrate uptake potential under various environmental conditions.

B. Methodology

Isolation and cultivation of microalgae: For isolation of high-performance algal species for maximum nutrient uptake potential, algal samples were collected from various water bodies throughout the metropolitan Phoenix area. Isolation of microalgae, including cyanobacteria, followed the procedure described in Allen (1973). Enrichment cultures for algal isolates were prepared using BG-11 growth medium (Rippka et al. 1979). Membrane filtered (0.45 um pore size) surface water and groundwater were used for nutrient uptake experiments.

Algal growth measurement: Algal growth was measured using four different methods, depending on the nature of individual species, e.g., unicellular versus filamentous species: optical density, cell count, chlorophyll concentration, and dry weight analysis.

Optical density of the culture was measured with a UV-Vis spectrophotometer at a wavelength of 750 nm.

Cell numbers were determined by placing an aliquot of well-mixed culture suspension on a hemocytometer. Two fields (0.1 mm^3) were counted per each of two hemocytometers. Average of four (4) counts were used to calculate cell concentrations. A linear regression equation between optical density and cell counts was established for individual algal species.

For dry weight measurement, a 20-ml aliquot of culture was filtered through pre-weighed Whatman GF/C filter paper. The filter paper was dried overnight in an oven at 100 ^{0}C. The difference between the final weight and the weight before filtration was the dry weight of the sample.

A 5-ml culture sample was harvested by centrifugation (14,000 rpm, 5 min), the resulting pellets was extracted with methanol at 4°C overnight. Absorbance of the supernatant at 665 nm was measured with a spectrophotometer.

Nutrient analysis: NO_3^- and PO_4^{-3} measurements were performed on a Bran-Luebbe TrAAcs 800 Autoanalyzer, a continuous flow wet chemistry autoanalyzer using the cadmium reduction method (APHA, #4-89). The instrument was operated according to the standard operating procedure provided by the manufacturer. The standards, QC, and reagents were prepared fresh the day of analysis. For nitrate nitrogen analysis, the standards were made from a 100 ppm concentration of sodium nitrate ranging from 0.01, 0.02, 0.05, 0.2, 0.8, 2.0, and 5.0 ppm. Every six samples the blank, QC, and drift were measured.

Nitrate uptake rate: Cellular nitrate uptake rate of individual algal species was calculated using the following equation:

Nitrate uptake rate (mg N L^{-1} h^{-1}) = $(LnN_2 - LnN_1)/(t_2 - t_1)$;

Where t_1 and t_2 represent different time points, and N_1 and N_2 represent nitrate concentration in the growth medium at time t_1 and time t_2, respectively.

C. Principal Findings and Significance

Isolation of high-performance microalgae

Frequent field sampling trips were made throughout the year to collect algal samples from diverse water environments including groundwater wells, surface canals, urban lakes, irrigation ditches, and wastewater lagoons, as well as private swimming pools. Three unicellular green microalgae, *Chlorella* sp., *Chlorococcum* sp., and *Scenedesmus* sp., one filamentous green alga, *Ulothrix* sp., and one filamentous cyanobacterium, *Pseudanabaena* sp., have been isolated and maintained in the laboratory. The photomicrographs of these algal isolates are shown in **Figure 1**.

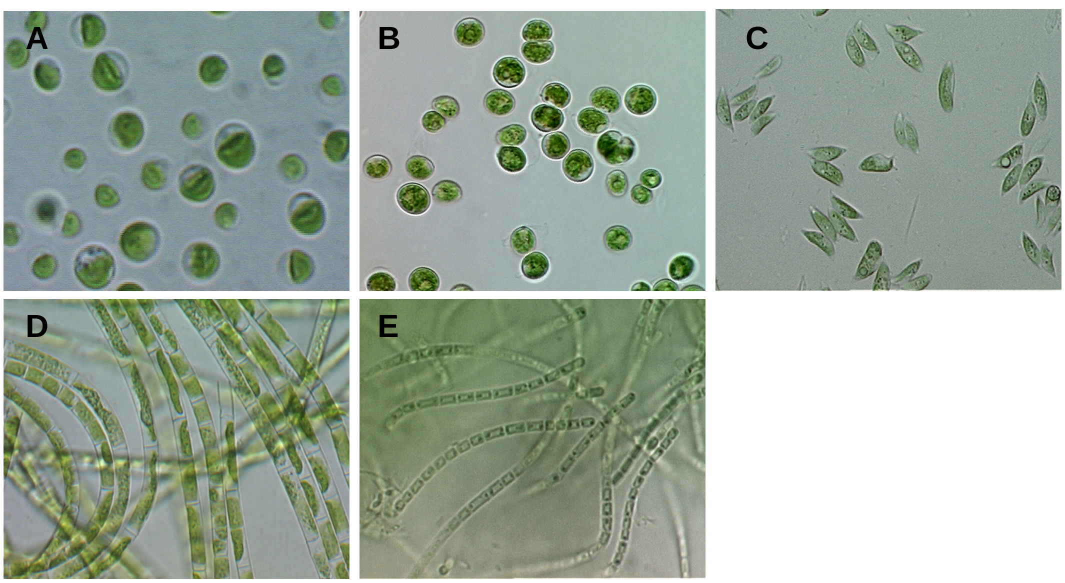

Figure 1. Light photomicrographs of microalgae isolated from metro-Phoenix area. A) *Chlorella* sp., B) *Chlorococcum* sp., C) *Scenedesmus* sp., D) *Ulothrix* sp., and E) *Pseudanabaena* sp.

Comparative growth and nitrate uptake kinetics

To characterize high-performance algal species, five algal isolates were compared in terms of growth potential and nitrate uptake rate. All cultures were grown in 300-ml glass column reactors at 25 ^{0}C and 185 ? mol m^{-2} s^{-1} light. Aeration was provided by compressed air enriched with 1~2% CO_2 to affect culture mixing. Algae grew in either groundwater or surface water containing 30 to 50 mg L^{-1} nitrate-N. As the control, BG-11 growth medium was used to support maximum algal growth under the given conditions.

Chlorella sp. – This organism grew well in the groundwater and assimilated nitrate. However, the cells grew more rapidly and removed nitrate faster in the BG-11 artificial growth medium than in the natural groundwater (**Figure 2**). However, 50 mg L^{-1} nitrate-N was reduced to levels below 10 mg L^{-1} nitrate-N from the BG-11 growth medium by *Chlorella* cells within first 24 h, whereas 36 h was required to reach the same reduction level using the groundwater as culture medium.

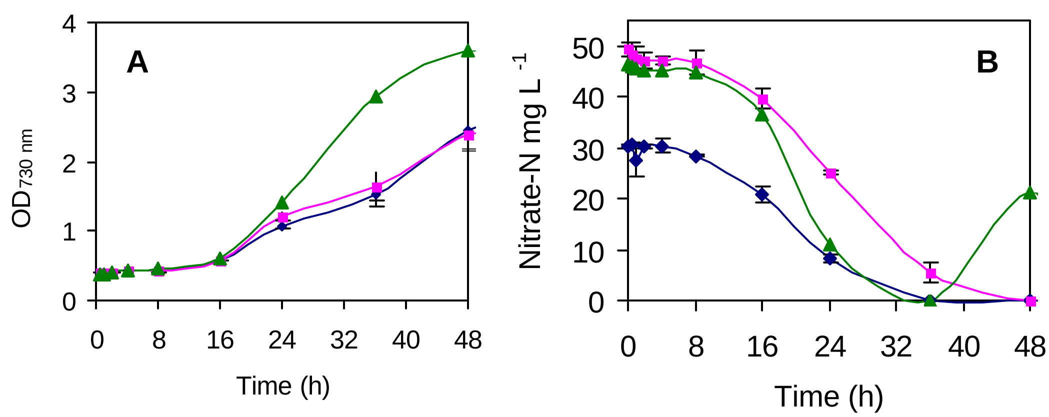

Figure 2. Growth (A) and NO_3^- uptake (B) of a *Chlorella* sp. ◆ = groundwater enriched with 4.5 mg L^{-1} PO_4^{-3}–P and 30 mg L^{-1} NO_3^-–N. ■ = groundwater enriched with 4.5 mg L^{-1} PO_4^{-3}–P and 50 mg L^{-1} NO_3^-–N. ▲ = BG-11 media containing 4.5 mg L^{-1} PO_4^{-3}–P and 50 mg L^{-1} NO_3^-–N.

Chlorococcum sp. – Cells exhibited similar growth potential both in groundwater and in the BG-11 growth medium, suggesting higher tolerance of *Chlorococcum* cells to groundwater than observed for *Chlorella* cells. As shown in **Figure 3**, complete removal of 50 mg L^{-1} NO_3^- -N occurred in both cultures within 32 h.

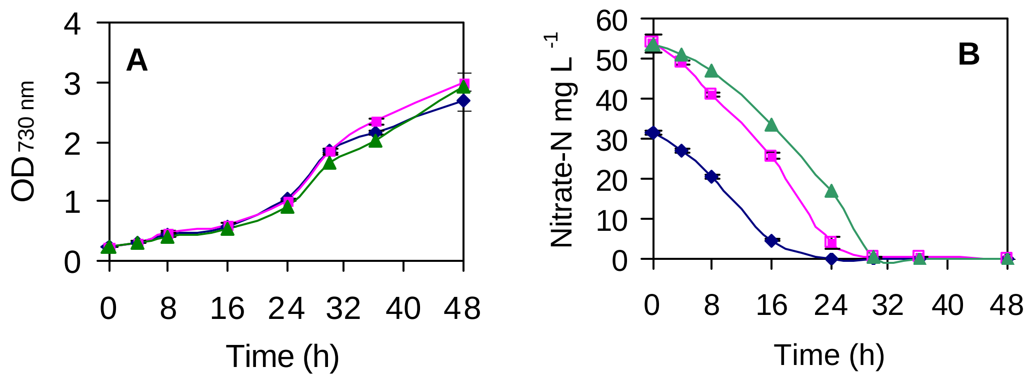

Figure 3. The growth (A) and NO_3^- uptake (B) of a *Chlorococcum* sp. ◆ = groundwater enriched with 4.5 mg L^{-1} PO_4^{-3}–P and 30 mg L^{-1} NO_3^-–N. ■ = groundwater enriched with 4.5 mg L^{-1} PO_4^{-3}–P and 50 mg L^{-1} NO_3^-–N. ▲ = BG-11 medium containing 4.5 mg L^{-1} PO_4^{-3}–P and 50 mg L^{-1} NO_3^-–N.

Scenedesmus sp. – Like *Chlorococcum* sp., *Scenedesmus* exhibited similar growth and nitrate uptake rates in the groundwater and the BG-11 growth medium. The nitrate concentration decreased from 50 mg L^{1} NO_3-N to below the detection level within 24 h (**Figure 4**).

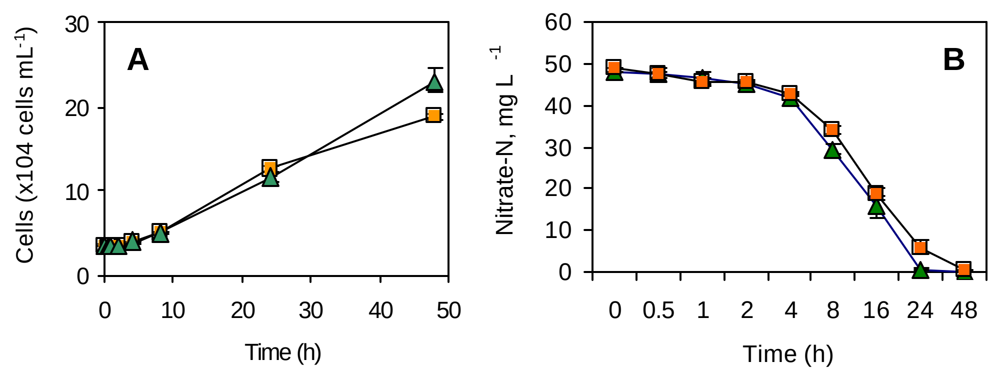

Figure 4. The growth (A) and NO_3^- uptake (B) of a *Scenedesmus* sp. ■ = groundwater enriched with 4.5 mg L^{-1} PO_4^{-3}–P and 30 mg L^{-1} NO_3^-–N. ▲ = BG-11 medium containing 4.5 mg L^{-1} PO_4^{-3}–P and 30 mg L^{-1} NO_3^-–N.

Ulothrix sp. – This alga exhibited similar growth and nitrate removal potential in surface water and BG-11 growth medium (**Figure 5**). When compared to the unicellular algal species described above, this filamentous alga performed poorly in terms of growth and nitrate removal. For instance, the *Ulothrix* culture resulted in a three-fold increase in biomass over a period of 48 h. In contrast, the *Scenedesmus* culture resulted in nearly nine-fold increase in algal biomass over the same period of time. As a result, by the end of 48 h cultivation period, only about 50% of the 50 mg L^{-1} NO_3-N was removed in the *Ulothrix* culture.

Pseudanabaena sp. – This filamentous cyanobacterial species growth and nitrate uptake rate was similar in the surface water and in BG-11 growth medium (**Figure 6**). The overall performance of the *Pseudanabaena* culture was better than that of *Ulothrix* species in terms of nitrate uptake rate. On the other hand, this species did not perform as well as the unicellular species.

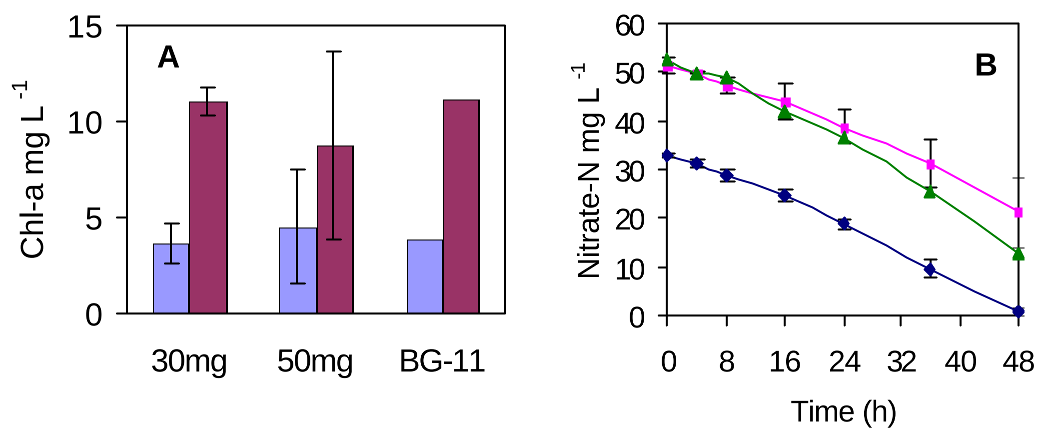

Figure 5. The growth (A) and nitrate uptake (B) of a *Ulothrix* sp. ■ = Chlorophyll-a at 0 h, ■ = Chl. a at 48 h, ◆ = surface water enriched with 4.5 mg L^{-1} PO_4^{-3}–P and 30 mg L^{-1} NO_3^-–N. ■ = surface water enriched with 4.5 mg L^{-1} PO_4^{-3}–P and 50 mg L^{-1} NO_3^-–N. ▲ = BG-11 media containing 4.5 mg L^{-1} PO_4^{-3} – P and 50 mg L^{-1} NO_3^- –N.

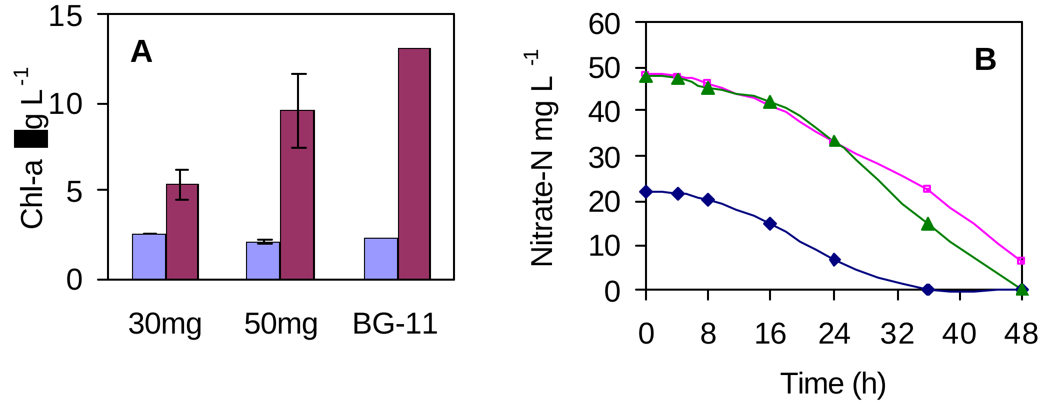

Figure 6. The growth (A) and nitrate uptake (B) of a *Pseudanabaena* sp. ■ = Chlorophyll-a at 0 h, ■ = Chl. a at 48 h, ◆ = surface water enriched with 4.5 mg L^{-1} PO_4^{-3}–P and 30 mg L^{-1} NO_3–N. ■ = surface water enriched with 4.5 mg L^{-1} PO_4^{-3}–P and 50 mg L^{-1} NO_3–N. ▲ = BG-11 media containing 4.5 mg L^{-1} PO_4^{-3}–P and 50 mg L^{-1} NO_3–N.

<u>Specific growth rate of isolated algal species</u>

Figure 7 shows the maximum specific growth rates of all five isolated algal species in a batch model under our culture conditions. It demonstrated that the unicellular algal species exhibit higher specific growth rates than the filamentous ones, paralleling the higher nitrate uptake rates. Among the three isolated unicellular green algae, *Scenedesmus* sp. appears to be the more desirable candidate for high performance nitrate removal.

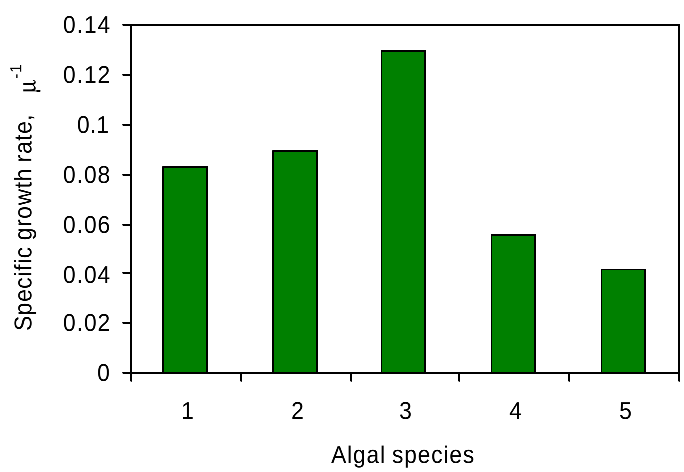

Figure 7. The maximum specific growth rate of microalgae isolated from metro-Phoenix area. 1. *Chlorella* sp; 2. *Chlorococcum* sp.; 3. *Scenedesmus* sp.; 4. *Ulothrix* sp.; and 5. *Pseudanabaena* sp.

Effect of temperature on growth and nitrate uptake

Scenedesmus sp. was subjected to further investigation to determine the optimal growth temperature and temperature tolerance for nitrate removal. It appears that the alga can tolerate a broad temperature range for growth and nitrate uptake, with the optimal temperature being from 30 to 35 ^{0}C which also results in the maximum cellular nitrate uptake efficiency (**Figure 8**). The high temperature tolerance of *Scenedesmus* sp. makes this organism particularly useful for mass culture outdoors in the Phoenix area.

Effect of light intensity on growth and nitrate uptake

As expected there was a positive relationship between light intensity and algal growth and nitrate uptake in cultures of *Scenedesmus* sp. Little growth and nitrate uptake occurred in cultures exposed to 15 ? mol m^{-2} s^{-1} light. As light intensity increased from 15- to 350 ? mol m^{-2} s^{-1}, the maximum specific growth rate increased from 0.035 to 0.12 h^{-1}, resulting in proportional increase in nitrate uptake (**Figure 9**). These results indicate that cellular nitrate uptake is a growth-dependent process: the higher the algal growth rate the higher the cellular nitrate uptake rate. Therefore, any efforts in improving algal growth rates will likely lead to enhancement in nitrate removal.

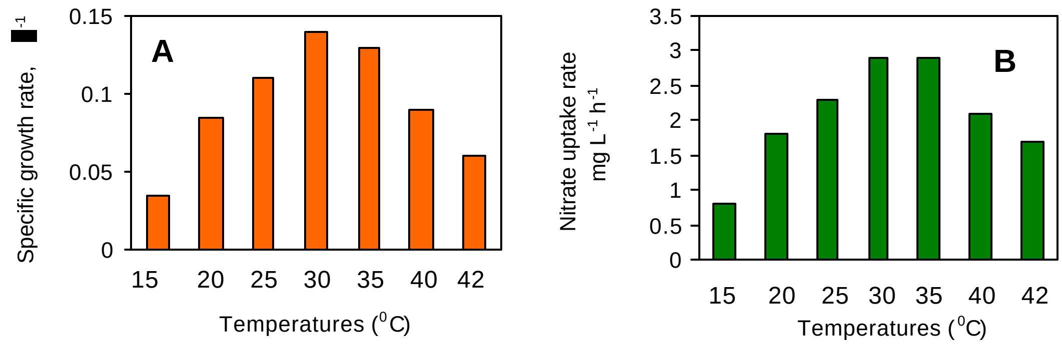

Figure 8. Effect of temperature on growth (A) and nitrate uptake (B) of *Senedesmus* cultures.

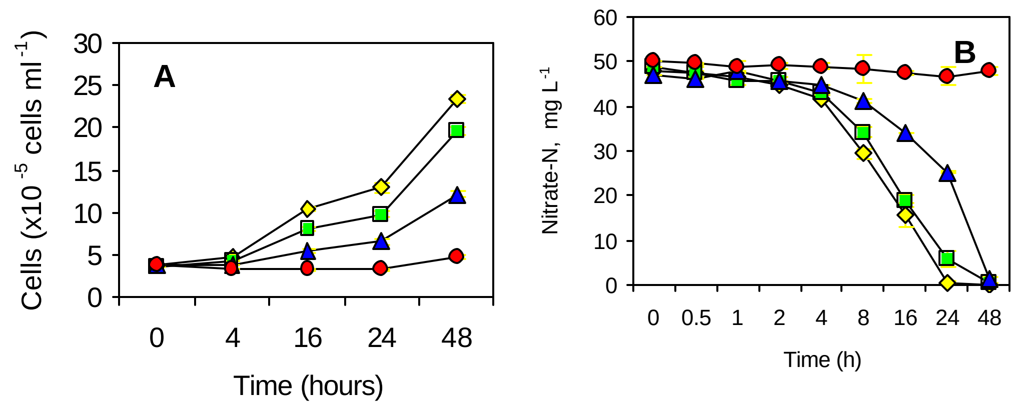

Figure 9. Effect of light intensity on growth (A) and nitrate uptake rate (B) of *Scenedesmus* sp. Light intensities (µmol m^{-2} s^{-1}): (○) = 15; (△) = 75, (□) = 200, and (◇) = 350.

In summary, four green algae (*Chlorella* sp., *Chlorococcum* sp.; *Scenedesmus* sp., and *Ulothrix* sp.) and one cyanobacterium (*Pseudanabaena* sp.) were isolated from various water environments in metro Phoenix area. Comparative growth and cellular nitrate uptake kinetics were studied among these algal isolates. The specific growth rate ranged from 0.035 to 0.14 h^{-1} with *Scenedesmus* sp. exhibiting the highest growth rate and *Pseudanabaena* sp. the lowest. Compared to the filamentous isolates, the unicellular species exhibited higher specific growth rates. The nitrate uptake rate was species-specific, and hence the algal species that exhibited higher growth rates assimilated nitrate more rapidly. As the high-performance algal strain, *Scenedesmus* sp. was subjected to further investigation, aiming at identifying the optimal culture conditions for sustainable nitrate removal. The specific growth rate and nitrate uptake rate increased with increasing light intensity from 10- to 250 ? mol m^{-2} s^{-1}. *Scenedesmus* sp. also exhibited a broad temperature tolerance, from 15 to 42 ^{0}C, with 30 to 38 ^{0}C resulting in the highest nitrate uptake rate. The average nitrate uptake rate of 2.6 mg $N\text{-}NO_3^-$ L^{-1} h^{-1} which occurred in cultures of *Scenedesmus* sp. is ca. 40% to 150% higher than those reported for nitrate removal by other microalgae and cyanobacteria.

The proposed project objectives have been successfully fulfilled, and the work represents a major milestone in the effort to demonstrate that microalgae have potential as an advanced engineered biological system for large-scale nitrate bioremediation. Continuation of this research is necessary in order to develop a highly efficient and cost-effective large-scale photobioreactor, and to reassess the growth physiology and nitrate uptake potential of *Scenedesmus* sp. under outdoor conditions.

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Impacts of Conservation Measures and Alternative Water Supplies on Groundwater

Basic Information

Title:	Impacts of Conservation Measures and Alternative Water Supplies on Groundwater
Project Number:	2003AZ18B
Start Date:	1/1/1997
End Date:	1/1/1997
Funding Source:	104B
Congressional District:	1st
Research Category:	Ground-water Flow and Transport
Focus Category:	Conservation, Groundwater, Water Supply
Descriptors:	WS, GW, CON
Principal Investigators:	Abe Springer, Lanya Ross

Publication

1. Springer, A.E. and J.A. Kessler. 2003. Groundwater model of the Redwall-Muav aquifer of the Coconino Plateau incorporating impacts of pumping and water conservation on small springs of the Grand Canyon. Annual meeting of the Geological Society of America, November 2-5, Seattle, WA.

A. Problem and Research Objectives:

Conservation of water and the use of alternative water supplies have become very important tools for water managers. The broad category of water conservation may include water efficiency, wise-water use, or curtailment of use (Pinkham and Davis 2002). Alternative supplies of water include graywater reuse, water recycling, rainwater harvesting, or wastewater reclamation and reuse. Alternative water supplies are a way to augment water supplies after the application of conservation measures and are an extremely important tool to overall water management.

Outside of Arizona's Active Management Areas (AMAs), the issues of conservation and alternative water supplies are becoming more important. Such recent issues as Canyon Forest Development, snowmaking with reclaimed City of Flagstaff wastewater, private wastewater treatment versus municipal wastewater treatment systems in rural areas and other issues have pointed out how few scientific tools water managers have to make these decisions.

Canyon Forest Village proposed to provide 10 percent of their water supply through rain harvesting and potentially another 20 percent or more of their water through reuse of reclaimed water (Grahl 2000). No predictions were made of the fate of these alternative water supplies and/or potential impacts to recharge to the underlying aquifers or runoff on nearby streams. Groundwater models built to predict the impacts of this community did not have scenarios to predict the impacts of these alternative water supplies on local springs in the Grand Canyon.

A model built to predict the impacts of safe yield and sustainable yield on a rural groundwater basin undergoing rapid conversion to residential noted the important roles of private wastewater system (septic) return flow to the aquifer (Navarro 2002). Predictions of future water use scenarios did not address the potential differences in recharge to the aquifer that graywater reuse would cause the aquifer.

In Tucson, effluent use currently meets about 5 percent of municipal water demand (Gelt and others 1999). As much as 31 percent of Casa del Agua's (an Arizona experimental home built in 1989 and used for water research conservation since then) total water budget is from recycled graywater. It is not known the fate of these alternative supplies of water on the local aquifer budgets (Gelt 1993).

This report addresses the impact of conservation measures and alternative water supplies on groundwater budgets. Conservation measures are described quantitatively in terms of their impact on the water budget, and the construction of a series of generic groundwater models allowed for the quantitative evaluation of alternative water supplies at the regional level. In addition, a specific northern Arizona groundwater model was adjusted to consider water conservation practices. The objectives of this research were:

1. To quantify the impacts of different conservation measures on groundwater budgets.

2. To develop generic groundwater models to understand the impacts of different alternative water supplies on groundwater budgets.
3. To determine the impacts of conservation measures on a calibrated groundwater flow model of a specific aquifer.
4. To determine the impacts of alternative water supplies on a calibrated groundwater flow model of a specific aquifer.

Impacts of Conservation Measures on Groundwater Budgets

A thorough review and compilation of existing published data was conducted to quantify the impacts of water conservation and available alternative water supplies in Arizona. The results of this literature review are presented in table 1.

Table 1. Water conservation measures and alternative water supplies available in the State of Arizona. This table includes published data regarding the quantitative effects these measures have on water budgets. Data was collected from resources specific to Arizona and the desert Southwest.

Water Conservation Measure	**Water Budget Impact of Applied Conservation**	**Seasonality of Impact**	**Source**
Water Use Reduction			
Note: In 1990, 4.6 m^3/day supplied a 5 person household. In 2000, 3.4 m^3/day supplied a 5 person household. General water use education has led to a reduction of up to a 25 percent in personal water use between 1990 and 2000. Sources: Arizona Department of Water Resources (ADWR); United State Environmental Protection Agency (EPA)			
Low-flow appliances			
Showerheads	Rated flows: 27 to 44 m^3/d → 4 to 14 m^3/d; average 70% reduction in water use	Year-round	Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA)
Toilets	Rated flows: 13-18% reduction in water use	Year-round	SAHRA
Faucets	Rated flows: 15 to 27 m^3/d → 8 to 14 m^3/d; average 50% reduction in water use	Year-round	SAHRA
Dishwashers	Rated flows: .05 to .1 m^3/d → .03 to .04 m^3/d; average 47% reduction in water use	Year-round	SAHRA

Water Conservation Measure	**Water Budget Impact of Applied Conservation**	**Seasonality of Impact**	**Source**
Washing Machine	Rated flows: 0.15 m^3/load $\rightarrow$ 0.1 m^3/load; 33% reduction in water use	Year-round	SAHRA
Efficient Yard Practices			
Graywater Use (dual plumbing systems)	0.13 to 0.17 m^3/d out of septic/sewer system	Mar. to Nov.	SAHRA; Whitney et al 2004
Xeriscaping (preservation of native landscape)	Reduction of irrigation volume by 50% or more	Mar. to Nov.	Arizona Department of Water Resources (ADWR)
Choose spa over pool	0.24 m^3/d $\rightarrow$ 0.06 m^3/d; 75% reduction in water use	Summer	SAHRA
Pool and/or spa cover	ET reduction by 95%	Summer	SAHRA
Recirculating water features in shade	Unknown (reduction in ET varies)	Summer	SAHRA
Increased Recharge			
Artificial Recharge/ Storing surface water in the aquifer (from CAP, effluent, & Salt/Verde River water)	Phoenix: 966,470 m^3/d (1999); 15,949 m^3/d (2001) stored in aquifer	Nov. to Mar.	ADWR - Phoenix AMA
	Tucson: 174,118 m^3/d (1999) stored in aquifer	Nov. to Mar.	- Tucson AMA
	Prescott: 222,446 m^3/d (1999) stored in aquifer	Nov. to Mar.	- Prescott AMA
	Pinal: 6,895 m^3/d (1999); 1,588,477 m^3/d (2000) stored in aquifer	Nov. to Mar.	- Pinal AMA
	Wastewater reclamation in Florida resulted in modeled increases to the water table of ~ 13 m; Modeled results of recharge in Mojave	Nov. to Mar.	O'Reilly 2002; Izbicki & Stamos 2003
		Nov. to	

Water Conservation Measure	Water Budget Impact of Applied Conservation	Seasonality of Impact	Source
	Desert, CA show water table increases of 3-30 m over a 20 year drought period.	Mar.	
Rain gardens	Rain gardens most effective when 10% the area of impervious surface in the model. Increasing rain garden area to >20% saw very little increased recharge.	Nov. to Mar.	Potter 2002
Reducing impervious surface from 18% to 2%	Increase stream baseflow 20%; Decrease surface runoff 90%; Increase regional groundwater flow 10%; Increase spring flow 5%	Year-round	Bannerman 2000
Alternative Water Sources			
Surface Water	Tucson: 676 m^3/d (1998)	Year-round	ADWR - Tucson AMA
Rain Harvesting	Two buildings in Tucson generate 0.15 m^3/d; Casa del Agua in Tucson collects 75% of annual precipitation that falls on its catchment area (14 m^3/year on 55.7m^2 area)	Snowmelt & Monsoon	City of Tucson Water Harvesting Guidance Manual; Gelt 1993 (Casa del Agua)
Reclaimed water	Tucson: 37,655 m^3/d (1998) ~ 311,129 m^3/d water used on AZ Central Valley golf courses	Year-round Mar. to Nov.	ADWR - Tucson AMA McKinnon 2002
Importation of groundwater from other groundwater basins	Tucson: 0 m^3/d (1998)	Year-round	ADWR - Tucson AMA

Impacts of Alternative Water Supplies on Groundwater Budgets

A generic aquifer was created to represent typical hydrologic characteristics for the State of Arizona. A generic water budget was then produced for this aquifer. The range in potential alternative water supplies were defined for use in the numerical modeling process based on this theoretical aquifer.

Generic Aquifer Characteristics

The following general aquifer descriptions have been taken from a literature review of regional and local hydrogeology. Basin and Range aquifers were stressed because most Active Management Areas (AMAs) in Arizona are located in this type of setting.

- Basin and Range aquifers are the principal source of groundwater in Southern Arizona. The aquifers are present in alluvium-filled basins between mountain ranges (Robson and Banta 1995).
- The regional aquifer in the Pinal Creek Basin (Pinal AMA) is made up of unconsolidated stream alluvium and consolidated basin fill (Angeroth 2002).
- The land surface of the basins generally slopes gently from the adjacent mountain fronts toward the flat-lying central parts of the basins (Robson and Banta 1995).
- Thickness of basin-fill is not well constrained, but ranges from 330 to 1600 m in many basins (Robson and Banta 1995).
- The hydraulic conductivity of alluvium has been measured in the Pinal Creek Basin to be 3-200 m/day, and the basin fill hydraulic conductivity was measured to be 0.5-250 m/day (Angeroth 2002).

A conceptual aquifer was constructed based on the information mentioned above. This aquifer has the following characteristics:

- Conceptual AMA area is 10.01 km^2, (100,200,100 m^2)
- Unconfined Aquifer
- Composed of homogenous and isotropic mix of alluvium and/or basin fill
- Thickness of 465 meters.
- Average hydraulic conductivity of 1 m/day
- Line of constant head (964 m) on the west side of the model, to represent the higher elevation of recharge occurring along a mountain front.
- Line of drains (930 m) simulating a seep face on the east side of the model, and representing the slope of a basin fill aquifer away from mountain ranges.

Generic Water Budget Characteristics

The following general water budget descriptions have been taken from a literature review of regional and local hydrogeology:

- Recharge to Basin and Range aquifers occurs primarily as precipitation in the mountains surrounding the aquifer. Only approximately 5 percent of precipitation that falls recharges the aquifer. Average mountain precipitation is 0.4 m/year (Robson and Banta 1995). Average precipitation in Arizona is .322 m/year (8.82 x 10^{-4} m/day) (National Climatic Data Center 2003).
- Some aquifer recharge occurs from irrigation of commercial crops, golf courses and other vegetation, and from percolation out of reservoirs, canals and sewage treatment plants. Between 1915 and 1980, about half of the water pumped from Arizona aquifers ended up going back into the ground as recharge from irrigation (Robson and Banta 1995).
- Underflow flow can be a significant component of recharge in some basins (Robson and Banta 1995).
- Most precipitation is lost to evapotranspiration. Evapotranspiration also depletes groundwater where the water table is very shallow (Robson and Banta 1995).
- Groundwater leaves the aquifers as discharge to streams and springs, underflow, and withdrawal by wells (Robson and Banta 1995).
- Roaring Springs pumps approximately 3700 m^3/day, and about 1300 m^3/day (35 percent) is processed at the Grand Canyon wastewater treatment plant (Mack 2003).
- The major wells supplying Tusayan, Arizona with water have a pumping capacity of approximately 1200 m3/day, and about 530 m3/day (45 percent) is processed at the Tusayan Wastewater Treatment Facility (Petzold 2003).

An initial conceptual water budget was constructed based on the information mentioned above. The volumes in this budget are subject to change with different management practices.

Table 2. Conceptual water budget for a generic basin-fill aquifer in Arizona.

Water Budget Component	**Value**	**Vol. in Conceptual AMA**
Precipitation	8.82 x 10^{-4} m/day	88,200 m^3/day
Natural Recharge	~5% Precipitation	4,410 m^3/day
Artificial Recharge	0% to 50% of pump vol.	0 to 4410 m^3/day
Evapotranspiration	~95% Precipitation	83,790 m^3/day
Pumping	Natural Recharge + Artificial Recharge	4,410 to 8,820 m^3/day
Spring Flow	Unknown – Variable	Defined by modeled potentiometric surface

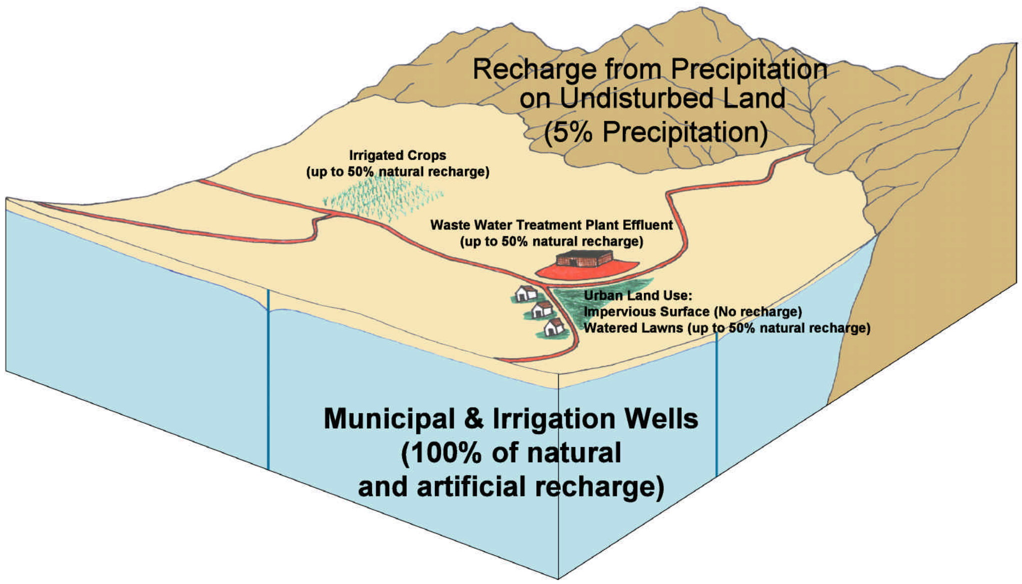


Figure 1. Conceptual model of theoretical basin-fill Arizona aquifer and associated land use.

B. Methodology

It was our objective to assess the impact of alternative water supplies on a theoretical Arizona aquifer under the constraints of Arizona's Safe-Yield policy. *Safe Yield is defined as the hydrologic concept of achieving and maintaining a long-term balance between the annual amount of groundwater withdrawn in an AMA and the annual amount of natural and artificial recharge in the AMA*. We assumed in this modeling process that water-use reduction practices, such as personal wise water use, installation of water efficient appliances, and effective infrastructure building and maintenance are balanced by the increasing water needs of a growing population. The alternative water supplies we explored are most commonly implemented after more traditional conservation practices are in place. In this project, we examined the impacts of irrigating crops and lawns with wastewater treatment plant effluent and rainwater harvesting.

The model variables we used to assess impacts of different water management scenarios were well pumping rates, recharge rates, spring discharge rates, changes in aquifer storage, and changes in the potentiometric surface of the aquifer. As stated above, the upper bound on pumping was constrained by the Safe Yield policy. In addition, the upper bound on artificial recharge rates was constrained by pumping rates. The models were calibrated based on an estimate of WWTP effluent volume of 25 percent of pumping volume.

Thus, the general mathematical form of the management objective was:

$$P = N + xP + yP + zR$$

Where:

P	=	Annual average total volume of water pumped from all wells in the aquifer study area
N	=	Annual volume of water that naturally recharges the aquifer in the study area (some average percentage of precipitation)
R	=	Annual average volume of water that falls as precipitation on rainwater harvesting collection areas in the study area
x	=	Annual average percentage of water pumped from the aquifer that is discharged as effluent from the study area's waste water treatment plant directly into the environment (in a natural channel, for example)
y	=	Annual average percentage of water pumped from the aquifer that is discharged as effluent from the study area's waste water treatment plant for use on irrigated lawns and/or crops
z	=	Annual average percentage of water harvested in rainwater collection areas that is discharged to the aquifer (as irrigation)

A description of five management scenarios based on the general management objective follow. These scenarios were used to create numerical models which were calibrated and then compared to quantitatively describe the effects large-scale water conservation and alternative water supplies can have on Arizona's Basin and Range-type aquifers.

<u>Management Objective 1</u>:

$P = N + xP + yP + zR$; where $x = 25\%$, $y = 0\%$, $z = 0\%$

Design a pumping scenario that 1) *does not* include irrigation of crops and lawns with waste water treatment plant effluent, and 2) maximizes the pumping rate in a theoretical AMA, with annual artificial and natural recharge volume to the AMA as an upper bound on annual pumping rates. The first estimate of annual artificial recharge is 25 percent of annual pumping, and represents wastewater treatment plant discharge to the environment along a channel.

<u>Management Objective 2</u>:

$P = N + xP + yP + zR$; where $x = 0\%$, $y = 25\%$, $z = 0\%$

Design a pumping scenario that 1) *does* include irrigation of crops and lawns with waste water treatment plant effluent, and 2) maximizes the pumping rate in a theoretical AMA, with annual artificial and natural recharge volume to the AMA as an upper bound on annual pumping rates. This scenario will distribute wastewater treatment plant discharge (25 percent of annual pumping) over an irrigated area.

<u>Management Objective 3</u>:

P = N + xP + yP + zR; where x = 0%, y = 25%, z = 10%

Design a pumping scenario that 1) *does* include irrigation of crops and lawns with waste-water treatment plant effluent, 2) includes harvested rainwater as an alternative water supply, and 3) maximizes the pumping rate in a theoretical AMA, with annual artificial and natural recharge volume to the AMA as an upper bound on annual pumping rates. In this scenario, 10 percent of rainwater harvested from impervious surfaces and reclaimed waste water (25 percent of annual pumping) are both used to irrigate urban and agricultural areas.

<u>Management Objective 4</u>:

P = N + xP + yP + zR; where x = 0% and y = 25%, z = 100%

Design a pumping scenario that 1) *does* include irrigation of crops and lawns with waste water treatment plant effluent, 2) includes harvested rainwater as an alternative water supply, and 3) maximizes the pumping rate in a theoretical AMA, with annual artificial and natural recharge volume to the AMA as an upper bound on annual pumping rates. In this scenario, 100 percent of rainwater harvested from impervious surfaces and reclaimed waste water (25 percent of annual pumping) are both used to irrigate urban and agricultural areas.

<u>Management Objective 5</u>:

P = N + xP + yP + zR; where x = 25%, y = 0%, z = 100%

Design a pumping scenario that 1) *does* include irrigation of crops and lawns with waste-water treatment plant effluent, 2) includes harvested rainwater as an alternative water supply, and 3) maximizes the pumping rate in a theoretical AMA, with annual artificial and natural recharge volume to the AMA as an upper bound on annual pumping rates. In this scenario, 100 percent of rainwater harvested from impervious surfaces was applied as irrigation to urban and agricultural areas, and reclaimed waste water (25 percent of annual pumping) was discharged to the environment along a channel.

<u>Management Objective 6</u>:

P = N + xP + yP + zR; where x = 0% and y = 0%, z = 0%

Design a pumping scenario that 1) *does not* include irrigation of crops and lawns with waste-water treatment plant effluent, 2) *does not* include harvested rainwater as an alternative water supply, and 3) maximizes the pumping rate in a theoretical AMA, with annual natural recharge volume to the AMA as an upper bound on annual pumping rates. In this scenario, 100 percent of rainwater harvested from impervious surfaces and all reclaimed waste water are recycled and never discharged to the environment.

1.1. Generic Numerical Flow Modeling

After defining the conceptual model's hydrologic characteristics, water budget components, and management objectives to be tested, a generic numerical groundwater flow model was built. This model was used to simulate the effects of the previously-defined range of conservation measures and alternative water supplies during a 100-year time period. Simple graphics were created to display the cumulative changes to the water budgets through time, and the impacts of different management scenarios were quantified.

Numerical Groundwater Flow Model Construction

Model Software:

Groundwater Vistas Version 3.47 (Environmental Simulations, Inc. Reinhold, PA), a Windows model-independent graphical user interface for the 3-D groundwater flow model MODFLOW.

Model Dimensions:

- Horizontal Grid:
  - Number of Rows: 572
  - Number of Columns: 572
  - X spacing: 17.5 meters
  - Y spacing: 17.5 meters
  - Total Model Cells: 327184
- Vertical Grid:
  - Number of Layers: 1
  - Model Bottom Elevation: 500 meters above sea level
  - Model Top Elevation: 965 meters above sea level
  - Layer is flat

Default Parameter Values:

- Aquifer is isotropic, homogenous
- Hydraulic Conductivity: 1 m/d
- S, S_y, Porosity: all 0.02 (Fetter 2001)

Time Steps:

- 10 Stress Periods, each stress period 3650 days
- 10 Time Steps per Stress Period

Solver:

- Preconditioned Conjugate Gradient Solution Package, Version 2.1
- Iteration seed computed by: MODFLOW
- Max. # Iterations: 1000
- # Iteration Parameters: 5
- Head Change criterion for convergence: 0.001

Boundary Conditions:

- No-flow boundary on the north and south sides of the model
- Constant head boundary on the east side of the model (964 m)
- 16 Wells (Constant Flux) are evenly distributed throughout the center of the model. Wells are all located at least 1000 m from boundary conditions. For each water use scenario modeled, the pumping rates were adjusted to balance that scenario's recharge rates. The range of pumping rates used in this project is 4339.4 m^3/d (271.2 m^3/d per well) to 8704 m^3/d (544 m^3/d per well).
- Line of 572 Drains (Head-dependent flux) along east side of model at an elevation of 930 m. Drain conductance is 8.75 x 10^3.

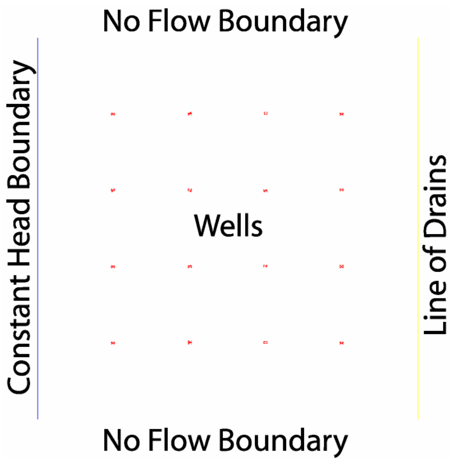


Figure 2. Spatial distribution of boundary conditions in generic numerical groundwater model.

Recharge Zones:

The distribution of recharge zones in the numerical groundwater model was based on the average state-wide distribution of land use in Arizona. 0.5 % of the area is rural roads, 2 % is urban, 61 % is natural, and 37 % is non-irrigated agriculture (US Census Bureau 2004).

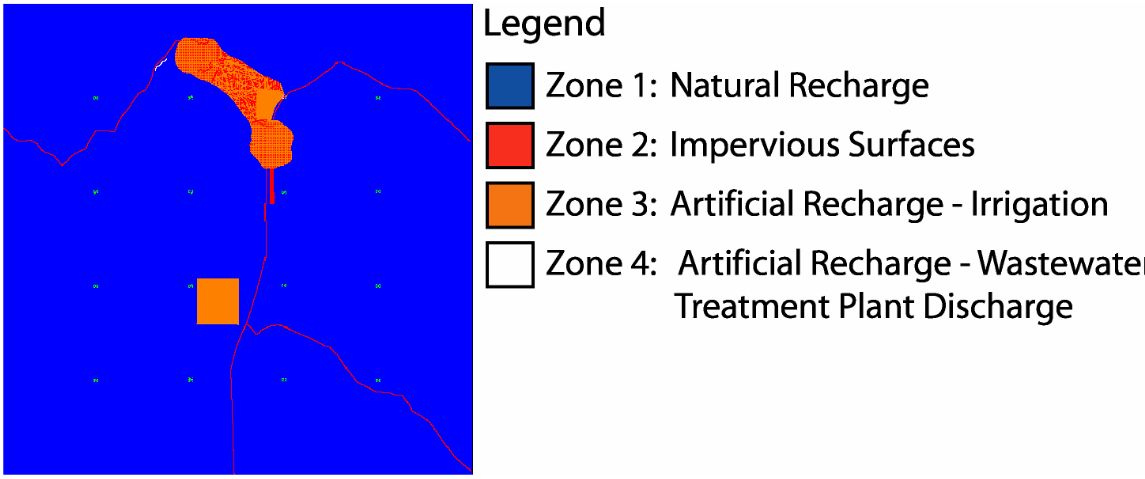
Zone 1: Natural Recharge. This zone represents areas of predominantly natural vegetation, with recharge rates of 5 % of precipitation, or 4.41 x 10^{-5} m/day.

Zone 2: Impervious surfaces. This zone represents land uses that include building roofs, roads, and parking lots. The recharge rate for this zone is 0.00 m/day.

Zone 3: Artificial Recharge/Irrigation. This zone includes lawns and irrigated fields. This recharge rate varies between 5 % of precipitation (4.41 x 10^{-5} m/day) and 5.21 x 10^{-4} m/day.

Zone 4: Artificial Recharge/Wastewater Treatment Plant Discharge. This zone represents the area that may receive discharge from a wastewater treatment plant. This recharge rate varies between 5 % of precipitation (4.41 x 10^{-5} m/day) and 50 % of maximum pumping (0.220 m/d).

Figure 3. Spatial distribution of recharge zones in a generic numerical groundwater model of an Arizona basin fill-type aquifer.



Description of Management Objective Variables

The following table summarizes the areas and volumes of water used by each source and sink in the generic numerical groundwater flow model (Table 3).

Table 3. Summary of values used in each numerical groundwater management model for a generic basin-fill aquifer in Arizona.

Scenario	**Pump Rate (m^3/d)**	**Zone 1 Recharge**	**Zone 2 Recharge**	**Zone 3 Recharge**	**Zone 4 Recharge**
Management Objective 1: *P = N+ xP+ yP+ zR;* *x = 25% y = 0%* *z = 0%*	***Per Well:*** 362.50 ***Total:*** 5,800	***Area (m^2):*** 98701618.75 ***Value (m/d):*** 4.41×10^{-5}	***Area (m^2):*** 1489906.25 ***Value (m/d):*** 0.00	***Area (m^2):*** 0.00 ***Value (m/d):*** 0.00	***Area (m^2):*** 8575 Value (m/d): 0.17
Management Objective 2: *P = N+ xP+ yP+ zR;* *x = 0% y = 25%* *z = 0%*	***Per Well:*** 363.29 ***Total:*** 5812.64	***Area(m^2):*** 95953331.25 ***Value (m/d):*** 4.41×10^{-5}	***Area (m^2):*** 1489906.25 Value (m/d): 0.00	***Area (m^2):*** 2756862.5 ***Value (m/d):*** 5.71×10^{-4}	***Area (m^2):*** 0.00 ***Value (m/d):*** 0.00
Management Objective 3: *P = N+ xP+ yP+ zR;* *x = 0% y = 25%* *z = 10%*	***Per Well:*** 373.50 ***Total:*** 5,976	***Area (m^2):*** 95953331.25 ***Value (m/d):*** 4.41×10^{-5}	***Area (m^2):*** 1489906.25 ***Value (m/d):*** 0.00	***Area (m^2):*** 2756862.5 ***Value (m/d):*** 6.34×10^{-4}	***Area (m^2):*** 0.00 ***Value (m/d):*** 0.00
Management Objective 4: *P = N+ xP+ yP+ zR;* *x = 0% y = 25%* *z = 100%*	***Per Well:*** 472.00 ***Total:*** 7552	***Area (m^2):*** 95953331.25 ***Value (m/d):*** 4.41×10^{-5}	***Area (m^2):*** 1489906.25 ***Value (m/d):*** 0.00	***Area (m^2):*** 2756862.5 ***Value (m/d):*** 1.21×10^{-3}	***Area (m^2):*** 0.00 ***Value (m/d):*** 0.00
Management Objective 5: *P = N+ xP+ yP+ zR;* *x = 25% y = 0%* *z = 100%*	***Per Well:*** 472.00 ***Total:*** 7,552	***Area(m^2):*** 95944756.25 ***Value (m/d):*** 4.41×10^{-5}	***Area (m^2):*** 1489906.25 ***Value (m/d):*** 0.00	***Area (m^2):*** 2756862.5 ***Value (m/d):*** 5.21×10^{-3}	***Area (m^2):*** 8575 ***Value (m/d):*** 0.22
Management Objective 6: *P = N+ xP+ yP+ zR;* *x = 0% y = 0%* *z = 0%*	***Per Well:*** 271.20 ***Total:*** 4339	***Area (m^2):*** 98710193.75 ***Value (m/d):*** 4.41×10^{-5}	***Area (m^2):*** 1489906.25 ***Value (m/d):*** 0.00	***Area (m^2):*** 0.00 ***Value (m/d):*** 0.00	***Area (m^2):*** 0.00 ***Value (m/d):*** 0.00

Graphical Illustration of Model Results

<u>Natural Environment</u>:

P = N + xP + yP + zR; where x = 0%, y = 0%, and z = 0%

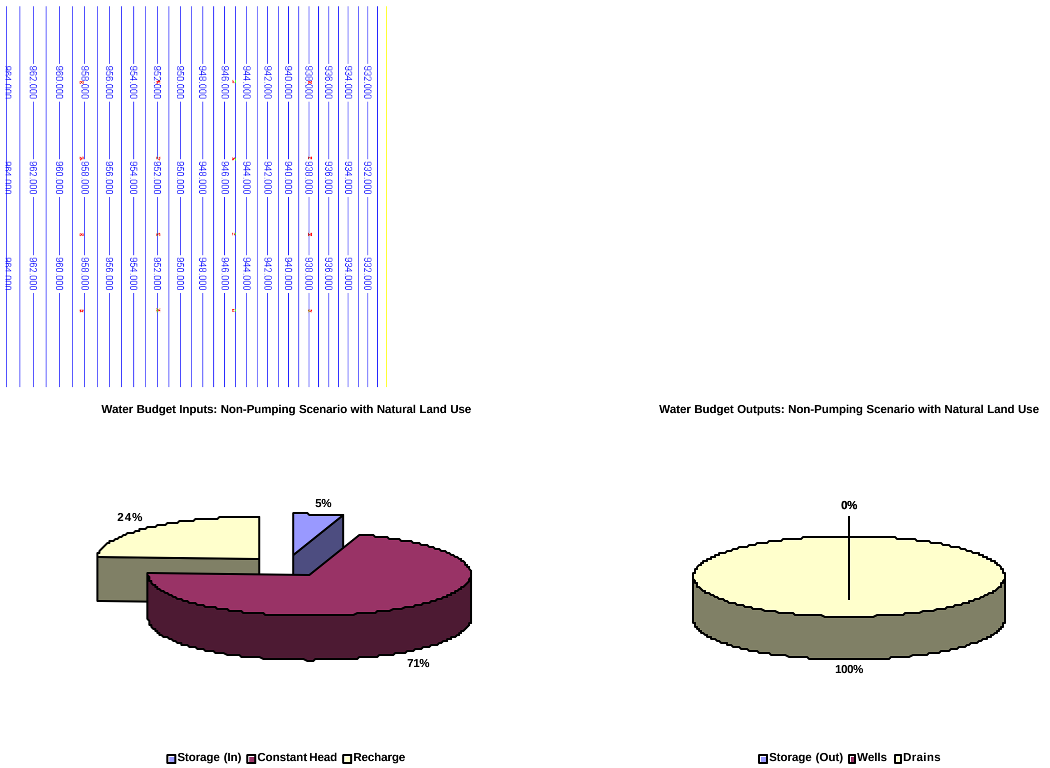
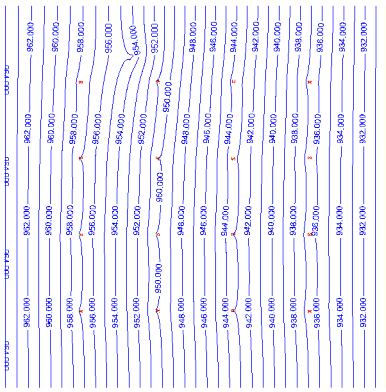
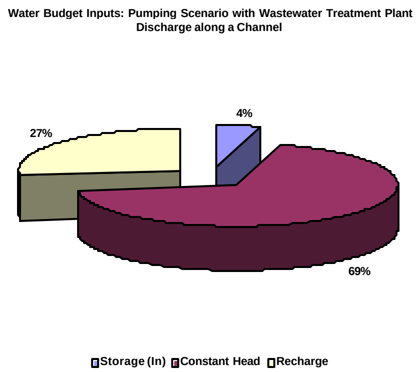


Figure 4. Water table elevation (left), water budget inputs (middle), and water budget outputs (right) in the generic numerical groundwater model under natural conditions (i.e. no pumping, irrigation or impervious surfaces).

<u>Management Objective 1</u>:

P = N + xP + yP + zR; where x = 25%, y = 0%, and z = 0%





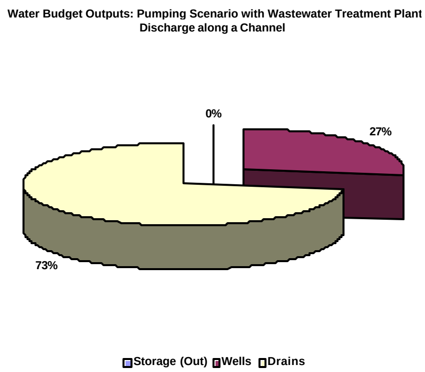
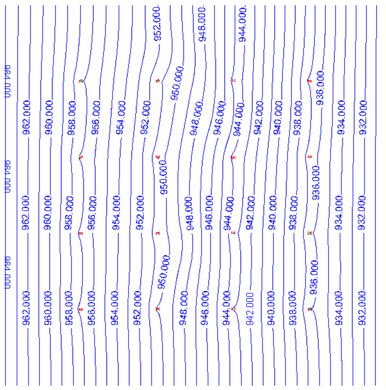
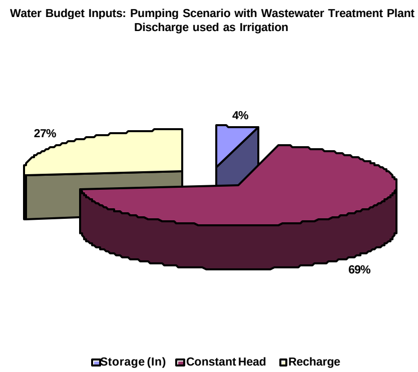


Figure 5. Water table elevation (left), water budget inputs (middle), and water budget outputs (right) in the generic numerical groundwater model under a pumping scenario with wastewater treatment plant effluent being discharged directly into the environment in a natural channel.

<u>Management Objective 2:</u>

P = N + xP + yP + zR; where x = 0%,   y = 25%, and z = 0%





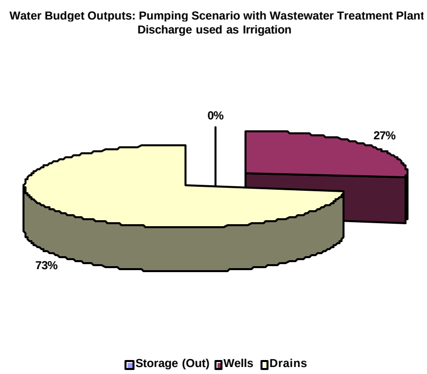


Figure 6. Water table elevation (left), water budget inputs (middle), and water budget outputs (right) in the generic numerical groundwater model under a pumping scenario with wastewater treatment plant effluent being used to irrigate crops and lawns.

<u>Management Objective 3:</u>

P = N + xP + yP + zR; where x = 0%, y = 25%, and z = 10%

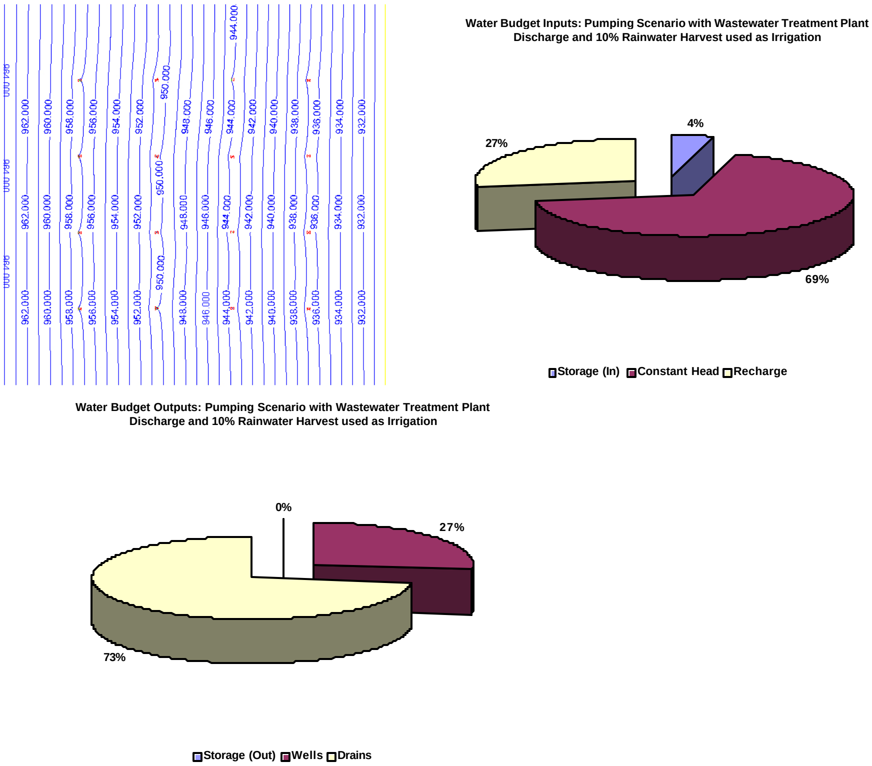
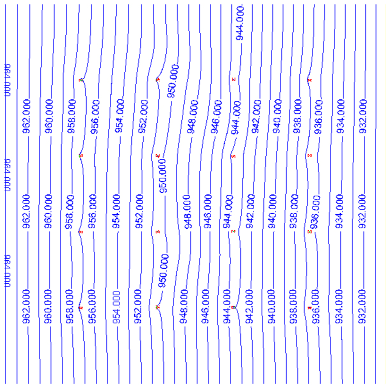
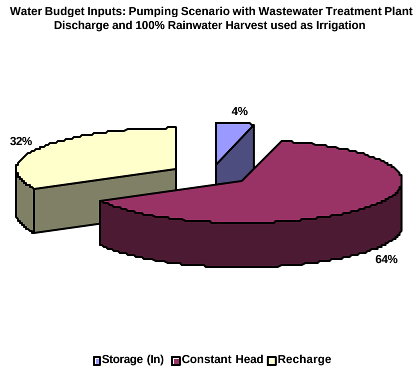


Figure 7. Water table elevation (left), water budget inputs (middle), and water budget outputs (right) in the generic numerical groundwater model under a pumping scenario with wastewater treatment plant effluent and 10 percent of precipitation falling on rainwater collection areas being used as irrigation on crops and lawns.

<u>Management Objective 4:</u>

P = N + xP + yP + zR; where x = 0%, y = 25%, and z = 100%





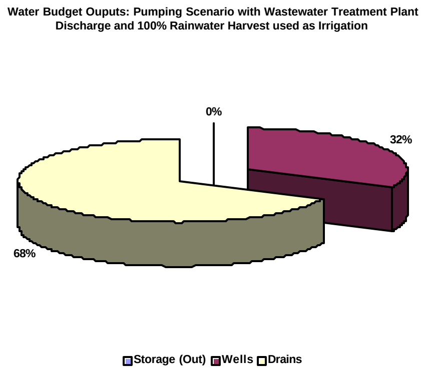
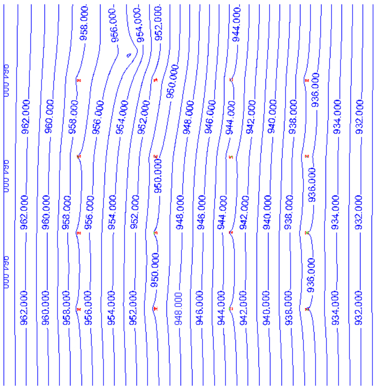
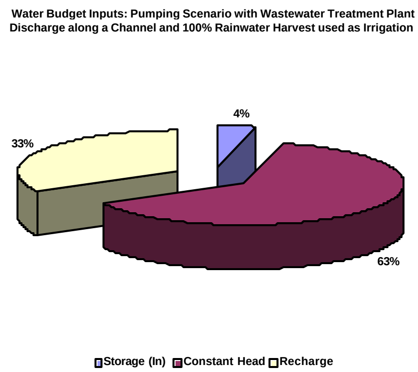


Figure 8. Water table elevation (left), water budget inputs (middle), and water budget outputs (right) in the generic numerical groundwater model under a pumping scenario with wastewater treatment plant effluent and 100 percent of precipitation falling on rainwater collection areas being used as irrigation on crops and lawns.

Management Objective 5:

P = N + xP + yP + zR; where x = 25%, y = 0%, and z = 100%





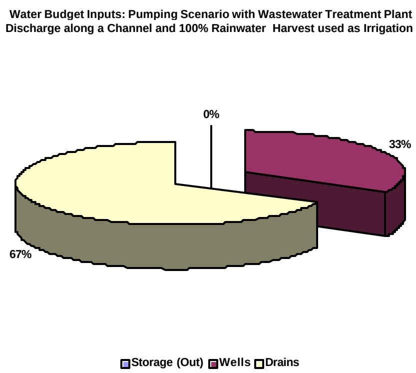
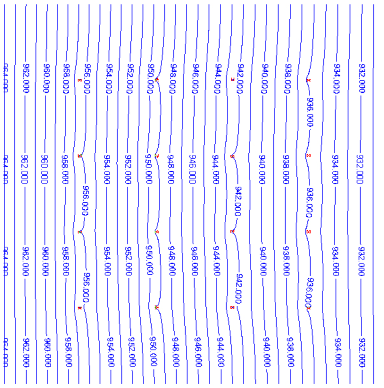
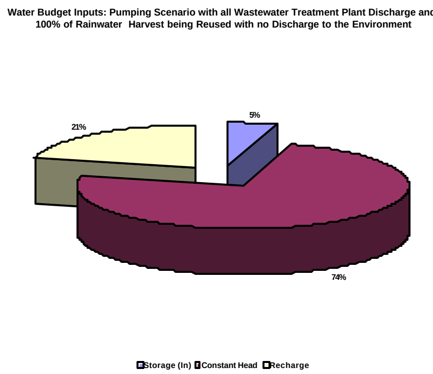


Figure 9. Water table elevation (left), water budget inputs (middle), and water budget outputs (right) in the generic numerical groundwater model under a pumping scenario with wastewater treatment plant effluent being discharged directly into the environment in a natural channel, and with 100 percent of precipitation falling on rainwater collection areas being used as irrigation on crops and lawns.

Management Objective 6:

P = N + xP + yP + zR; where x = 0%, y = 0%, and z = 0%





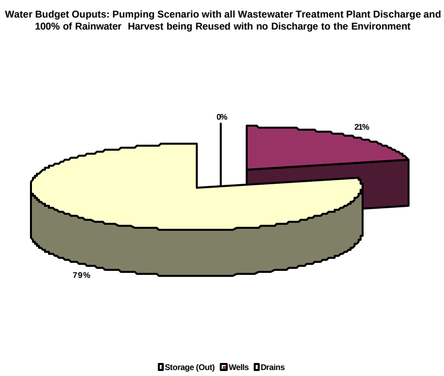


Figure 10. Water table elevation (left), water budget inputs (middle), and water budget outputs (right) in the generic numerical groundwater model under a pumping scenario with wastewater treatment plant effluent and 100 percent of precipitation falling on rainwater collection areas being reused without being discharged back into the environment.

Quantified Results of Conservation Measures

Table 4. Quantitative differences in water budget values between different numerical groundwater management models for a generic basin-fill aquifer in Arizona.

	Total Volume of Water (m^3) into Aquifer after 100 Years			**Total Volume of Water (m^3) Out of Aquifer after 100 Years**		
Scenario	***Storage***	***Constant Head***	***Recharge***	***Storage***	***Wells***	***Drains***
Natural	3.20×10^{7}	4.65×10^{8}	1.61×10^{8}	2109.3	0	6.60×10^{8}
Management Objective 1: *P = N+ xP+ yP+ zR; x = 25% y = 0% z = 0%*	3.39×10^{7}	5.36×10^{8}	2.12×10^{8}	6298.5	2.12×10^{8}	5.71×10^{8}
Management Objective 2: *P = N+ xP+ yP+ zR; x = 0% y = 25% z = 0%*	3.38×10^{7}	5.45×10^{8}	2.12×10^{8}	1671.0	2.12×10^{8}	5.80×10^{8}
Management Objective 3: *P = N+ xP+ yP+ zR; x = 0% y = 25% z = 10%*	3.38×10^{7}	5.45×10^{8}	2.18×10^{8}	1775.2	2.18×10^{8}	5.80×10^{8}
Management Objective 4: *P = N+ xP+ yP+ zR; x = 0% y = 25% z = 100%*	3.36×10^{7}	5.44×10^{8}	2.77×10^{8}	1694.7	2.76×10^{8}	5.79×10^{8}
Management Objective 5: *P = N+ xP+ yP+ zR; x = 25% y = 0% z = 100%*	3.38×10^{7}	5.34×10^{8}	2.77×10^{8}	22312	2.76×10^{8}	5.68×10^{8}
Management Objective 6: *P = N+ xP+ yP+ zR; x = 0% y = 0% z = 0%*	3.4×10^{7}	5.45×10^{8}	1.58×10^{8}	1669.9	1.58×10^{8}	5.79×10^{8}

Task 4:

Based on the results of the generic modeling of Task 3, we applied the potential conservation measures and alternative water supplies to a site specific numerical groundwater flow model. The model was constructed as the result of earlier studies (Wilson 2000, Kessler 2002) and modified to simulate conservation measures and alternative water supply impacts.

As part of the Tusayan Growth Environmental Impact Statement, a numerical flow model was built to project potential impacts to springs from 1989 to 1999, and potential future pumping of groundwater due to the proposed development (Montgomery and Associates 1999). A digital geologic framework model and a numerical groundwater flow model were constructed by Wilson (2000) and coupled with conceptual ecosystem and cultural information to characterize the impacts of groundwater withdrawals from this regional aquifer (Springer and Wilson 2000). Wilson (2000) delineated capture zones of the three major springs which discharge nearly 99 % of the water from the aquifer to determine which portions of the aquifer were influenced by which proposed wells. The conceptual ecosystem and cultural information were used to assess impacts of the changes in spring discharge on ecosystems and significant cultures.

Spring discharge from the three major springs is estimated to be 1,830 l/s from Havasu Springs, and 19 l/s each from Hermit Springs and Indian Garden Springs (Montgomery and Associates 1999). Total discharge from 17 minor springs is about 35 l/s (Kessler 2002). There are approximately another 60 springs with unmeasurable discharge (Kessler 2002). Thus, the total discharge out of the springs of the Redwall-Muav aquifer of the Coconino Plateau is about 1,900 l/s. About 97 % of the total discharge from the aquifer discharges to one spring complex, Havasu Springs.

While volumes of spring discharge from the aquifer are known with a relatively high degree of certainty, little else is. There are only about ten wells and a few other boreholes to describe the subsurface geology. There is only one specific capacity test (no constant-rate aquifer tests) from one well to measure aquifer properties. Although the rocks are marginally deformed tectonically and likely have significant dissolution enhancement, there are no subsurface measurements of this away from outcrops below the South Rim. There are no continuous records of water levels in wells to describe climatic and seasonal fluctuations. Because of the lack of data, Wilson (2000) built digital geologic framework models to help conceptualize and visualize the aquifer. These digital geologic framework models were updated and revised in this study and used to construct three-dimensional conceptual and numerical groundwater flow models (Kessler 2002).

Kessler (2002) constructed a model using the numerical code MODFLOW (Harbaugh and others 2000) to simulate the 3 major springs and 17 minor springs for steady-state, pre-pumping (pre-1989) conditions. Changes in discharge from the springs were assessed for transient pumping conditions from 1989 to 2002. Capture zones were delineated for all of the springs with the advective particle-tracking postprocessor for use with MODFLOW, MODPATH (Pollock 1994). Groundwater Vistas (Environmental Simulations Inc. 2003) was used as a pre- and post-processor for all modeling.

The spatial framework was imported from the digital geologic framework model (Kessler 2002). The groundwater model grid was created with 500 m square model grid cells so that each of the 20 springs below the South Rim of the Grand Canyon was simulated in individual model cells. The grid was rotated N60W so that the y-axis of the model grid coincided with the primary direction of groundwater flow, which is toward the northwest, and to the assumed principle direction of anisotropy of aquifer parameters along major fault and fracture zones. Because monoclines likely play an important role in the flow of groundwater before it infiltrates to the fracture- and conduit-flow dominated Redwall-Muav aquifer, the overlying Supai Group was simulated as a leaky, upper confining layer. The underlying Bright Angel Shale was assumed to be the lower confining layer for the model and was assumed to be a no-flow boundary. Therefore, the model had two layers, the Redwall-Muav aquifer and the Supai Group.

The model utilized specified-flow and head-dependent boundary conditions. Specified-flow boundaries of no flow were used to simulate the bottom of the model and the lateral hydrologic boundaries of the modeled region. These lateral no-flow boundaries were the Toroweap-Aubrey fault system to the west, the ill-defined groundwater divide with the adjoining Verde River groundwater basin to the south, the combination of the Mesa Butte Fault, East Kaibab Monocline, and the Grandview-Phantom Monocline to the east, and the escarpment of the South Rim to the north (Figure 1).

Recharge to the aquifer was also simulated with a specified-flow boundary condition. For the pre-development, steady-state model, the aquifer was assumed to be in a state of equilibrium, meaning that the amount of recharge to the aquifer was equal to the total amount of average discharge from springs in the Grand Canyon, 161,586 m^3/d. This represents about two percent of average annual precipitation, or about 8 mm per year. A zone of high recharge was applied around the fault zones, or zones of high hydraulic conductivity. This zone received 70 % of the recharge, while the rest of the recharge was distributed evenly over the remaining non-fractured areas of the model.

A final type of specified-flux boundary was to simulate pumping from wells. There were no pumping wells in the aquifer prior to 1989, so pumping stresses were only applied to the transient model. Pumping rates for the transient model were based on maximum well yields reported on the drillers well logs and do not represent actual rates at which the wells were pumped from 1989 to 2002 (Montgomery and Associates 1999).

Springs were simulated with a head-dependent boundary condition. Target flux values were determined from field measurements taken at the spring, or, in the case of inaccessibility to a spring or other logistical constraints, historical measurements of discharges (Montgomery and Associates 1999, Kessler 2002). Elevations of the springs were known with a fair degree of certainty, but the conductivity values of the springs were derived through the calibration process.

Property values were assigned based on measured values and literature values (Montgomery and Associates 1999; Wilson 2000). Four zones of hydraulic conductivity were applied to the two model layers. The zones represented the upper leaky Supai Group, matrix flow in the Redwall-Muav (lowest value), fracture flow in the Redwall-Muav (intermediate value), and major fault flow in the Redwall-Muav (highest value). The location of fault and fracture zones were modified from those of Montgomery and Associates (1999)(Figure 3). Porosity and storage zones mimic those of hydraulic conductivity.

The model was calibrated to measurements of water levels from nine wells and discharge measurements from the 20 springs. Water-level measurements only exist from the date the wells were drilled, and are at best only estimates of the steady-state condition of the aquifer. The residuals of hydraulic head at these wells were simulated to be within 5 to 10 % of the ratio of root mean squared error to total head change across the model (Anderson and Woessner 1992).

Because spring discharge measurements were more frequent in time and space than the water-level measurements in wells, they were assumed to be more accurate for calibration than water levels. The differences between simulated and observed spring discharges in the steady-state model were less than 5 % of the total observed spring discharge. There was no calibration of the transient simulation because of the lack of transient measurements of water levels in wells and transient measurements of spring discharge. Therefore, the transient simulation is only a predictive scenario. The changes in spring discharge for the large springs predicted by the transient model were similar to the changes predicted by the model created for the Tusayan Growth EIS (Montgomery and Associates 1999), but Kessler (2002) was the first study to predict changes in discharge for the small springs.

The transient simulation predicted decreases in discharges of 4 and 34 % from Hermit and Indian Garden Springs, respectively, and between 2 and 100 % decrease at nine of the smaller springs in the vicinity of Grand Canyon Village (Table 3). Havasu Springs discharge is predicted to decrease by 1.8 %, but accommodate nearly 80 % of the total volume of flow decrease (Table 3). Although accurate measurements of the quantities of decreased discharge predicted by the model have not been measured at all of the springs, there have been observed decreases in discharge at Cottonwood Spring which has been instrumented since 1994. Additional studies are being conducted to document decreases in flow at these smaller springs.

In general, the highest hydraulic heads are to the groundwater divides to the east, south and west and the lowest hydraulic heads are in the vicinity of the springs (Figure 4). Hydraulic head contours form "v" patterns which point up hydraulic gradient along the prominent fault and fracture zones. The capture zone analysis shows that most of the regional flow system is captured by the largest spring complex, Havasu Springs (Figure 5). All of the other springs have small capture zones with recharge areas located close to the South Rim. Because these springs have smaller capture zones, they are likely more influenced by short-term changes in climate and by local well pumping.

We collected discharge data for the Grand Canyon waste water treatment plant (WWTP) and the Tusayan WWTP. The Grand Canyon WWTP has been in operation during entire transient period of the model (1989-2002). Treated effluent from the WWTP discharges directly into an ephemeral stream channel located in the Bright Angel Fault zone. Average total annual discharge is approximately 190 ac-ft/yr. The Bright Angel Fault connects to Indian Gardens Springs at the South Rim.

The Tusayan WWTP has been in operation since 1992 (3 years into the transient simulation). Treated effluent from the WWTP is discharged into an ephemeral stream channel in the Vishnu Fault zone. Since 1992, total annual discharge has been approximately 70 ac-ft/yr.

We simulated additional recharge to the Grand Canyon regional flow model from the treated effluent from both the Grand Canyon WWTP and the Tusayan WWTP. We assumed that the total annual amount of effluent was available to recharge the aquifers along the two fault zones (Bright Angel and Vishnu).

The results of this modeling are preliminary and need more study after this project. Preliminary results indicate diminished decreases in discharge at Indian Gardens due to recharge from the Grand Canyon WWTP during the pumping scenario. Recharge from the Tusayan WWTP into the Bright Angel Fault zone indicates a delay in the diminishment of discharge of springs connected to this structure due to the recharge from treated waste water.

C. Principal Findings and Significances

Aquifer Storage

An examination of the generic numerical modeling results shows that the management scenario #6 caused significantly less water to come out of aquifer storage than any other management scenario. This is a result of the low limit on pumping set by the Safe Yield Policy (with no artificial recharge, pumping must balance natural recharge). Management scenario pulls slightly less water from storage than other scenarios; using WWTP discharge along with 100% of the rainwater harvest as recharge supplies pumping centers with enough water to reduce the volume pulled from storage.

Groundwater Divides

Management scenarios #1 and #5 pull less water from the constant head boundaries than scenarios #2, #3, #4, and #6. This suggests that discharging large quantities of water in a small area (directly from a WWTP, for example) can minimize the amount of water that is captured from adjacent watersheds. Spreading WWTP discharge over a larger area may lead to more significant shifts in the location of groundwater divides, as the reduced local recharge may not be large enough to counter the effects of pumping.

Pumping Rates

Management scenarios #4 and #5 allow for the largest volume of water to be pumped from the aquifer under Safe Yield conditions. Both of these scenarios utilized 100% of the rainwater harvest and 25% of WWTP effluent as recharge. There is no quantitative difference in the water budget between discharging WWTP effluent directly to the environment or distributing it over an irrigated area. Reducing the amount of rainwater harvest used significantly reduced the volume of artificial recharge. There was no significant difference between using 0% and 10% of the rainwater harvest as irrigation. Scenario #6 allows for the smallest volume of water to be pumped. It is easy to see why scenario #6 has the lowest limit for pumping; no rain or WWTP discharge recharges the aquifer, reducing allowable volume for pumping under the Safe Yield policy.

Spring Discharge

Management scenarios #1 and #5 result in lower spring discharges than scenarios #2, #3, #4 and #6. This suggests that discharging WWTP effluent directly to the environment can reduce spring flow when compared to distributing WWTP effluent across the study area as irrigation. This is because management scenarios which increase the amount of recharge may allow for greater amounts of pumping to achieve Safe Yield.

Management Considerations

If a water management scheme is optimized to provide maximum pumping rates, using waste-water treatment plant effluent as irrigation is the best scenario; the more effluent used to recharge the aquifer, the more groundwater can be pumped out again. However, discharging effluent directly to the environment causes more dramatic shifts in regional groundwater flow patterns than distributing effluent across a larger irrigated area. These shifts become more complex in management scenarios that demand seasonal variation in discharge volumes.

If a water management scheme is optimized to provide for the lowest reduction in spring flow while operating in a Safe Yield mode, using both WWTP effluent and rainwater harvest is the best scenario. Varying the percentage of rainwater harvest used as irrigation caused only a slight change in spring flow; the volume of wastewater treatment plant effluent dominated the model.

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Integrating Research and Education to Assist Watershed Initiatives: A Survey of Three Arizona Watershed Organizations

Basic Information

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A. Problem And Research Objectives

Arizona watershed organizations hold great promise for improved water management statewide, but rural communities, the Arizona Department of Water Resources, and Arizona state legislators have identified a need to evaluate the effectiveness of watershed organizations in terms of their capacity to achieve their goals. The Arizona Rural Watershed Initiative was specifically created with a view to supporting local management of water resources, but no tool existed to evaluate the efforts of the various watershed organizations under its umbrella. In addition, Arizona watershed organizations have faced increasing pressures to find water management solutions in a timely manner because of drought[1] and Growing Smarter requirements. Recently state watershed organizations have been looking at each other, especially ones like the Upper San Pedro Partnership, for lessons or models on how to increase their capacity to address water management issues more effectively.

With these needs in mind, our research questions in a general sense are "How do watershed organizations move from being a collection of interests to cooperating on collaborative resource management?" and "How do these organizations find a balance among competing interests and move to the point where they can agree among themselves on: (1) what their mission is, (2) what strategies they use, (3) how they obtain community support, and (4) how they obtain political and economic support for implementing their plans?" One of the characteristics that distinguishes collaborative watershed groups from government agencies is the voluntary network of horizontal actors rather than the hierarchical or vertical arrangement with formal control mechanisms characteristic of government agencies (Imperial and Kauneckis 2004:1012-1013). In terms of decision-making, collaboration is thus a process of social construction where organizations and agencies pool their expertise and resources (Altheide 1988; McGuire 1988). It is the development of the collaborative process that we are examining in the three Arizona watersheds: the Upper San Pedro, Verde, and Santa Cruz River Basins.

The research objective of "Integrating Research and Education to Assist Watershed Initiatives" was to create a pilot survey instrument to assess watershed organizations in Arizona and to test that instrument in the three watersheds. Our intent was that the findings of this survey would benefit not only the watershed organizations themselves in terms of identifying strengths and weaknesses, but also in pinpointing strategies in organizational structure and problem-solving processes that Arizona watershed organizations generally could benefit from.

B. Methodology

1. Watershed Organization Survey

In preparation for constructing the survey instrument, materials on the three Arizona watersheds, specifically agency documents (particularly those of ADWR on watershed initiatives), documents from the organizations themselves, the results of previous watershed surveys from the three basins, and the general literature on watershed organizations were reviewed by the research team. In addition, University of Arizona cooperative extension agents from the three watersheds (Susan Pater in Cochise County,

[1] See Johnson and Murphy, "Drought Settles In, Lake Shrinks and West's Worries Grow.

Jeff Schlau in Yavapai County, and Dean Fish in Santa Cruz County) shared experiences working with their respective watershed organizations on watershed and natural resource issues and provided contacts with watershed organization participants and other watershed stakeholders. The team also reviewed previous fieldwork notes regarding watershed organization meetings and discussions with watershed stakeholders in each of these basins.

Based on this document review, the survey instrument was designed in collaboration with the PIs and the extension agents in each county where the watershed organization was located. During the process of its development, select stakeholders from each basin examined and offered comments on drafts of the survey instrument. The survey was revised and a prototype watershed organization assessment subsequently created.

Members of each of the Arizona watershed organizations were individually surveyed by phone or in person to determine: 1) the nature of basin water issues; 2) management goals and priorities; 3) organizational structure; 4) stakeholder identification and positions; 5) the method of selecting and interpreting scientific and technical information; 6) the nature of stakeholder collaboration within the watershed; 7) the processes of planning and decision-making; 8) the method of leader or facilitator selection, including the qualities of effective leadership; and 9) the method of establishing authority within the regional community. Meeting (audience) participants were also interviewed in order to obtain non-member evaluations of the organizations. This was necessary in order to avoid the bias towards success that has been associated with only interviewing coordinators. Surveying both participants and knowledgeable non-participant observers produces complementary information about group success and function (Leach 2002: 647).

2. Characteristics of Population Sample

While we initially intended to survey only one organization for each watershed, we found that no one group stood out above the others in terms of its capacity to address the issues specific to that watershed in the cases of the Verde and the Santa Cruz Basins. This left us with the possibility of increasing non-member evaluations or surveying the other organizations within the watershed. Since there were fewer organizations in the Santa Cruz, we decided to survey those groups. With the Verde, the number of organizations has been growing almost monthly, so conducting enough surveys under those conditions was not feasible given the time and costs. Instead, we sought evaluations from a larger number of non-members who regularly attended meetings and were familiar with the Yavapai County Water Advisory Commission (WAC). In each of the three basins we surveyed at least 30 watershed organization participants, including members and non-members, with 30 for the Partnership, 36 for the Verde WAC and 31 total for the Santa Cruz groups (15 for FOSCR, 11 for the SCAMA GUAC, and 5 for the Settlement Group[2]).

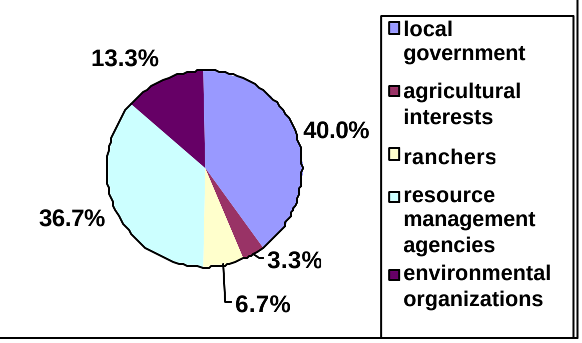
San Pedro Basin Participants

Within the surveys from the Upper San Pedro Partnership, 40 percent represented local government, 3.3 percent agricultural interests, 6.7 percent ranchers, 36.7 percent resource

[2] One person was a member of both the GUAC and FOSCR, thus making a total of 30 persons interviewed.

management agencies, and 13.3 percent environmental organizations (see Figure 1). Of those surveyed, 36.7 percent were local (basin) residents. Five respondents (16.6%) were not current USPP members. In regards to length of time participating in the watershed group's activities, 96.7 percent of those surveyed had been participating in Partnership activities since the beginning of the group in 1991.

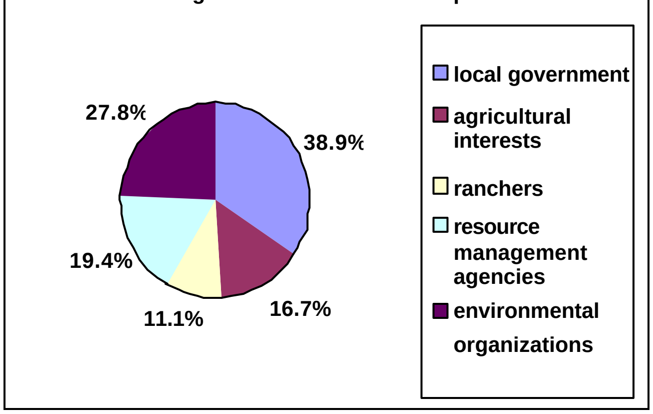
Figure 1. Upper San Pedro Partnership Participants.



Verde Basin Participants

Within the Verde WAC, 38.9 percent represented local government, 16.7 percent agricultural interests, 11.1 percent ranchers, 19.4 percent resource management agencies, and 27.8 percent considered themselves representative of environmental interests (see Figure 2). Of those surveyed, 66.7 percent were local residents. For participating in WAC activities, 59.5 percent of those surveyed had been involved for three years or more, with 25 percent for 5 years. Six respondents (16.6%) were non-members.

Figure 2. Verde WAC Participants.



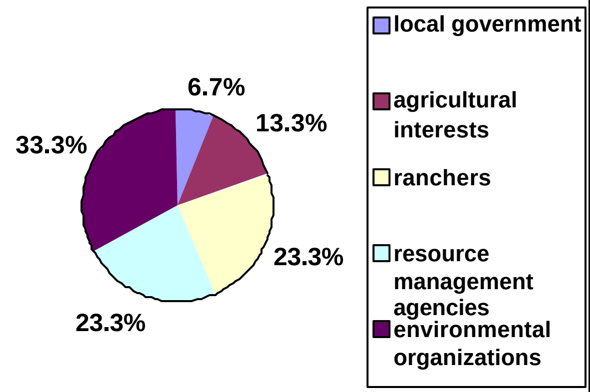
Santa Cruz Basin Participants

The study's thirty-one respondents from the Santa Cruz basin (see Figure 3) were recruited from the meetings of two watershed groups (Santa Cruz Active Management Area Groundwater Advisory Committee (SCAMA/GUAC), the Santa Cruz Settlement Group, the Friends of the Santa Cruz River (FOSCR), and the Santa Cruz River Alliance

(Alliance). Fourteen percent of all respondents from this basin described themselves as members of more than one local group. In addition to this latent permeability of group boundaries, there exists an interest among an apparently significant number of local group members in establishing more formal unions between groups. Given these circumstances—and for the purpose of making inter-basin comparisons—the authors have opted to treat all surveys received from respondents affiliated with one or more of these four Santa Cruz basin groups as originating from a single Santa Cruz 'coalition' of groups.

Within the Santa Cruz groups, 6.7 percent represented local government, 13.3 percent agricultural interests, 23.3 percent ranchers, 23.3 resource management agencies, and 33.3 percent environmental interests. Sixty percent of the Santa Cruz groups were local residents. In all cases respondents could select more than one category indicating their interests. The majority of the Santa Cruz group participants had been involved in their group's activities for 5 years or more.

Figure. 3 Santa Cruz Basin Participants.



3. Quantitative Data Analysis

Respondent affiliations and characteristics[3] and the responses to the first section of survey questions[4] (see Appendix A) were entered into a quantitative database (SPSS) and assessed using descriptive statistics and bivariate correlations.[5,6,7] Due to the fact that

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[3] Including committee membership, leadership, years of involvement, and representation within a certain watershed group.

[4] These first 31 questions regarded group members' perceptions of a range of issues. Each required the respondent to respond with a number between one (highest/most frequent) and five (lowest/least frequent).

[5] Unless stated explicitly, the reader can assume all correlations to be positive and significant (with p </= 0.05).

[6] Bivariate correlations were calculated using Spearman's rho (for nonparametric distributions) for all possible question-pairs, by basin. All elements were utilized excluding those containing pairs with one or more missing values. Significance was defined as p </= 0.05 in a two-tailed test.

[7] Our decision to not employ inferential statistics was based on a conservative assessment of the potential impact on the validity of results of such procedures in relation to the particular character of our dataset. In particular, the combination of factors—such as sample sizes, variation in response rates, the character of the sampling procedures employed, dependence on ordinal data, and concerns regarding the independence of respondents—required that we responsibly exercise caution.

respondent affiliations and characteristics tended—with the exceptions of "years involved"[8]—to be categorical variables, these were described in terms of their frequency of occurrence among respondents from a given basin. The first battery of survey questions dealt with perceptions regarding watershed group efficacy and character and respondents were asked to express their perceptions as a numeric value associated with a five point Likert scale. Data from these questions were ordinal and could be summarized in terms of frequency of response and frequency-based expressions of central tendency (i.e. median and mode.)[9]

The goal of this analysis was to identify which questions elicited similar patterns of intra-respondent response—i.e. whether, among completed surveys from a particular basin, fluctuations in scores for one question tended to mimic those of another (either by direct or inverse correspondence). By creating a matrix of correlations between all possible combinations of questions, we can map out webs of association between respondent perceptions regarding a variety of issues and, ultimately, better understand the complex significances of these issues for watershed groups and coalitions within and between basins. Such "webs of association" provide guidance in developing hypotheses regarding the nature of the potential relationships between the associated variables that can be evaluated through the employment of more powerful statistical tests and ethnographic methods in larger studies.

4. Qualitative Data Analysis

The final section of the survey includes five open-ended questions dealing with factors for successful leadership, most important projects undertaken, conflicts and conflict management, constraints of water policy in Arizona and suggestions to improve state water policy. The Santa Cruz survey also included an additional question on suggestions for improving cross-border collaboration with Mexico in managing the Santa Cruz River resources. For each question participants had the opportunity to provide multiple responses. In order to evaluate these lists, we looked for key words suggesting thematic categories and concepts and then constructed a coding scheme for them in what Bernard good naturedly calls "the interocular percussion test" where patterns strike the researcher as s(he) reviews the data (Bernard 1995: 201). The results of this qualitative analysis will be presented for each basin.

C. Principal Findings and Results

1. Upper San Pedro Partnership

Organizational Structure

Partnership participants were asked a series of questions about stakeholder representation, participation in discussion and qualities for leadership selection as a

[8] Because this category was subjected to various interpretations by respondents (it was intended to refer to years of involvement with a particular watershed group but was often interpreted as years of involvement in local watershed issues, etc.), its utility as a characteristic of respondents is compromised.

[9] Due to the potential for non-equivalence between intervals on a Likert scale, the operations most valid when analyzing ordinal data are non-computational comparisons, such as <. >, or =.

means of assessing the effectiveness of the group's organizational structure. Partnership respondents evaluated stakeholder representation as average, with the numbers distributed fairly equally on the scale. Stakeholder investment of time, money, or energy (measured individually) was above average. Regarding the leadership selection process, participants were very satisfied with the process and with leadership capacity to mediate conflicts. In addition, members cited stakeholder participation and dedication as the most important factor for successful leadership of the watershed organization. One participant expressed the opinion that success requires "open-minded members willing to risk serious debate on the possible range of issues and methods to mitigate over-consumption." Other salient factors identified were 1) balanced stakeholder representation of all interested parties and 2) collaboration with other resources agencies, the Nature Conservancy, local elected officials, and key political subdivisions. For leadership qualities, knowledge and understanding of scientific and technical issues in the basin and the ability to communicate those to USPP members and to the public were mentioned by one-third of all members. Other important leadership qualities listed by participants are listed in Table 1 below. [10]

Table 1: Most Important Leadership Factors Identified by USPP Members

Leadership Factor	Percent of Respondents
Stakeholder participation and dedication	40%
Balanced stakeholder representation and collaboration	33.3%
Knowledge and understanding of basin issues, including scientific and technical background, and ability to communicate this to a diverse audience	33.3%
Respect, honesty, credibility	20%
Objectivity, fairness and openness to different viewpoints	16.6%
Obtaining funding for project implementation	16.6%
Skills in communication and working with people	13.3%

Decision-making Process

In evaluating the Partnership's decision-making process, respondents rated the group's accomplishment of its mission and its capacity to identify water problems both as relatively high. Likewise, the Partnership's success in addressing basin water problems was rated as high. Participants thought trust among members was also high, as were the strategies to manage conflicts over natural resources. In evaluating the group's use of scientific research to understand basin water issues, members rated the Partnership very high. Partnership participants rated researchers' explanations of their basin work very highly. Understanding scientific research was rated as most important by participants. Actual use of scientific research for management decisions was rated at very high most high.

Project Planning and Implementation

In evaluating the project planning and implementation processes, respondents rated the Partnership's identification of costs and benefits of each project as very high, while they

[10] The percentages at the right represent the percent of total respondents in each basin that gave an answer within the specified category.

cited the Partnership's efforts at identifying project outcomes as average. Furthermore, participants rated the Partnership's decision-making process as average. However, participants rated the Partnership's capacity to implement its projects as very high. On-the-ground activities are considered most important, and actual follow-though on Partnership projects was evaluated very high. Participants evaluated the group's use of monitoring and evaluation results to change project strategies (feedback or adaptive management) as average.

Most Important Projects

Basin resource projects were listed by 53.2 percent of Partnership participants: wastewater effluent recharge projects (in Bisbee and Huachuca City), efforts to work with Mexico, detention basins, purchase of land conservation easements and adoption of the Sierra Vista Water Management Strategy as integral to USPP support of the Biological Opinion goals established by the US Fish and Wildlife Service. Related to the implementation of these projects, members mentioned the importance of process development, organizational structure, water budget development, strategic planning, and obtaining multilevel funding to carry out projects within the basin. Educational outreach, such as Water Wise programs in Fort Huachuca and surrounding communities, public input, and public awareness of the importance of conserving the San Pedro River were also mentioned by 10 percent of respondents (see Table 2).

Table 2: Most Important Projects Undertaken by the USPP

Scientific studies to assess resources	90%
Resource projects (e.g., basin recharge, effluent recharge, wastewater, conservation)	53.2%
Educational and outreach programs for public	10%

Conflict and Collaboration

In terms of conflicts in the San Pedro basin, the most frequent answer given by 43.3% of respondents was the conflicted nature of USPP's role in protecting the river and managing human consumption of water resources. Other conflicts identified by individuals in the study were lack of local control over water, lack of information and misconceptions about what is covered under the Endangered Species Act, USPP process, and regulatory requirements.

At the same time, since collaboration is frequently seen as a means of increasing the political and economic strength of resource organizations, we considered Partnership participants' rating of collaboration and how often they experienced it. Participants considered it very important to most important. However, they evaluated their actual collaboration with other groups as average. This may be because the group already considers itself a collaborative resource management organization, with representatives from every agency level, as well as from the commercial sector and elected representatives. Participants regard those actual efforts at collaboration as average.

Economic, political and institutional (including legislative) forms of support are recognized as essential for the survival of watershed organizations. Partnership respondents considered economic and political support for their objectives as very high. USPP perspectives about the degree of support from federal, state, or local laws for their objectives were average. However, participants considered existing laws as detrimental or even very detrimental.

Constraints: Arizona Water Policy

The most commonly mentioned constraints (see Table 3) in Arizona's water policy centered on inadequate water laws (66.6%) and the challenges of growth (43.3%). In terms of water laws, four main problems emerged: inability to price water based on consumption, lack of well monitoring, lack of local control of water management and the legal separation of ground and surface water (percentages noted below).

Table 3: Constraints in Arizona Water Policy Identified by USPP Members

Growth and development	43.3%
Inability to price water based on consumption	23.3%
Lack of monitoring unincorporated domestic wells or pumping	20%
Lack of local control of water management	13.3%
Legal separation of ground and surface water	10%

Concerning development issues, nearly one-third (30%) of respondents listed wildcat subdivisions as a major obstacle for water policy. Other specific problems included the "inability to restrict new agricultural use where an insufficient water supply exists or where public interest dictates restriction is necessary," the failure to tie development to water availability and a watershed plan, dense zoning, lack of requirement for developers to produce water demand analyses, and a general "unwillingness to face frankly the necessity to control and limit population, economic development and water consumption" on the part of decisionmakers and community members.

Suggestions for improving Arizona water policy (see Table 4) mainly concerned increasing public outreach and involvement, legislative changes to empower county and local government, regulation of development and requiring water demand analysis by law, and setting scaled water prices based on consumption so that high end users would be charged substantially higher prices. Public education was viewed as a means to improve water policy by inciting citizens to push for legislative change and to elect representatives who are more responsive to water issues.

Table 4: Suggested Improvements to Arizona Water Policy by USPP Members

Increase public education and community involvement	20%
Change laws to empower counties and local authorities	16.6%
Regulate development/growth	13.3%
Set water prices based on consumption	10%

2. Yavapai County Water Advisory Committee (Verde WAC)

Organizational Structure

Verde WAC participants evaluated stakeholder representation as average and stakeholder participation in meeting discussions high. Regarding the amount of time, money or energy spent in participating in WAC activities, participants considered that they contributed very frequently. They assessed the process of leadership selection and leadership management of conflicts as average. When asked to list the five most important factors for successful leadership, WAC participants offered a variety of leadership qualities, which are listed in Table 5 below.

Table 5: Most Important Leadership Qualities Identified by WAC Members

Leadership Factor	Percent of Respondents
Objectivity and fairness	40%
Balanced stakeholder representation and regional vs. local perspective	40%
Knowledge and understanding of basin issues, including scientific/technical background, laws and politics	36.6%
Planning and problem-solving skills	33.3%
Public outreach and education of members	33.3%
Ability to build trust, consensus and compromise	26.6%
Respect and honesty	13.3%
Commitment and dedication	10%

Planning and problem-solving

Under planning and problem-solving skills, responses included the ability to define goals and objectives, long-range planning, innovative ideas and the ability to build consensus around them, decision-making based on fact, project implementation, and willingness to proactively work toward solutions to water issues. In evaluating the WAC's decision-making process, participants felt the WAC was very successful, but they also thought the WAC was experiencing average success with its mission. WAC participants felt their capacity to identify basin water problems was very high. Respondents ranked trust among members and strategies to manage resource conflict above average.

Seen from a process perspective, the WAC very frequently identified the costs and benefits of its projects and project outcomes. WAC participants rated the smoothness of the decision-making process as average and felt they had achieved above average success in building their capacity to implement projects. Participants considered on-the-ground projects very important. WAC participants rated themselves as average or above in following-through on projects. While participants considered the WAC's use of the results of monitoring and evaluation average, some considered the WAC had not reached that stage of their planning and decision-making yet. WAC participants evaluated their success in addressing watershed problems as average or above, but they considered their success in changing water policy or management as average.

Most Important Projects

According to WAC members, the most important projects undertaken have been related to scientific resource assessment in the basin (see Table 6 below). Nearly all participants (86.1%) who answered this question listed at least one science-related project. The most common response, mentioned by 43.3% of respondents, was the USGS aeromagnetic study of Big Chino basin. In addition to scientific studies, education and outreach programs and development of strategies for watershed management were frequently reported, as indicated below. Among strategies mentioned were the regional management plan, the water conservation plan, formation of subcommittees, and the ordinance that mandates the use of effluent for golf courses.

Table 6: Most Important Projects Undertaken by the Yavapai County WAC

Scientific studies to assess resources (e.g., USGS Big Chino Basin study, flow gauges, well monitoring and relationship between surface and groundwater).	86.1%
Educational and outreach programs for WAC members and public	36.6%
Develop watershed management strategies	26.6%
Build partnerships with other agencies (USGS) and groups in region	20%
Forming a collaborative group that brings stakeholders together	13.3%

Conflict and Collaboration

Regarding collaboration, the WAC's attempts to work with other watershed groups was rated average or above. While WAC participants regarded the importance of collaboration as most important, they saw their participation in other watershed groups' activities as average or above. A very high number of WAC participants considered the WAC's collaborations with other groups successful.

Perception of the degree of economic support by WAC members was very high, while political support was viewed as average or above. The group was much more negative in their view of the extent of support from federal, state or local laws; participants saw them as least helpful or unhelpful. This is probably consistent with their view of the detrimental effects of laws on the WAC's objectives and projects; participants regarded laws as very detrimental.

Conflicts experienced in the Verde basin centered on water and land rights, lack of funding, real estate development, political representation, and the WAC's role and authority vis-à-vis the county Board of Supervisors (see Table 7). Many respondents mentioned the conflicts occurring between the Verde Valley and Prescott, which was primarily defined as a "value conflict" in which each area has different opinions regarding pumping the Big Chino basin, land use for recreation and development and the issue of upstream vs. downstream water rights holders and users.

Table 7: Conflicts in Verde Basin

Regulatory requirements for water and land rights	23.3%
Value conflicts between Verde Valley and Prescott	16.6%
Conflict with BOS over the role of the WAC	13.3%
Lack of funding for water issues	6.6%
Unsustainable growth and development	6.6%

Constraints: Arizona Water Policy

Nearly all participants (83.3 percent) who answered the question concerning perceived constraints in current Arizona water policy identified problems with Arizona water laws (see Table 8). Besides legal and policy constraints, WAC members also cited the environmental threats posed by rapid development in the area, most notable the unrestricted “wildcat” developments in Prescott Valley. One member noted that liberal granting of assured water supply certificates to developers fails to take into account that there is not enough water to sustain this pace of growth. In terms of political representation, two members referred to recent political turnover in county representation in the state legislature (which has resulted in increased advocacy for development and growth) as a major constraint as well as the failure of interest groups to come together for the common good.

Table 8 : Constraints in Arizona Water Policy Identified by WAC Members

Inadequate water laws in Arizona	83.3%
Development and growth	33.3%
Lack of public awareness of state water problems	20%
Unequal political representation	13.3%

Respondents from the WAC offered a variety of suggestions (see Table 9 below) for improving Arizona’s water policy. Most (60%) concerned legislative or policy changes, such as regulated pumping, control of well monitoring, separation of land and water ownership, and laws requiring review of water resources in light of population growth and water pricing based on consumption. Public education was also viewed as an important means to improve the ethics of water use and consumption and to encourage conservation measures. Finally, respondents identified a need for research concerning the quality of water recharge, minimum stream flows, well data, and new ways to monitor water mining that are quicker and less expensive than drilling. This category was not addressed by members of the USPP.

Table 9 : Suggested Improvements to Arizona Water Policy by WAC Members

Legislative and policy changes	60%
Public education and behavioral change	36.6%
Research and monitoring	13.3%

3. Santa Cruz "Coalition"

Organizational Structure

Santa Cruz participants view stakeholder representation as average, but stakeholder participation in discussions was rated very high. Most considered their participation as average in terms of time, money and energy spent in the groups' activities. Participants also though the leadership selection process was very effective, and leadership's management of conflict very successful. Specific leadership qualities listed by participants emphasized scientific and technical knowledge, communication/management skills, and commitment to the environment with a long-term vision (see Table 10).

Table 10: Most Important Leadership Factors Identified by Santa Cruz Groups

Leadership Factor	Percent of Respondents
Knowledge and understanding of basin issues, including scientific and technical background	43.3%
Skills in communication and working well with people and ability to compromise	36.6 %
Commitment to environment and long-term vision	36.6 %
Objectivity and fairness	20%
Balanced stakeholder representation and collaborative alliances with other groups in area	20%
Confidence, courage, and conflict management skills	16.6%
Organizational skills	16.6%
Commitment of members	13.3%
Public outreach	10%

Decision-making Process

Looking at the decision-making process, Santa Cruz participants decided the group was very highly successful at accomplishing its mission. The group also rated their capacity to identify basin water problems as most high, but only average in its actual success in addressing water problems. Trust among members was evaluated at most high. In their use of strategies to manage conflicts, Santa Cruz participants rated the group's efforts very highly. Regarding the use of scientific research, the participants considered the group's efforts most highly successful and researchers most effective in explaining the results of their basin work. They likewise considered it extremely important that water stakeholders understand such research and very frequently such information was used to make management decisions.

Santa Cruz participants noted that costs and benefits of projects in the decision-making process were identified very frequently, but project outcomes identified with average frequency. They described project implementation as a very smooth part of the decision-making process, but their follow-up on projects as average. They rated their ability to build its capacity for project implementation as average or above. They rated on-the-ground activities as most important for the organization's success and their use of the results from monitoring and evaluation as very frequent. They also evaluated the organization's success in addressing basin water problems as average.

Most Important Projects

In discussing actual projects undertaken, the Santa Cruz participants decided the following were the most important:

Table 11 : Most Important Projects Undertaken by Groups in the Santa Cruz Basin

Scientific studies to assess resources (e.g., water quality and use monitoring, effluent monitoring, measurement of river flows, hydrological modeling).	73.3%
Educational programs for public	60%
Build partnerships with other agencies and groups in area	23.3%
River restoration projects	20%
Clarify land claims (e.g., creating an Inventory of Rights to assist settlement process and guidance on legal issues)	13.3%
Upgrade of effluent ownership under wastewater treatment plan	10%

Conflict and Collaboration

Santa Cruz participants regarded collaboration with other basin groups as most important and considered themselves working with them and attending their meetings on a very frequent basis. They also rated these collaborations as very successful, although some did not chose to evaluate these collaborations. Perceptions of economic support were evaluated as average and political support as very high. SCAMA participants viewed exiting local, state and federal laws as above average in helping advance their objectives and very frequently being detrimental to their objectives and projects.

In terms of conflicts identified in the Santa Cruz basin, the most common response was legal requirements for water and land rights (see Table 12). This includes the issue of assured water supply for real estate development, ownership of water from the international wastewater treatment plant in Mexico, the role of ADWR regarding individual vs. riparian water rights, and conflicts between surface and groundwater rights. Process problems refer to issues arising in the course of determining land and water rights; for example, inaccurate census information and water that is unaccounted for, buying and subdividing lots, and giving water rights to new users (developers) instead of converting existing rights.

Table 12 : Conflicts in Santa Cruz Basin

Legal requirements for water and land rights	63.3%
Process problems	36.6%
Development	16.6%
Effluent from Mexico	13.3%

Constraints: Arizona Water Policy

The most commonly reported problem with existing water laws is the inability of state law to recognize the hydrologic reality and interaction between surface and groundwater (cited by 26.6% of respondents). Respondents also mentioned constraints related to public perception of water issues in the state, such as a lack of long-term perspective and understanding of drought and conservation on the part of the public and of watershed groups. One person commented that "water policy has been captured by interests of growth and development instead of real science."

Table 13 : Constraints in Arizona Water Policy Identified by Santa Cruz Groups

Unclear, inadequate, or conflicting water laws	50%
Growth and development	13.3%

Suggested legislative and policy changes (see Table 14) were varied and included conjunctive water management, completion of water rights adjudication through the Settlement Group, renewable water banking, starting a fourth management plan and giving water management more authority to move water from one place to another. Another idea offered was to exchange money from the electricity plant in Mexico to pay for Mexican effluent. Increased conservation measures were also deemed important for policy changes.

Table 14: Suggested Improvements to Arizona Water Policy by Santa Cruz Groups

Legislative and policy changes	60%
Public Education and Outreach	20%

As mentioned above, members of the Santa Cruz watershed groups responded to an additional question about collaboration with Mexico. The most common response referred to the Mexican wastewater treatment plant and sales of effluent from the plant. One participant stated, "The main issue for the Santa Cruz basin is the problem with the wastewater treatment plant, especially who pays for a new plant. It is not economical for Mexico to recover treated effluent." Others mentioned the need for better communication with Mexican colleagues through joint meetings and projects, well monitoring and programs in Mexico to reduce river pollution and promote water conservation.

Table 15: Suggested Collaborations with Mexico by Santa Cruz Groups

Expansion of international water treatment plant and sales of effluent from the plant to benefit Mexico	23.3%
Better Communication with Mexico, (including hands-on projects, attending Mexican meetings, creating a binational water agreement, and working with school children).	20%
Well monitoring in Mexico	6.6%
Conservation programs and pollution reduction in Mexico	6.6%

Conclusions

Developing the Collaborative Process: Lessons Learned

The history of watershed organizations in this study indicates that collaboration is a process that requires gaining trust among members, agreeing on the nature of the problem(s), having the capacity to bring resources (technology, science, funding, political and economic support) to the table, and a basic knowledge about basin hydrology and water laws. Much of this process revolves around obtaining "collaborative know-how" or learning how to “cooperate and work with organizations that have different values, procedures and processes” (Imperial and Kauneckis 2004: 1049)

- Existing Arizona water law provides confusing guidelines in regards to the relationship between ground and surface water. This makes water resource management difficult because ground and surface water are not treated as a coherent hydrological system under the law.
- Balancing the water needs of industrial, residential, and municipal interests in even middle-sized communities such as Sierra Vista and Prescott is challenging enough, but adding ranching and agricultural interests (or upstream vs. downstream users) makes balancing a water budget on a basin scale a long term and complex process because of water data needs and the implications of scientific research.
- Growing Smarter/Plus and AMA legislation have provided strong incentives for watershed groups to learn how to construct water budgets, but they do not guarantee equitable distribution of water.
- As Glennon notes, prior appropriation transforms water from a shared common resource into property. Water use based on right rather than need and heavy dependence on groundwater have contributed to the state’s aridity and heightened the need to locate new sources of water (Glennon 2002: 16-17, 31).
- The degree to which watershed organizations are successful in addressing water basin problems depends largely on 1) the group’s capacity to identify water basin problems, 2) building its capacity to implement projects (through obtaining resources and knowledge), 3) investing stakeholder time, money and energy, 4) interpretation and use of scientific research findings to make water management decisions, 5) leadership’s successful management of conflict, and 6) access to economic and political support.
- Building trust among group members is essential in managing conflict, which in turn contributes to efficient implementation of projects. This trust-building usually starts with framing the issue or problem, which “limits the potential outcome and plays an important role in who has a legitimate case for membership in the collaboration” (Phillips et al, 2000: 6).
- Objectivity and fairness, along with a scientific background, communication skills, respect and honesty, are essential for effective leadership. However, one of the requirements of fairness is balanced stakeholder representation.
- Scientific studies to assess water resources are the most important project of watershed groups, although educational outreach programs and building partnerships with other agencies or groups are also very important.
- Growth management vs. managing human water consumption is the greatest source of conflict in watershed basins, although the legal and regulatory requirements for water and land rights promote conflict among stakeholders as well. These are both regarded as the biggest constraints on Arizona water policy.
- These latter constraints could best be remedied by changing Arizona water laws, including those laws regarding local control of resource management, and by increasing public education and outreach regarding basin hydrology and water use.

- If watershed groups are to become the new form of water management, then they must have access to the power to make decisions crucial to the collaboration, including the authority to implement projects and programs. Effecting changes in water resource management requires that collaborators have power in the water resource arena from the start (Phillips et al 2002:11).

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Agricultural Chemicals as a Major Non-Point Source of Arsenic: Microbial Transformation of Organic Arsenicals

Basic Information

Title:	Agricultural Chemicals as a Major Non-Point Source of Arsenic: Microbial Transformation of Organic Arsenicals
Project Number:	2002AZ9G
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End Date:	8/31/2005
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Congressional District:	AZ05
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Descriptors:	WQ, AG,NPP
Principal Investigators:	James Field, A. Jay Gandolfi, John R Garbarino, Reyes Sierra, Robert L Wershaw

Publication

Second Year Progress Report

During the last year research was conducted on two families of organoarsenical compounds. Firstly the anaerobic and aerobic biodegradation of methylated arsenical pesticides was examined. Secondly, the anaerobic biotransformation of nitrogen substituted phenylarsonates used as feed additives in poultry was studied. Furthermore toxicity experiments were conducted with the AMES test and mitochondrial toxicitry test as well as ecotoxicity testing with methanogenic activity assay. Cooperation has been established with Dr. C. L. Folt of Dartmouth College to initiate ecotoxicity testing with water fleas (*Daphinia*) as a multicellular eukaryotic target.

Biodegradation of Methylated Arsenicals.

<u>Anaerobic biodegradability</u>. Numerous experiments examined the biodegradability of monomethylarsenate (MMA(V)) and dimethylarsenate (DMA(V). Typical experiments for both of these compounds are shown in Figures 1 and 2 in which their biodegradability was examined under denitrifying, sulfate reducing and methanogenic conditions in anaerobic sludge. Both compounds were susceptible to anaerobic biodegradation under methanogenic and sulfate reducing conditions and both compounds were found not to be biodegradable under denitrifying conditions. MMA(V) degraded slower compared to DMA(V) and sulfate reducing conditions provided the most rapid degradation of MMA(V). The only major biotransformation product detected from DMA(V) degradation was MMA(V), a product resulting from demthylation of DMA(V). The only major biotransformation product observed from MMA(V) degradation was monomethylarsenite (MMA(III)), a product resulting from MMA(V) reduction. Numerous anaerobic biodegradation experiments of these compounds were conducted under a variety of conditions and concentrations. In all experiments, the results were similar to those reported in the figures. The average molar recovery of MMA(V) during the degradation of DMA(V) was 14.1% of DMA(V) degraded. The average molar recovery of MMA(III) during the degradation of MMA(V) was 18.0% of MMA(V) degraded. Several unidentified As-containing metabolites were observed during the anaerobic degradation of both DMA(V) and MMA(V).

<u>Aerobic biodegradability</u>. MMA(V) and DMA(V) biodegradation was also tested under aerobic conditions with agricultural soil from a cotton field in Arkansas. After, 4 months of incubation there is as of yet no evidence for their degradation in the presence of air.

Biodegradation of Nitrogen-Substituted Phenylarsenates.

The organoarsenical, roxarsone (Figure 3), has become an emerging water and soil arsenic pollutant issue in the United States. The compound is used extensively in poultry broiler feed to enhance growth, improve efficiency and control coccidial intestinal parasites. Since only a small fraction of roxarsone is retained in chicken meat, a large portion is excreted into chicken manure. Most manure is disposed via land application either directly or after composting. Based on broiler production and roxarsone feed dosage, approximately 900 metric tons of roxarsone is estimated to be released into environment in the U.S. annually, equivalent to 250 metric tons of arsenic. The environmental impact is significant when considering that these quantities of arsenic are spread onto relatively small land areas in the direct vicinity of poultry houses.

Relatively little is known about the biotransformation of roxarsone in the environment. Most of the roxarsone is excreted unchanged in the manure. Nitrophenols are known to undergo facile reduction to corresponding aminophenols in anaerobic environments. Thus the formation of the 4-hydroxy-3-aminophenylarsonic acid (HAPA, Figure 3) should be anticipated during poultry litter storage. HAPA has previously been detected in fresh poultry manure and litter, accounting for 13 to 18% of total arsenic species. Preliminary studies from this research project have demonstrated that under anaerobic conditions roxarsone is readily converted by anaerobic sludge to HAPA as shown in a typical experiment illustrated in Figure 4. The conversion occurs rapidly under methanogenic and sulfate reducing conditions and is accelerated by addition of electron-donating substrates such as lactate. Poor conversion occurred under denitrifying conditions. The conversion was shown to be biological, since sterile medium and heat killed sludge were ineffective. The results suggest that during anaerobic conditions, prevailing during poultry litter storage, HAPA formation from roxarsone can be expected.

After extended incubations of 120 days, HAPA that had previously accumulated was largely eliminated (by more than 90%). Only a partial recovery of products from the elimination of HAPA has been detected. The combined recovery of arsenate and arsenite accounted for about 20% of the arsenic added initially to the system as roxarsone. The results suggest anaerobic biodegradation of HAPA had occurred and this is consistent with the finding in parallel experiments that a closely related compound, *p* arsanilic acid (Figure 3), is also biodegraded under methanogenic and sulfate reducing conditions.

Toxicity of Biotransformation Products

Initially toxicity testing was based on using the AMES test and mitochondrial toxicity testing (MTT). Parent compounds and incubates from the biodegradation of DMA(V) and MMA(V) were found to be non-toxic in both the AMES and MTT. Incubates from the biotransformation of roxarsone gave weak toxic responses in the AMES test. In project meetings, a large number of questions regarding AMES and MTT testing were raised. On the one hand, incubates need to be diluted, and on the other hand the tests have very specific targets. In order to address these concerns, we decided to use ecotoxicity testing. Toxicity to methanogens was evaluated by incubating arsenicals with anaerobic sludge and monitoring impacts on the methane production rate. Table 1 summarizes the results. Pentavalent compounds, such as As(V), MMA(V) and DMA(V) were basically non-toxic. Trivalent compounds, As(III) and MMA(III) were very toxic.

Roxarsone displayed toxicity which was not as severe as As(III). HAPA, the biotransfomatiom product of roxarsone, was non-toxic. However, HAPA was only non-toxic if autoxidation was prevented by preparing stock solutions with 200 mg/l ascorbic acid. Allowing HAPA to become autoxidized resulted in toxicity, indicating that autoxidations products were toxic. Roxarsone and HAPA were also tested for their toxicity to *Daphinia* and preliminary tests indicate they display toxicity in the 10-15 mg/l range. The results taken as a whole suggest that certain products from organarsenical biotransformation can be toxic. MMA(III) a biotransformation product of MMA(V) displayed high toxicity. As(III) a biotransformation product from the long term incubation of roxarsone with anaerobic sludge was also toxic. HAPA a biotransformation product of roxarsone was itself non-toxic; however the compound upon exposure to air generates toxic autoxidation products, which may have been responsible for the toxiciy in the *Daphinia* test as well as weak response in the AMES test.

TABLE 1. Concentrations of arsenical compounds causing a 20, 50 and 80% inhibition of the methanogenic activity of anaerobic sludge with acetate as substrate

Compound	**Molecular Weight**	**20% IC (µM)**	**50%IC (µM)**	**80%IC (µM)**
Inorganic species				
As(III)	122.9	9.1	15.5	23.5
As(V)	138.9	>500	> 500	> 500
Methylated organoarsenic compounds				
MMA(V)	140.0	> 5,000	> 5,000	> 5,000
DMA(V)	138.0	> 5,000	> 5,000	> 5,000
MMA(III)	123.9	2.2	9.1	17.9
N-substituted Phenylarsonates				
Roxarsone	263.0	251	425	780
HAPA	233.1	> 600	> 600	> 600
p-arsanilic acid	217.1	> 2,300	> 2,300	> 2,300

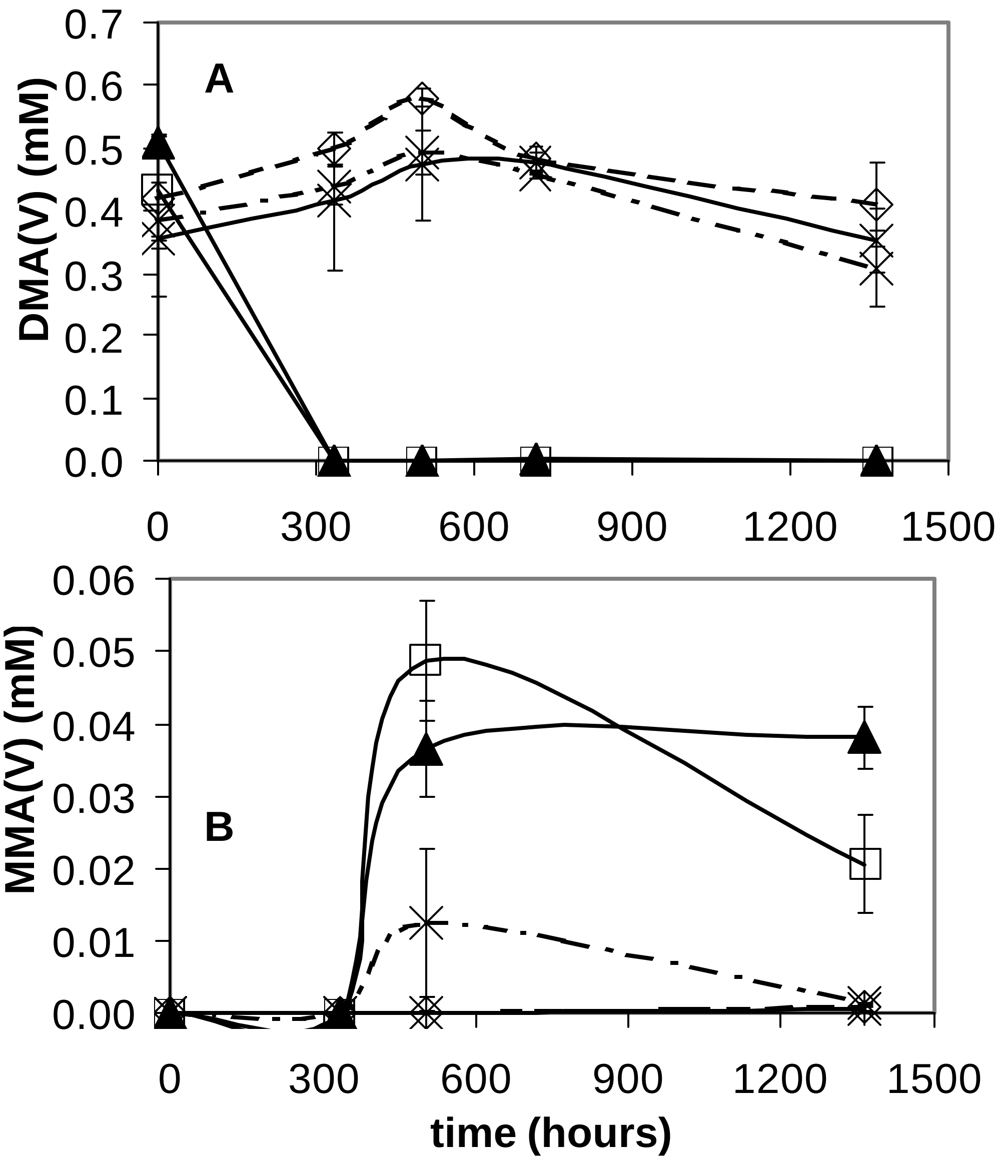

Figure 1. The reduction of DMA(V) (500 μM) catalyzed by a stable mixed anaerobic consortium (1.5 g volatile suspended solids l^{-1}) as inoculum under methanogenic (—? —), sulfate reducing (—ð—) and nitrate reducing (— —) conditions. A control culture with heat killed inoculum (---? ---) and an abiotic control (– -? –) were included for comparison. **(A)** DMA(V) concentrations. **(B)** Metabolite MMA(V) formation.

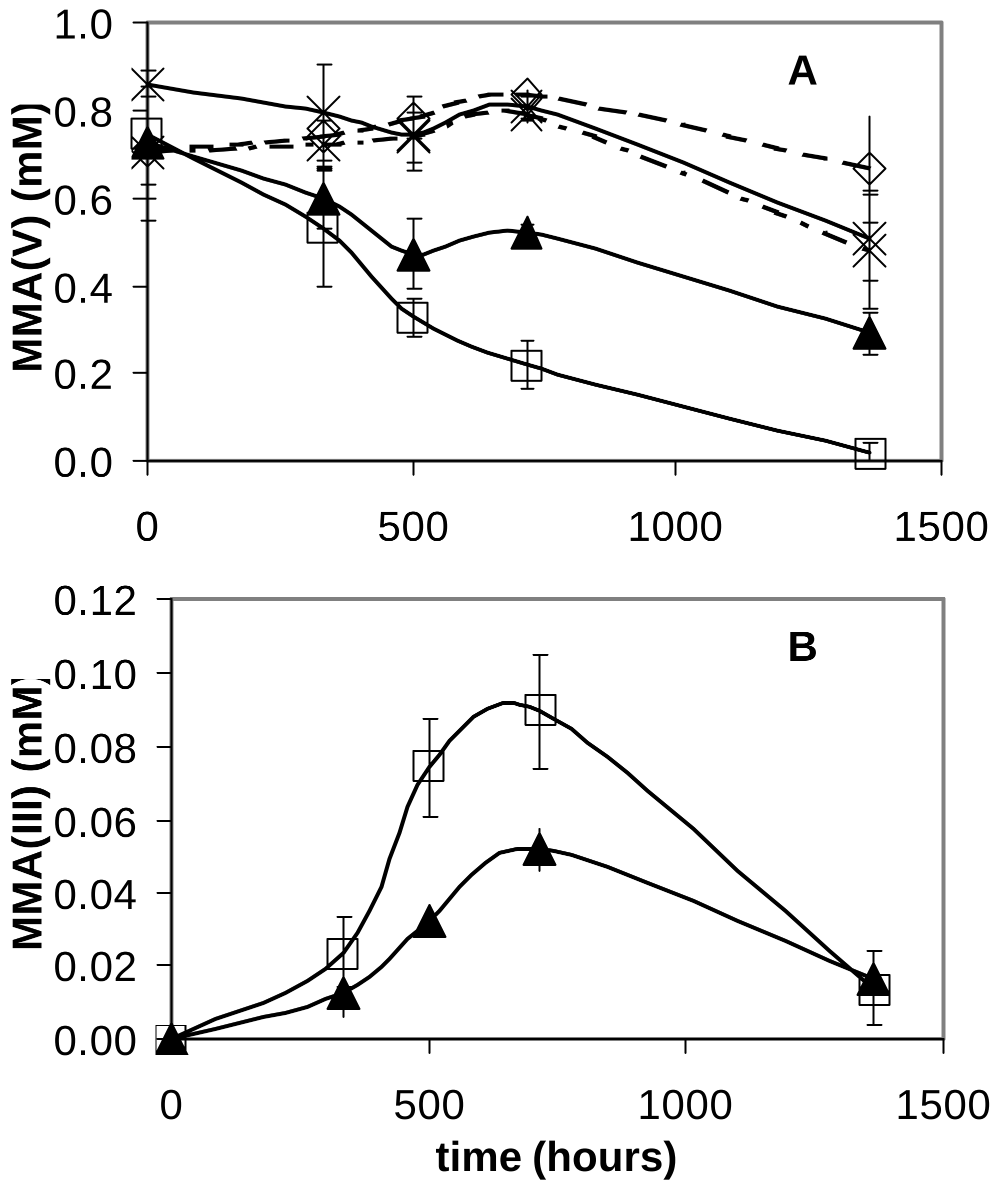

Figure 2. The reduction of MMA(V) (714 μM) catalyzed by a stable mixed anaerobic consortium (1.5 g volatile suspended solids l^{-1}) as inoculum under methanogenic (—? —), sulfate reducing (—ð—) and nitrate reducing (— —) conditions. A control culture with heat killed inoculum (---? ---) and an abiotic control (– -?- –) were included for comparison. **(A)** MMA(V) concentrations. **(B)** Metabolite MMA(III) formation.

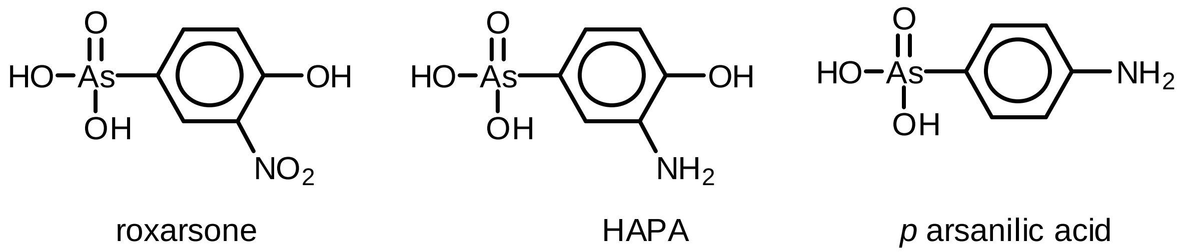

Figure 3. Structures of nitrogen substituted phenylarsonate compounds.

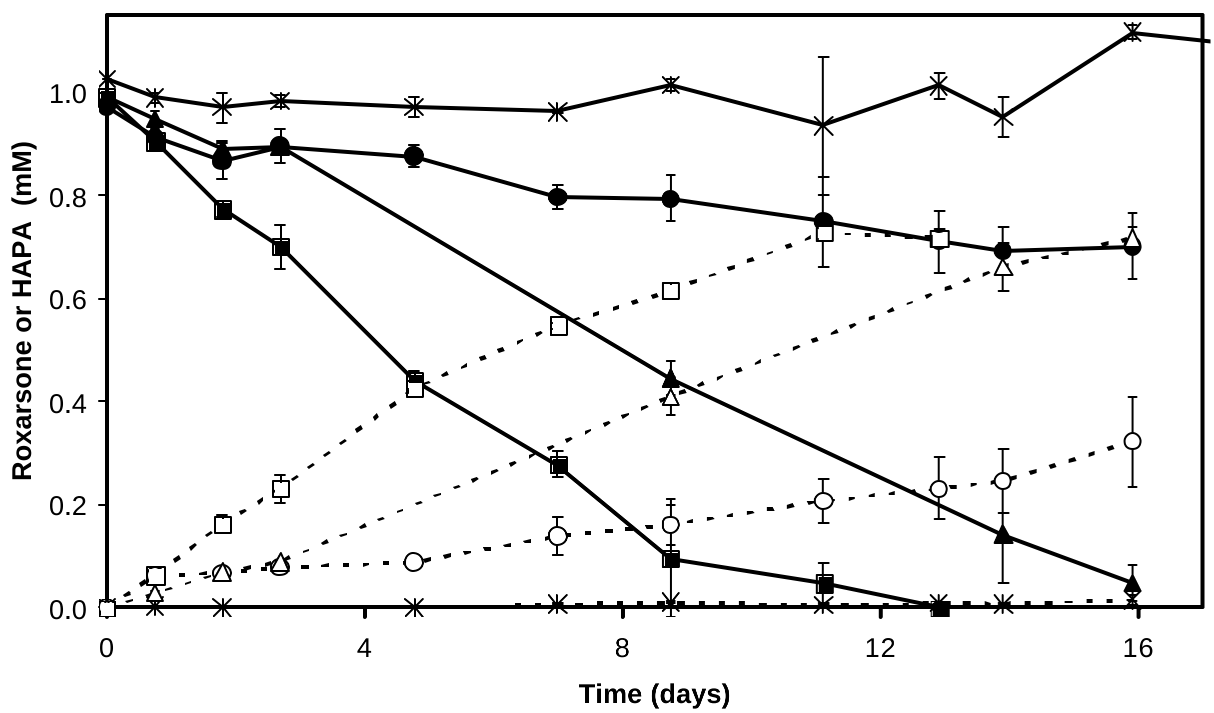

Figure 4. The conversion of roxarsone to HAPA in anaerobic sludge. Legend: *astericks*, abiotic medium; *circles*, killed sludge; *triangles*, methanogenic no added substrate; *squares*, methanogenic with 10 mM lactate. *Closed symbols with soild lines*, roxarsone concentration; *Open symbols with dashed lines*, HAPA concentrations

Develop Arid West Bioassay Capability for Modification of Water Quality Criteria & Effluent Testing

Basic Information

Title:	Develop Arid West Bioassay Capability for Modification of Water Quality Criteria & Effluent Testing
Project Number:	2003AZ23B
Start Date:	3/1/2003
End Date:	2/29/2004
Funding Source:	104B
Congressional District:	7
Research Category:	Biological Sciences
Focus Category:	Water Quality, Waste Water, Surface Water
Descriptors:	WQ, WW, SW
Principal Investigators:	Donald Baumgartner, Kevin Fitzsimmons, Stephen G Nelson

Publication

A. Problem and Research Objectives:

Most states and Indian Nations establish water quality standards for surface waters within their geographic area of responsibility using a national data base of aquatic organism toxicity data developed by the U. S. Environmental Protection Agency. The aquatic species employed in the EPA bioassays reflect taxa found in perennial streams of the non-arid regions of the nation. A few arid states have been able to justify modified standards by demonstrating that no fish, let alone fish used by EPA (frequently Salmonids), can live in certain arid streams, but other arid states have had to accept EPA numerical criteria for heavy metals, conventional pollutants (e.g., ammonia, chlorine), and toxic organic compounds irrespective of the absence of comparable fish habitat in ephemeral, effluent dependent watercourses of the arid West. Additionally, bioassay species used by EPA to regulate effluent discharges (Whole Effluent Toxicity Tests) are believed not representative of aquatic species found in arid West watercourses.

Conferees at a meeting to discuss research needs for arid West water quality criteria (PCWWM, 1997) concluded bioassay techniques incorporating exposure conditions representative of arid West waters, and use of representative species would improve risk assessment and efficient risk management of river and lake water quality. Without improvements, many municipal and wastewater dischargers may be expending funds to treat effluents to a degree higher than required by the Clean Water Act, or alternatively reusing treated effluents rather than maintaining aquatic and riparian habitats in an ephemeral watercourse. The EPA-funded Arid West Water Quality Research Project (WQRP) has for several years stated that a project of this type may be conducted, but so far the project has not materialized. In addition, the Water Environment Research Foundation (WERF), in collaboration with EPA, has funded a biotic ligand model (BLM) study plan to determine if a more general and fundamental method could more accurately account for metal toxicity than EPA presently uses based on calcium and magnesium concentrations. Unfortunately the BLM study does not include alternate species, nor does it investigate the effects of hardness over 400 mg/l, thus would not address a concern of arid West regulators and dischargers.

B. Methodology:

Develop and demonstrate maintenance of culture stock of several candidate arid West fish and invertebrate species. Demonstrate survival in mock (control) bioassay procedures, including in relation to standard EPA procedures. Some trial toxicity determinations with a standard toxicant (e.g., copper) will be attempted for two of the species that show promise. These data and demonstrations would then be used to propose longer term research on toxicants and typical arid West waters for grant support by EPA and/or several states.

The Gila chub, *Gila intermedia*, historically found in much of the Gila River watershed, is now restricted to 24 or fewer refugia streams or cienegas in Arizona and Mexico. A captive population of Gila chub is already established at the Environmental Research Lab of the University of Arizona. Approximately 60 fish were collected from Sabino Creek in early 1999 for use in a competitive chub-crayfish feeding trial.We propose to use these fish, which are nearing maturity as the broodstock population.

A population of flannelmouth sucker, *Catostomus latipinnis*, has also being cultured in fiberglass tanks at the Environmental Research Lab. This fish is found in larger, stronger flowing streams of the Colorado River. As with all other native big river fishes, the original range is considerably reduced. Since this population may require a year or longer to reach reproductive maturity, broodstock would be purchased to provide preliminary information in the interim.

Species of the Crustacean Division Eubranchiopoda are among the most characteristic aquatic organisms of temporary bodies of water, such as are common throughout the arid West. The Division consists of three orders: the Anostraca (fairy shrimp), the Notostraca (tadpole shrimp) and the Conchostraca (clam shrimp). Eubranchiopods live in fish-less habitats, and they all produce resting eggs that can withstand prolonged periods of dessication.

Of the three orders we chose to focus on clam shrimp for several reasons. The fairy shrimp, aside from those in the genus *Artemia* (brine shrimp) are difficult to maintain in culture. In contrast, the tadpole shrimp *Triops longicaudatus* can be cultured in the laboratory, and their eggs are commercially available. Techniques for the mass production of *Triops* have been worked out in conjunction with their usefulness in mosquito control, and this techniques could be easily adapted to the culture of this species for bioassays. The clam shrimp, however, fall in between. We have been able to culture them in the laboratory from eggs hatched from playa soils, but little information is available on their mass production; which is needed to develop protocols for routine use in bioassays. We suspect that the mass culture of clam shrimp will be feasible because they have been reported, in some cases, to be a pest in fish ponds.

We also have maintained a culture of *Moina macrocopa* , a species of cladoceran widely used for fish food because of the ease with which they are cultured, their high reproductive rate, and toleration for high density populations. It is a useful species for toxicity tests for these reasons, and because it demonstrates high susceptibility to toxic substances and in particular, metals. Structurally, *M. macrocopa* appear similar to *D. magna* and *D. pulex*. M. macrocopa is also a local species, which we believe will be responsive to metal concentrations and a range of hardness concentrations.

Trial demonstration toxicity tests with copper will be conducted following EPA harmonized guidelines: Ecological Effects Test Guidelines, OPPTS 850.1400, Fish Early-Life Stage Toxicity Test, and Ecological Effects Test Guidelines, OPPTS 850.1010, Aquatic Invertebrate Acute Toxicity Test, Freshwater Daphnids.

The guidelines for culturing the clam shrimp will be similar to the harmonized guidelines in use bioassays with freshwater daphnids. We propose to conduct a series of replicated laboratory experiments designed to determine optimal conditions for rearing clam shrimp with particular regard to: 1) feed (unicellular algae) concentration; 2) water hardness; and 3) temperature. The experiments will be conducted in 500-ml beakers of water each stocked initially with 10-20 adult clam shrimp.

C. Principal Findings and Significance:

Crustacean culture: We have been successful in establishing and maintaining cultures of an ostracode found in samples of soil from Mirror Lake, California. Previously these small crustaceans were identified as clam shrimp (conchostracans), but we recently found that they were actually seed shrimp (ostracoda). Cultures have been established in approximately 15-l containers of distilled water and Tucson municipal water with a 2-cm layer of playa soil. The cultures develop and prosper without supplemental feeding. We used ten replicates at three temperatures each in 150-ml flasks to assess the effect on development of the cultures. Temperatures were 23, 28, and 33 ^{o}C, maintained by water baths equipped with thermoregulators.. By the fourth day ostracode larvae began to emerge. By day ten 48 ostracodes had hatched and developed into adults. Of these, 9 were in the high-temperature group, 17 in the low-temperature group, and 22 were in the middle temperature groups. The counts were significantly different among groups (Chi-square value=22.5; p=0.0041). We found that the ostracode eggs can be easily obtained by isolating adults in glass containers. The orange eggs are negatively buoyant and can be collected from the bottom of the containers. This is a favorable response with respect to the warm watercourse temperatures of the arid West we must represent in the bioassays.

<u>Crustacean bioassays</u>: Early tests were conducted with few replicates (four or eight) to determine generally what concentrations of copper would produce mortality. As we narrowed in on the LC50, more replicates were used (up to 20). Final results indicate that our Ostracode species has a 24-hour copper LC50 of 0.11 mg/l, at a medium water hardness concentration of 75-80 mg/l as $CaCO_3$. Varying water hardness concentrations had little effect on survival, with preliminary tests showing essentially identical survival at hardness between 0 and 300 mg/l.

<u>Fish culture and bioassay</u>: We have successfully maintained cultures of several native species of fish (longfin dace, *Agosia chrysogaster*), (Gila chub, *Gila intermedia*) and the standard EPA test species (fathead minnow *Pimephales promelas*), and conducted bioassays with a range of copper solutions in moderately hard water. Based on the 96 hour median survival response (LC_{50}) it appears the native species may be more sensitive to copper than the EPA standard. This result, if substantiated with more rigorous bioassays, and a range of hardness concentrations, would be of direct interest to water quality regulatory agencies, as it would tend to justify the approach they have been following for years. It might also placate the wastewater dischargers who have been anticipating, if not asserting, that native species would be less sensitive.

The Gila chub were eventually induced to spawn in captivity at the Environmental Research Lab. A captive population can now be provided to researchers and regulators who may desire to utilize this fish as a native bioassay. The chub were spawned by adjusting temperatures and light levels to approximate spring-time conditions. A spawning tray was utilized that allowed the scattered eggs to fall into a plastic grid which kept the parents from cannibalizing the fertilized embryos. Artemia and prepared dry feeds were used to rear fry to the point where they could accept conventional prepared fish feed.

An additional population of Bonytail chubs have been introduced. The recirculating system to support these fish has been duplicated to also support Apache Trout, another Endangered Native species. The information developed from these systems is allowing us to consider these cooler water species for potential bioassay organisms in high elevation locations.

Information Transfer Program

Information Transfer

Basic Information

Title:	Information Transfer
Project Number:	2003AZ22B
Start Date:	3/1/2003
End Date:	2/31/2004
Funding Source:	104B
Congressional District:	5th
Research Category:	Not Applicable
Focus Category:	Education, Management and Planning, Water Supply
Descriptors:	EDU, WS, M & I, LIP
Principal Investigators:	Peter J. Wierenga, Kathy Jacobs, Jackie Moxley

Publication

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2. Gelt, Joe. 2003. Fire and Drought Aid Recovery of Native Species, Arizona Capitol Times, July-August.
3. Jacobs, Katharine. 2003. Planning Climate and Global Change Research: A Review of the Draft U.S. Climate Change Science Program Strategic Plan (Committee Report). National Research Council, National Academy Press.
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5. Jacobs, Katharine and Roger Pulwarty. 2003. Water Resource Management: Science, Planning and Decision-Making, in Water: Science, Policy and Management, Water Resources Monograph 16, American Geophysical Union, December.
6. Megdal, Sharon. 2004. Securing Sustainable Water Supplies in Arizona, Paper prepared for IDS0Water 2004 On-line Conference with approximately 10,000 registrants.
7. Megdal, Sharon. 2003. Fiscal 2000 Committee Report Was Accurate, Arizona Capitol Times, May 2.
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10. Sprouse, Terry W. 2003. Equitable Management of Mexican Effluent in Ambos Nogales, Journal of

the Southwest 45 (3).

11. Sprouse, Terry W. and Lisa Farrow Vaughn. 2003. Water Resource Management in Response to El Niño-Southern Oscillation (ENSO) Droughts and Floods: The Case of Ambos Nogales, Chapter 6 in Climate, Water, and Transboundary Challenges in the Americas, edited by Henry F. Diaz and Barbara J. Morehouse (The Netherlands: Kluwer Academic Publishers).

Information Transfer

Introduction

The University of Arizona's Water Resources Research Center continues its involvement in water policy research and analysis and in information transfer activities, such as publications, conferences, lectures, seminars, and other formats to inform and educate water professionals, elected and appointed officials, students and the public.

In October 2003, the Center welcomed the addition of Kathy Jacobs to its ranks as an associate specialist. Along with her WRRC position, Jacobs also serves as associate staff scientist at the UA Institute for the Study of Planet Earth. She left the Arizona Department of Water Resources after 21 years, having served for 14 years as the Tucson Active Management Area director.

Outreach and Education

The WRRC places great importance in utilizing its experience and expertise to be actively involved in statewide water issues. Water Center staff reaches out to the community through presentations and lectures, service on boards, committees and panels, written articles and research activities. Applied research serves as a foundation for outreach and education.

In particular, Associate Director, Sharon Megdal, and Kathy Jacobs have both made numerous presentations on topics related to water management, drought planning, climate and rural water resources issues to audiences ranging from undergraduate classes to keynote addresses at conferences. Megdal and Jacobs are both significantly involved in writing the background report for the upcoming Arizona Town Hall on water.

In 2003 Sharon Megdal made many presentations within Arizona. Groups addressed by Megdal included the Arizona Hydrological Society, Agribusiness groups and rural watershed organizations. She has given presentations as far away as Torreón, Coahila, Mexico, and Santiago, Chile. Megdal gave interviews to the radio and television media in Tucson and Phoenix, and writes a regular column for the WRRC *Arizona Water Resource* newsletter. Megdal also served on the Arizona Water Quality Appeals Board. Sharon Megdal has been named Director of the WRRC, effective July 1, 2004.

Kathy Jacobs is a lead staff person developing Arizona's first drought plan in cooperation with the Arizona Department of Water Resources and the Climate Assessment for the Southwest. Jacobs serves as chair of the Education and Outreach Committee of the University's Water Sustainability Program, linking four water centers and enhancing connections between University research activities and stakeholders. Jacobs has been involved in two National Academy panels over the past two years.

WRRC researcher, Terry Sprouse, received a Fulbright Grant to study bi-national effluent management in Nogales, Sonora and Nogales, Arizona. The study is titled "Developing options for equitable management of Mexican effluent in Ambos Nogales." The use of effluent is a strategy to increase the quantity of available water for both countries. Resolving the issue of Mexican effluent use has broad implications for long-term watershed management in that region.

The WRRC is also represented on the International Boundary and Water Commission's (IBWC) Southeast Arizona Citizen's Forum, Board of Directors. The Forum is a link between the border communities and the IBWC to promote public input on IBWC projects, and to inform the public of upcoming projects. Meetings by the IBWC are held in different border communities on a quarterly basis.

The Center's Brown Bag Luncheon Seminar Series provides a forum for university personnel and other experts from around the state. Of the six seminars presented in 2003-2004, the panel on the "San Pedro Partnership" was particularly well attended and received. This seminar addressed a multitude of front-page issues in Southeastern Arizona. These issues included surface water-groundwater interface, military base closure, sharing of transboundary water resources and "economic development vs. water conservation" issues.

The "Arizona Water Resource" newsletter is published six times per year. With a mail circulation of over 2,400 people, the 12-page newsletter focusing on Arizona state and regional water issues is distributed free of charge. A feature story, guest view, public policy column and other shorter features are included. Feature articles in the newsletter for the past year addressed prominent topical issues, such as "source tracking" of waterborne pathogens, desalinization of saline water, Navajo water rights, and perchlorate in Arizona groundwater, to mention a few. Editor, Joe Gelt, had two of his newsletter articles and three of his "Guest View" columns re-published in *the Arizona Capital Times*.

A valuable addition to the acclaimed "Arizona Water Resource" newsletter began in 2004 with the inclusion of supplements inserted in the newsletter. These supplements provide important information about the water research and programs of outside agencies. USGS provided the first outside agency supplement, entitled, "Effects of Natural and Human Factors on Stream Water Quality in Central Arizona." The supplement was published in the January-February 2004 issue of "Arizona Water Resource."

The WRRC web site provides access to the newsletter and to other WRRC papers. It is updated regularly to include presentations made by WRRC faculty, who are in great demand as speakers within Arizona, nationally and internationally. Annual reports from 104B funded research projects are posted on the web page. The web site includes links to many state and national water related web sites, including the NIWR homepage.

The WRRC hosted the 2004 Spring Semester sabbatical of Professor George Frisvold from the Department of Agricultural and Resource Economics at the University of Arizona. His research included examining the intricate aspects of measuring water use in agriculture. Dr. Frisvold also worked actively with the WRRC on preparations for the 2004 WRRC water conference.

The Water Conservation Alliance of Southern Arizona (CASA), an independent organization housed at the WRRC, is a consortium of small water utilities. Water CASA is developing a database to analyze existing conservation measures, study the actual amount of water saved from a given conservation measure, and perform a cost benefit analysis and cost effectiveness analysis on each measure. The research focuses on water conservation efforts within the Southwest, which faces water demand dilemmas brought on by drought, rapid urban growth, and water supply shortages in the region.

Second Year of TRIF Grant Proposals Received

Part of the recent growth of the WRRC was made possible through new funding from the University. In the November 2000 general election, voters passed Proposition 301, which provided an increase of 0.6% in sales taxes to support education. Ten percent of the new sales tax money was allocated to the three State Universities in Arizona. The president of the University of Arizona selected seven areas on campus to receive TRIF funds. Based on the University's strength in nearly all facets of water resources, the president decided that water would be one of the four specific research areas to be strengthened with Proposition 301 money. For fiscal years beginning July 1, 2002 and 2003, $500,000 was allocated to the Proposition 301 water program, with the amount increasing gradually to $3,500,000 per year in the fifth year of the program. The Arizona Board of Regents designated this money as the Technology and Research Initiative Fund (TRIF).

The money allocated to the water area is co-managed by the directors of four campus water centers, the Dean of the College of Agriculture and Life Sciences, and the Vice President for Research, Graduate Education and Economic Development. The WRRC is collaborating with three-NSF funded water centers on this program. The three other centers are focused on water sustainability in semi-arid regions, water quality and high quality water for manufacturing, respectively. Between $100,000 and $115,000 is allocated each year to each of the four water centers. Starting in FY04 a $1,000,000/year competitive grants program in water research, outreach and education was initiated. In addition to the grants program, a $100,000 fellowship program for graduate and undergraduate students was initiated. An external advisory committee, consisting of water industry leaders from the private and public sectors, provides guidance to the program.

The Prop 301 water program is now called Water Sustainability Program. WRRC has played a central role in implementing the Water Sustainability Program and in developing and managing the grants and fellowship programs, and will continue to do so. Expectations are that the program will continue to be funded by the Arizona Board of Regents after the first five-year funding cycle ends on June 30, 2006. This will allow the four centers and the large U of A water community to continue to expand its water resources research, education and outreach.

In 2003, 21 proposals were funded by $1,000,000 in TRIF funding. The projects involve 54 UA primary investigators from four colleges, and 19 departments/schools/units across campus. Seventy-two entities are listed as partners, including schools and school districts, municipal, county, state and federal government agencies, private sector companies and other associations. Over $300,000 was been secured from off campus as direct dollar matches. The WRRC hosted six of the Water Sustainability grants. The titles of the hosted grants were:

1. "Evaluation of M & I Water Conservation Measures Through Actual Water Savings & Cost/Benefit Analysis;"

2. "Know Your Water: Manual of Water Quality and Treatment for the Home Owner;"

3. "The Water Wagon: A Mobile Laboratory and Education Center;"

4. "Arizona Water and Pesticide Safety;"

5. "Tailored Drought Planning for Arizona;"

6. "Improved Turf and Landscape Irrigation Management for Northern Arizona."

WRRC researcher, Jackie Moxley, was a collaborator on the project, "Know Your Water: Manual of Water Quality and Treatment for the Home Owner."

In January 2004, the University of Arizona Water Sustainability Program received 48 new proposals for year two of the competitive grants program under TRIF. Research utilizing the state tax funds is expected to attract additional matching support from the private and public sectors. It was estimated that $420,000 would be available for new grants in FY 2004.

Water Briefing for State Legislators and Public Officials

As part of the University of Arizona's Water Sustainability Program, the WRRC organized a briefing on water for Arizona Legislators and other invited agency guests. The successful program was held on March 23, 2004 in Phoenix. Educational briefings were provided by Sharon Megdal and Kathy Jacobs. WRRC Project WET Director, Kerry Schwartz, was a member of a panel of experts who provided an overview of their water programs. Dr. Megdal provided an overview of state water issues at a special session of the Navajo County Board of Supervisors. She has been invited to organize a session on water for the annual meeting of the Arizona League of Cities and Towns.

Project WET

The WRRC's Project WET (Water Education for Teachers) increased its efforts to provide water education to teachers through in-service workshops. This statewide K-12 program encourages the use of a water education curriculum within classrooms. Project WET also offers teachers new teaching methods and skills promoting inquiry-based teaching and problem solving, team building, critical thinking and group decision-making techniques. Presently WRRC has two full time Water Educators, one housed at the WRRC in Tucson, and a second Educator housed with Cooperative Extension in Phoenix and funded with TRIF funds.

The two water educators from WRRC train facilitators who in turn train teachers in two-day workshops all over the state. At present the Project has 90 volunteer facilitators giving workshops for K-12 teachers. Thus, through this multiplying effect, many thousands of students are educated about water each year.

Project WET Water Festival

This year, Project WET conducted, not one, as was done in previous years, but two Arizona Water Festivals, on Sept. 26, 2003 National Water Education Day. One festival was conducted in a metropolitan area and the second in a rural area. Project WET-coordinated water festivals are an annual occurrence. The 2003 dual event was the fourth in a series.

Water festivals are exercises in water creativity, with participants expanding their awareness of the uses, value and importance of water. But above all, water festivals are fun as well as educational, as students and their teachers participate in interactive water activities and demonstrations. Participants gain an increased appreciation of water in its varied uses and come away with a better understanding of an ethic of stewardship for preserving and protecting the state's water resources.

One of the two festivals was held in Surprise, Arizona at the Surprise Recreation Campus and involved about 1,000 fourth-grade students from the western part of the Phoenix Metropolitan Area. The Surprise festival was a collaborative effort, with the U.S. Bureau of Reclamation, Salt River Project, Arizona Department of Water Resources Phoenix AMA, Arizona Department of Environmental Quality, Central Arizona Project and the cities of Surprise and Peoria working with Project WET to ensure the success of the festival.

A water festival was also conducted on the same day in Safford. The event involved about 600 fourth grade students, from local rural Graham County Schools. Sponsors of the event included the U.S. Bureau of Reclamation, Arizona Department of Environmental Quality, Gila Resources and Valley Telecom. Gila Resources and the UA Safford Agricultural Center assisted Project WET in coordinating the event.

Project WET director, Kerry Schwartz, serves on the Project WET USA Council, and serves on the steering committee for new the new teachers guide, "Discover a Watershed – The Colorado."

Annual Water Conference

The Annual Water Conference continued to extend the WRRC's outreach with a highly successful program in 2003. The conference was expanded from its one-day format to two-days and was held in a non-urban area of the state. Titled "Local Approaches to Resolving Water Resource Issues," the conference brought together people actively engaged in resolving water resource issues from all over the state. Participants' expertise in solving problems was woven into the conference, which had the subtitle, "What's Working, What Hasn't Worked and Building on Existing Efforts."

Two key ideas that developed throughout the conference presentations as major conference themes were: (1) diverse problems call for diverse solutions, with no single remedy fitting all situations and (2) involve all interested individuals and parties when addressing an issue. Media coverage of the event was encouraging, and conference attendees included about 200 people from more than 40 Arizona communities.

The WRRC newsletter provided both pre-conference information and post-conference results and commentary. A newsletter article written after the 2003 conference presented an exposition and summary of lessons learned from the conference. The article was oriented to local and regional approaches to water management in Arizona, and was specifically directed to the lay reader. Dr. Megdal examined some of the practical applications that emerged from the conference in her monthly newsletter column. Also, Megal and Jackie Moxley authored an article in the *Arizona Review* with information gleaned from the conference.

Planning for the 2004 WRRC Conference was done in late 2003 and early 2004. An innovative aspect of the preparation for the 2004 Conference was the preparation of background, written materials, which involved substantial new information and analysis. These new materials, which involved USGS in the effort, were posted on the WRRC web site after the April 28, 2004 conference on The Future of Agricultural Water Use in Arizona. Over 250 people registered for the 2004 conference.

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	4	0	0	0	4
Ph.D.	2	0	0	0	2
Post-Doc.	0	0	0	0	0
Total	14	0	0	0	14

Notable Awards and Achievements

Sharon Megdal organized the well-received 2003 WRRC conference. Titled Local Approaches to Resolving Water Resource Issues, the conference brought together people actively engaged in resolving water resource issues from all over the state. The conference was expanded from its one-day format to two-days and was held in a non-urban area of the state. Conference attendees included about 200 people from more than 40 Arizona communities.

Sharon Megdal organized the much acclaimed Future of Agricultural Water Use in Arizona conference, which was co-sponsored by the Departments of Agricultural and Resource Economics, and attracted over 250 participants. She consulted with various agricultural groups and organizations to gain their interest and financial support and to invite their participation.

Sharon Megdal presided over a successful and well attended University of Arizona-sponsored educational briefing dinner for state legislators and other agency guests.

Sharon Megdal served on the Water Quality Appeals Board.

It was announced that Sharon Megdal would become director of the WRRC as of July 1, 2004.

Sharon Megdal and Kathy Jacobs are both significantly involved in writing the background report for the upcoming Arizona Town Hall on water.

Kathy Jacobs is a lead staff person developing Arizonas first drought plan in cooperation with the Arizona Department of Water Resources and the Climate Assessment for the Southwest.

Kathy Jacobs has served on two National Academy panels over the past two years.

Peter Wierenga, WRRC Director, received the 2003 Administrator of the Year Award from the College of Agricultural and Life Sciences.

Kerry Schwartz, serves on the Project WET USA Council, and serves on the steering committee for new the new teachers guide, Discover a Watershed The Colorado.

Joe Gelt had two of his Arizona Water Resource newsletter articles re-published in the Arizona Capital Times.

Terry Sprouse carried out effluent research on the U.S. Mexico border with support from a Fulbright Grant.

Terry Sprouse serves as a Board Member of the International Boundary and Water Commissions Southeast Arizona Citizens Forum.

Publications from Prior Projects

None