NSF Science and Technology Center

SAHRA

Sustainability of semi-Arid Hydrology and Riparian Areas

Renewal Proposal

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I. Project Summary

Semi-arid regions of the world are experiencing unprecedented hydrologic stress. Approximately one-third of the land surface of the earth, including the Southwestern U.S. (hereafter called SW U.S.), is arid or semi-arid. These regions are experiencing some of the highest levels of population growth and development, land use changes, new and competing water uses, socioeconomic changes, legal and institutional adaptations, and climate variability, leading to hydrologic stress. Their populations are therefore faced with the problem of how to support *sustainable* development and, in particular, how to maintain *sustainable* water resources. Key issues include protecting the quantity and quality of the water supply and ecosystem health. Of greatest concern is how to properly allocate scarce water resources among competing uses during a decadal drought such as the one experienced most recently in the mid 1940-50's throughout the SW U.S. As urban demand continues to increase, severe local and regional imbalances between supply and demand occur, stimulating interest in methods for improved water management, and in institutional approaches such as water marketing. There is an enormous need for accurate scientific information to facilitate and support such methods. However, the distribution, magnitude, and mechanisms of key water fluxes within the basin are still poorly known, and few tools are available to facilitate rational decision making at the river basin scale.

The crisis is beginning to impact water resources policy. The public in the SW U.S. now generally recognizes that water resources issues are reaching a crisis point. Recent polls show New Mexicans rated water resources as the second most important issue in the state, after education [*Albuquerque Journal,* 2002]; the Albuquerque business community rates it as *the* most important issue (78% of respondents) [*Albuquerque Journal*, 2003]. Headline articles in local and national newspapers frequently address issues of water shortage resulting from drought conditions [*Arizona Daily Star*, 2002; The *Arizona Republic*, 2002 and 2003; *Albuquerque Journal*, 2002; *New York Times,* 2003] as well as the coincident need to maintain in-stream flows to comply with the Endangered Species Act [*Albuquerque Journal,* 2003; *New York Times,* 2003]. Public conflicts between municipal and agricultural water users in the basin are leading to shifts in policy. After 50 years of almost complete reliance on groundwater, the cities of Tucson, Albuquerque, and El Paso are implementing plans to fully utilize available surface water resources. These actions are a direct result of recent technical reassessments of groundwater recharge rates and the projected effects of continued pumping at current rates. Internationally, tensions have increased between the U.S. and Mexico over the shared waters of the Colorado River and Rio Grande/Rio Bravo. Reduced cross-border flows in the Colorado River have drastically reduced the Colorado River delta, while reduced flows in the Rio Conchos are impacting the lower Rio Grande.

However, while crises tend to raise the public awareness of long-term water resources issues, responses have tended to be mostly in the legal and legislative arenas, and little attempt has yet been made to develop basin-wide hydrological understanding of the stresses on the system and the consequent hydrologic responses to those stresses. Additionally, we know little about how the public will respond to the crisis. Finally, there remains the problem of linking disciplinary research.

SAHRA is responding by developing integrated multidisciplinary understanding. SAHRA, the NSF Science and Technology Center for *Sustainability of semi-Arid Hydrology and Riparian Areas*, was established in 2000 to address this situation. Our original proposal noted the existence of a critical gap between the products of the conventional individual- and multiple-investigator research projects and the tools used by water resources practitioners, and also the lack of an "effective mechanism for rapidly moving the state of scientific knowledge into widespread usage by the public and private agencies responsible for managing our water resources." SAHRA's vision continues to be to "develop an integrated, multidisciplinary understanding of the hydrology of semi-arid regions, and to build partnerships with a broad spectrum of stakeholders (both public and private organizations) so this understanding is effectively and rapidly brought to bear on the management of water resources and rational implementation of public policy." The key question that we seek to address is *How can SAHRA use science to help communities manage their water resources in a sustainable manner?* We are therefore concerned with: a) advancing the understanding of fundamental principles in semi-arid hydrology through stakeholder-responsive multidisciplinary research; b) understanding the demand and supply aspects of water resources and their linkages; and c) developing strategies for implementing scientific understanding on a practical level through aggressive knowledge transfer and strong education initiatives (K-16, graduate, and public).

Considerable progress has been achieved. SAHRA's greatest challenge is to bring about a high level of coordination and integration across a broad range of scientific disciplines, and among scientists, policy and decision makers, and the general public. We have made considerable progress during our first three years. First and foremost, SAHRA has achieved an integrated, multidisciplinary and multi-institutional approach to research, from which a number of interesting scientific results have begun to emerge (these are highlighted in section III.A). Integration has taken four forms:

- Extensive input from over 100 key water decision makers, researchers and various stakeholders has been integrated into the SAHRA research agenda, through numerous formal and informal meetings. This process is ongoing.
- A multidisciplinary team drawn from institutions throughout the Southwest has been effectively integrated through frequent team meetings, co-location of full-time research associates, and development of research questions that cut across disciplinary boundaries.
- A process for end-to-end (scenarios to research findings) integration has been implemented. Research activities are designed to provide the information needed to support the supply and demand aspects of decision-making in the context of plausible scenarios that link causes with impacts and responses.
- Hydrologic processes are being studied in the context of their role in the hydrology of an entire basin. Research tasks are designed to fill gaps in existing knowledge, particularly at the interfaces between traditional scientific disciplines (see sections III.A.1-A.3). Multi-resolution integrated modeling is being used to help integrate individual local-scale research findings, and to facilitate overall understanding of the complex interactions that occur at various spatial and temporal scales (see section III.A.4). Given the large size of the team and the immense scope of the modeling endeavor, considerable dialogue has been required to arrive at a workable structure for coordinating model development. Through a series of workshops, a consensual framework has emerged. The process of arriving at a conceptual model structure has resulted in considerable cross-disciplinary education of all parties involved.

Second, SAHRA research findings already are improving our hydrologic understanding and changing the way water resource managers view policy options. Isotopic analysis of samples from the Rio Grande has revealed that saline groundwater discharge associated with sedimentary basins is the dominant solute input, implying that changes in irrigation and agricultural practices will have little effect on salinity levels. Research on moisture fluxes beneath grasslands and desert shrubs has revealed minimal downward fluxes and even upward fluxes in the vadose zone, suggesting that large areas of the SW U.S. have significantly less recharge than previously thought. Research in riparian corridors has shown that flood events are an important driver for nutrient cycling and are a critical control on the structure and diversity of riparian vegetation. Vegetation water source was found to vary based on plant type and season. This information is critical for assessing the groundwater needs of riparian ecosystems and for developing effective restoration strategies. Overall, SAHRA field research is focused on understanding how vegetative cover controls water balances and the partitioning of precipitation between evaporation, transpiration, infiltration, runoff and recharge.

Third, SAHRA has established a cohesive program for building understanding of key water issues into K-16 science education (section III.B). Our mission is to improve the hydrologic literacy of a broad range of stakeholders, particularly teachers. Considerable effort has been directed toward high school, undergraduate, graduate, and professional-level course development based on a careful assessment of needs. Workshop activities have included high school teacher training on "integrating inquiry and water issues," and environmental education outreach for Native American K-12 students and teachers. Another important goal is to attract diverse students into hydrology. Review and development of a comprehensive diversity plan is currently underway. Our Research Experiences for Undergraduates program allows promising students within water resources fields to work alongside SAHRA researchers during the summer in both field research and laboratory settings.

Fourth, SAHRA has developed a diverse and effective approach to knowledge transfer (KT), (section III.C). Through working relationships with key stakeholders in the region, we have ascertained their needs and solicited feedback to guide SAHRA's research efforts. We have implemented an ambitious Web-based resource that furthers multidisciplinary hydrologic literacy and communicates research findings, data sets, and tools to water resources managers and policy makers. KT activities also inform the general public through services such as our Web-based "Water News Watch" and "Residential Conservation Information" sites, Rural Water Resource Centers, public education displays, and periodic press briefings. SAHRA's Sabino Canyon display, electronic kiosk and web site exemplify our ability to tap near-real-time data streams and ongoing research efforts to produce informal experiential exhibits that raise hydrologic literacy.

Fifth, SAHRA is beginning to broaden the scope and geographic coverage of its international activities (sections III.A.5 and III.C). Our primary focus has been to develop collaborations with researchers in northern Mexico and to promote binational basin coordination of water policy. Collaborations with other countries (e.g., Morocco, Egypt) are also being deliberately developed, with the initial focus on bidirectional knowledge exchange through scientific meetings and workshops.

Finally, SAHRA is making considerable progress toward achieving post-NSF sustainability. In addition to numerous short-term grants that support various science, education, and outreach activities, SAHRA has been awarded significant long-term State of Arizona Proposition 301 funding.

Why SAHRA funding should be renewed: During the first three years SAHRA has evolved into a creative, mature, and well-integrated organization. The staff is exceptional and the working relationships between SAHRA management, scientists, and administrative staff are excellent. Strong leadership and a directed but consensual approach to decision-making ensure a high level of buy-in among participants. SAHRA integrates the activities of a large number of investigators. While individual investigators receive limited direct financial support, participation is active, widespread and enthusiastic because SAHRA is achieving cutting-edge and coordinated science of a kind that is not possible through conventional grants. By maintaining good communication, coordination, and co-location of research activities (each task is designed and carried out by multiple investigators), by directing the tasks towards major knowledge gaps, by supporting calculated risk-taking, and by giving individual investigators sufficient responsibility and ownership for their part in the research effort, the product far exceeds the sum of the individual parts. This is clearly apparent in section III of this document, which highlights SAHRA's major scientific, educational. and knowledge transfer achievements and outlines our plans for ongoing activities in these three interlinked areas. We believe these experiences and successes will have considerable influence on the way hydrologic science is conducted in the U.S. and elsewhere.

II. Table of Contents

III. Project Description

A. Research

SAHRA research during the first three years has addressed a number of knowledge gaps resulting in a refocusing of our research priorities. This section details our major research achievements, their impact, and our plans for the future. A comprehensive sense of achievements can be obtained by reviewing the full list of publications (section IX). Likewise, future research and methods are detailed on the SAHRA web site at www.sahra.arizona.edu.

The research tasks outlined in this section are the outcome of a progressive and logical evolution in our science plan. The original research agenda involved five primarily science-focused thrust areas with a large variety of research tasks that were not explicitly geographically coordinated. Through a lengthy process, including a comprehensive evaluation of SAHRA activities conducted by SAHRA research staff and management, regular meetings of the Executive Committee, a very productive series of workshops, and a comprehensive internal review of all science tasks, we have concluded that a river basin focus can provide the necessary context and motivation to help identify knowledge gaps and drive both the inter-disciplinary and end-to-end integration processes. Most SAHRA research activities are therefore being conducted in the Rio Grande and San Pedro River basins, with supportive work in the Rio Conchos (Mexico) basin and at the scale of the regional SW U.S. Note that close connections have also been achieved between the science and educational/knowledge transfer activities (see sections III.B and III.C).

The organization of science tasks presented here reflects the matrix-like interaction between a "science" focus and the emergent "river basin" focus. There are seven subsections. *Basin Scale Water Balances* (subsection A.1) addresses the mountainous portions of the basin where much of the precipitation occurs as snow and is converted into runoff and deep infiltration, and the extensive low-elevation basin floor areas where this "excess" precipitation is evapotranspired. *River Systems* (A.2) addresses the quantity, quality and riparian ecosystem aspects of the river systems, through which the natural and anthropogenic processes in a basin are integrated, and where much of the biodiversity resides. *Regional Scale Hydrometeorology* (A.3) investigates methods for estimating regional water budgets. *Integrated Basin Modeling* (A.4) develops a multi-resolution approach to integrate research findings and to evaluate potential basin-scale scenarios such as a modern day recurrence of the 1950's drought. *International Collaboration* (A.5) develops collaborative research relevant to both sides of the U.S.-Mexico border and seeks to promote binational basin coordination of water policy. Finally, *Data and Information System* (A.6) and *Technology and Equipment* (A.7) develop needed infrastructure support.

A1. Basin Scale Water Balance

Semi-arid environments such as those of the SW U.S. express a division of the water budget that is quite different from that of humid settings. Both precipitation and temperature depend strongly on elevation. As a result, the high-elevation portions of drainage basins tend to be the areas where precipitation is converted into runoff and deep infiltration and the low-elevation areas tend to be those where this "excess" precipitation is evapotranspired. This organization of the water budget provides a natural structure for SAHRA's fundamental research at the river basin scale.

SAHRA research is focused on understanding and linking the key processes controlling the hydrology in each of these regions. In particular, we seek to understand the mechanisms by which precipitation (rain and snowfall) is partitioned into evaporation/sublimation, interception loss, runoff and infiltration, and how snow and soil moisture storages are partitioned into transpiration, recharge, and streamflow. In addition, we are concerned with how these key variables and processes can be estimated and modeled. To date, SAHRA research has emphasized the following issues:

- Basin floor areas: What are the processes governing water fluxes through thick vadose zones in the basin floor areas? How does vegetation influence the partitioning of water and energy fluxes and soil moisture storage?
- Mountain environments: What factors control the distribution of snow accumulation and melt, and its partitioning into evapotranspiration (ET), deep infiltration and runoff?

A more complete understanding of these issues is necessary to close water budgets at the basin scale and to predict the nonlinear response of the system to long-term water balance perturbations, including a fair assessment of uncertainty in these predictions. Our approach has involved intensive field measurements at test sites, use of remotely sensed data, and modeling.

Achievements to date

The more mature sub-projects have made considerable progress as documented in the publications listed in section IX. Some noteworthy achievements/findings follow.

Water balance above the mountain front

- The best method for estimating basin-wide snow water equivalent (SWE) from point data depends on the spatial arrangement of data and the environmental or physiographic factors that characterize a basin [*Fassnacht et al. a&b*, in review]. Interpolation errors are comparable using either SNOTEL or snow course data [*Dressler et al.,* in preparation]. Snow surveys appear to provide more accurate spatial maps of SWE particularly during drought years [*Molotch et al.,* in preparation]. The implication is, that without improvements in measurement network design, uncertainty in SWE estimates used for decision-making will remain high.
- Remotely sensed snow grain-size data were incorporated into spatially distributed energy-balance snowmelt models, with a 34% increase in accuracy of our prediction of snow pack ablation, and thus basin-scale snowmelt [*Molotch et al.,* in preparation].
- A 30-meter micro-meteorological tower (hereafter called the Mt. Bigelow site) was erected and instrumented to measure water, energy and carbon fluxes in a 2400 m elevation ponderosa pine-Douglas fir forest. Observations revealed that the trees essentially "shut down" during the pre-monsoon season, with the exception of brief periods in the morning and afternoon when CO_2 uptake directly correlates with low rates of ET. After monsoon precipitation, the ecosystem responds rapidly, with Bowen ratios (ratio of sensible to latent heat flux) near one, and high levels of CO_2 uptake (photosynthesis) (Figure 1.1). Micro-meteorological stations distributed throughout the forest showed surface flux potential (surface air temperature gradient) to vary significantly over space and time, and to be directly related to canopy characteristics and aspect [*Brown-Mitic et al.(a&b)*, in preparation].

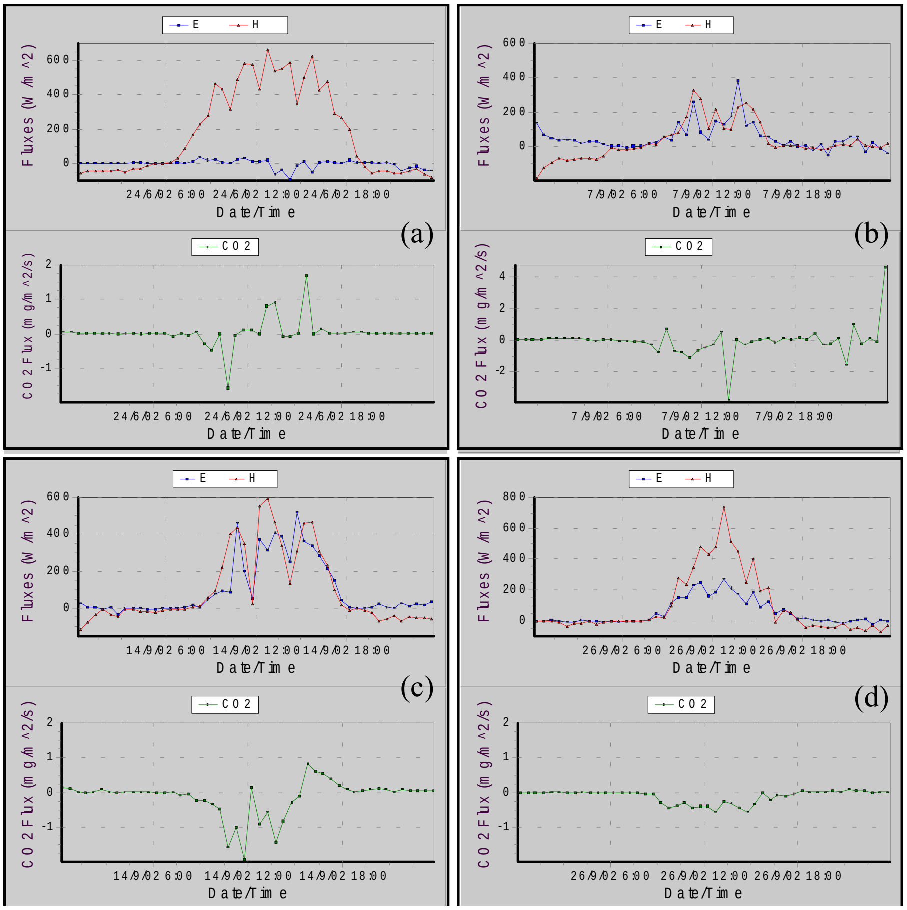

Figure 1.1 – Mt Bigelow Pre and Post-Monsoon Evapotranspiration (Latent Heat, E), Sensible Heat (H) and Carbon Dioxide (CO2) Fluxes. (a) Pre-monsoon where S dominates the energy budget, E fluctuates around zero with small advection. (b), (c) Post-monsoon where E recovered rapidly to Bowen ration of 1. (d) End of monsoon where S begins to dominate, E remains significant and the vegetation is actively assimilating CO2.

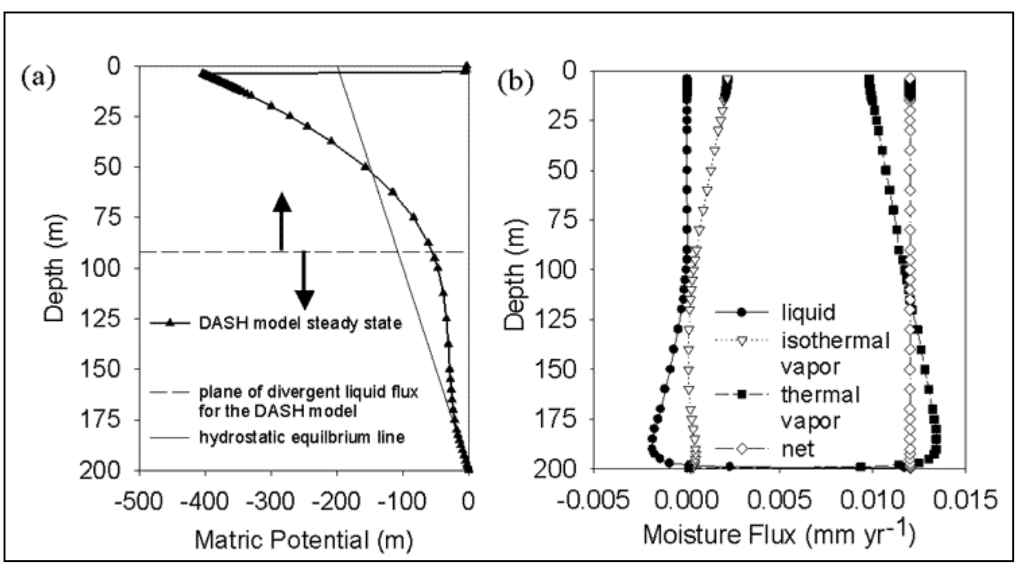

Figure 1.2 – (a) Comparison of steady-state ψ profiles predicted by our model and the linear ψ profile described by the conventional hydrostatic equilibrium model. (b) Steady-state moisture flux profiles predicted by our model. Negative values indicate downward fluxes. Vertical axis is depth, in meters.

• Modeling of high-elevation environments suggests that topography, bedrock permeability and vegetation exert a strong control on deep infiltration, and hence recharge. Topographic and geologic data are readily available. The relationship between these abiotic controls and the biotic components of the system are still unknown, although our simulations show that the interactions are critical [*Wilson and Guan.,* forthcoming].

Water balance on the basin floor*:*

• Water fluxes in typical basin floor environments under the current climate have been shown to be upward in the top ~50 m of the vadose zone during the Holocene, driven by a combination of very negative water potentials produced by the roots of desert vegetation and by the geothermal gradient (Figure 1.2). However, comparison of vadose zone profiles under different types of vegetation and modeling of past periods when climate change caused migration of plant communities have both shown that under slightly less xeric types of vegetation, fluxes can be downward through the root zone (Figure 1.3) [*Walvoord,* 2002; *Walvoord et al.,* 2002].

• The method by which grassland is invaded by woody species, and the resulting impact on surface and vadose zone water and energy cycling have been quantified through intensive measurements on controlled plots within the Sevilleta long term ecological research (LTER) site. Overall, the spatial distribution of biomass and the physiology and phenology of plant types exert a fundamental control on water and energy fluxes. As illustrated in Figure 1.4, more infiltration occurs beneath plant canopies than beneath interspaces, although shrubland subcanopy infiltration is much deeper and more widely spaced [*Bhark and Small,* in preparation]. The total ET flux from these two ecosystems is similar, but drying following rainfall is faster in shrubland. Leaf-level measurements show that ET is partitioned into evaporation and transpiration differently in the two environments, with greater evaporation in the shrubland due to more bare soil area [*Kurc and Small,* in review]. Shrub invasion of grassland, the most extensive natural land-surface change throughout the Rio Grande valley, is expected to continue.

• Analysis of streamflow data has shown that low-frequency oscillations in seasonal to interannual and decadal climatic forcing interact with the long time scales of deep soil moisture and groundwater storage to amplify low-frequency modes in runoff in ephemeral, intermittent, and perennial streams of the Rio Grande basin. Low-frequency components in mountain front runoff are consistent with the El Niño-Southern Oscillation, quasi-biennial, and quasi-decadal signature [*Duffy,* forthcoming].

• A three-component study of disaggregated water demand, involving experimental studies, household data loggers, and evaluation as database of monthly household demand, all indicate that individual and household behaviors appear to be significant determinants of water demand, while physical characteristics of households and landscapes are less important than previously believed [*Brookshire et al.,* 2002; *Krause et al.,* forthcoming; *Chermak and Krause,* 2002]. The study contradicts findings based on aggregated data and suggests the need for new approaches to demand management.

• Research on municipal water demand historically has been based on data aggregated over large geographic areas (e.g., service areas) and/or time periods (months/years). A major SAHRA research effort has been developing and analyzing highly disaggregated demand data. Three research approaches are leading to improved understanding of water demand: experimental economic work on decision-making at the level of the individual (Krause); development of household data loggers at the level of individual water uses (Woodard); and factors controlling residential and industrial water demand evaluated using a large database of household level monthly demand. A general result is that individual and household behaviors are more significant determinants of water demand than suspected, whereas physical characteristics of households and landscapes are less important than previously believed. (e.g., operation and maintenance of irrigation systems vs. landscaping and type of irrigation system) [*Brookshire,* et al., 2002; *Krause,* et al., forthcoming].

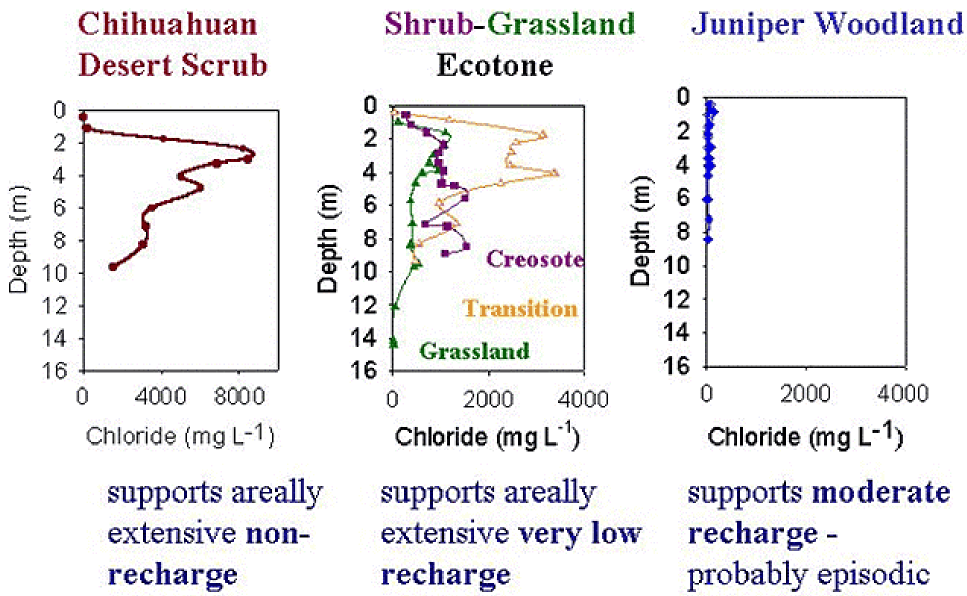

Figure 1.3 - Chloride profiles under three vegetation communities. Greater chloride concentration indicates less recharge.

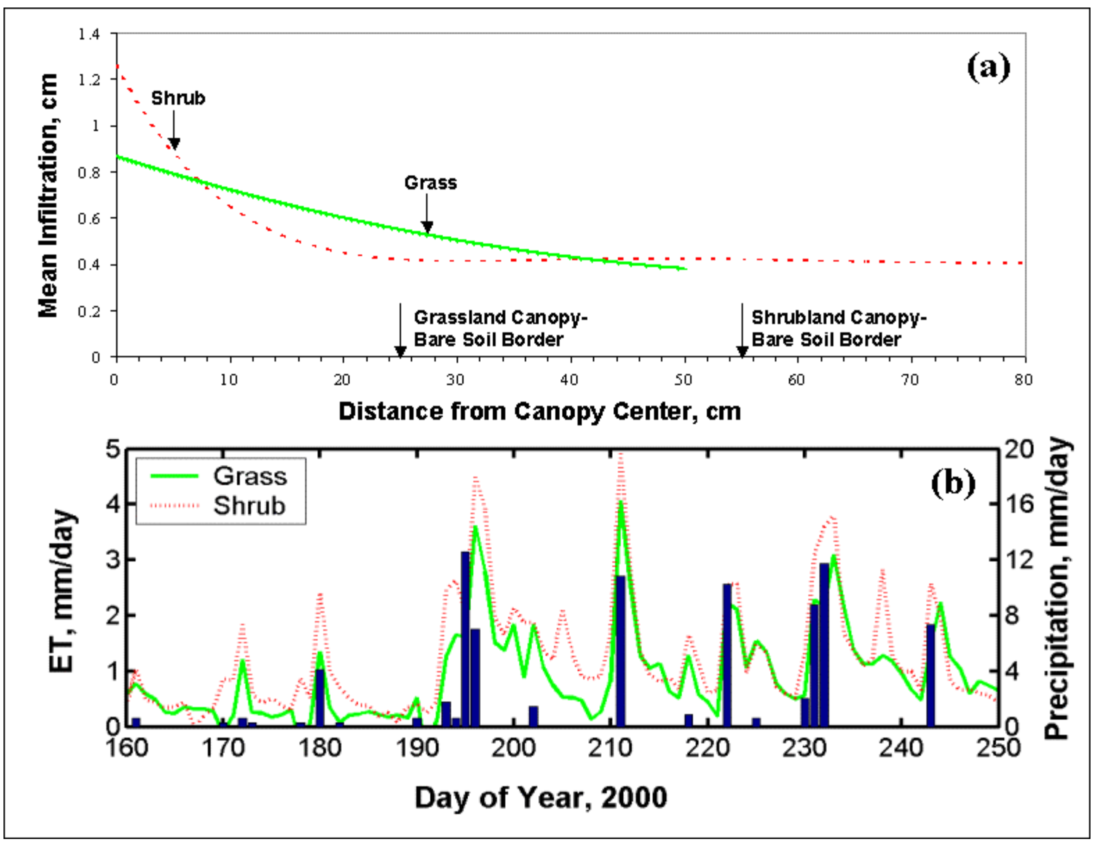

Figure 0.4- Semiarid grassland and shrubland exhibit many differences, including infiltration pattern (a), and evapotranspiration (ET) dynamics (b). The ability of shrubs to transpire for longer periods following precipitation events may help to explain the replacement of grass during drought episodes.

Plans for ongoing research

The findings summarized above have demonstrated that the most critical "missing links" in our understanding of semi-arid region hydrologic responses are the role of vegetation in water partitioning and the ability to scale up understandings obtained at the plant scale to the basin scale. We have therefore reevaluated the critical knowledge gaps and reformulated our research questions. They are relevant to the full range of environments that exist in semi-arid regions, from basin floors to high elevation areas:

- How do ecohydrological interactions control the water fluxes and storage that constitute the basin scale water balance?
- How can ecohydrological interactions, which are the outcome of processes that occur at the meter to hillslope scale, be represented at the scale of landscapes to basins?
- How can the important hydrometeorological, physiographic, and physiological interrelationships be accurately represented in a distributed hydrologic watershed model that includes snow and vegetation processes?

This focus on ecohydrological interactions is particularly relevant to the goal of promoting sustainable water management. Ecosystems change dramatically on timescales from years to decades, due to natural (e.g., climate change or drought) and anthropogenic processes (e.g., land-use change) that can have drastic impacts on basin-wide water and solute budgets. To address these knowledge gaps, we plan to first develop a physically based understanding by investigating water-partitioning processes at the plot-to-hillslope scale. The next step is to identify physically based methods to parameterize these processes at the landscape to basin scale. Once this is accomplished, the conceptual models and parameters can be incorporated into numerical models that can be tested against the actual historical behavior of the integrating system outputs. Finally, these results can be integrated into a model, or series of linked models, that will incorporate human interactions and be employed to predict responses of the system under a variety of imposed stresses and management responses. The approach is to combine intensive observations at multiple scales with modeling. Major tasks planned follow.

<u>Task 1. 1 Plot-to-hillslope scale processes</u>

<u>Task 1.1a.</u> Expand measurements of landscape features and fluxes *(Small, Wilson, Bales):* Data will be collected that span the full range of environments that exist in semi-arid regions. The heavily instrumented experimental plots established in creosote shrub, desert grassland, and mixed shrub/grassland habitats on the basin floor (Sevilleta) will continue. In addition, a complementary network of measurement stations and plots will be established in the piñon-juniper and ponderosa pine forests of the Rio Grande headwaters. The presence or absence of plant canopies and associated micro-topography and soil properties are believed to exert a strong control on the patterns of infiltration (e.g., *Dunne et al.,* [1991]). The data will facilitate characterization of the spatial covariance between landscape elements influencing flow and transport. In addition, coordinated measurements of key variables related to vegetation, snow and soil moisture (and linked to land surface and geologic properties) will be carried out through both continuous monitoring and field campaigns.

<u>Task 1.1b.</u> Investigate water, energy, and carbon cycling in SW U.S. subalpine forests *(Shuttleworth, Brown, Bales)*: Research at the Mt. Bigelow site, which is located at 2400 m in an area where precipitation exceeds ET, will be extended in space and time to capture the strong interannual variabilities and effects of altitude-related changes in vegetation on water, energy, and carbon cycling. Methods will involve high-resolution terrain and vegetation surveys of soil and snow, as well as the deployment of additional hydro-meteorological stations. Results will be integrated with those from task 1.1a to estimate partitioning of water fluxes, and task 1.2a to estimate energy and snowmelt fluxes over the forested, seasonally snow-covered headwater parts of the Rio Grande and other basins.

Task 1.1c. ***Model plant-to-hillslope processes across environments*** *(Wilson, Small):* Building on our existing mountain block recharge model, a small-scale model for simulating surface and vadose zone flow and transport across the range of semi-arid environments (above and below mountain front) will be developed. The full range of processes controlling partitioning of precipitation into various fluxes will be included. tasks 1.1a and 1.1b will provide landscape properties and observations (including both water and tracer data) for evaluating simulations. The goal is to derive effective parameters at the 30 m grid spacing scale required by the land surface component of the high-resolution integrated modeling system under development by SAHRA co-investigators at Los Alamos National Laboratory (see section III.A.4). Variance estimates of the parameters will also be provided so simulation uncertainties can be assessed.

Task 1.2 Landscape to basin scale water balances

Task 1.2a. ***Investigate spatial distribution of snow cover, energy balance and melt in seasonally snow-covered catchments*** *(Bales, Davis, Brown)*. Sub-canopy snow covered area (SCA) and vegetation characteristics (e.g. type, density and topographic features) developed through tasks 1.1a and 1.1b will be used to estimate the spatial energy balance and snow distribution over time across the seasonally snow-covered headwater parts of the Rio Grande and other basins. The relationship between the density of measurements and the error in the interpolation of measured variables will be investigated. Point scale water and energy budget relationships (e.g. Mt. Bigelow study new installations) will be extended to larger scales, using a combination of geostatistical and physical methods. These will be linked with the high-altitude flux scale results from task 1.1b to enable simulation of the fate of snowmelt at the scale of the headwater basin.

Task 1.2b. ***Remote sensing of evapotranspiration at the landscape scale*** *(Hendrickx, Hsu, Gau):* The least-known component of the water balance in the Rio Grande basin is the temporal and spatial distribution of evapotranspiration. Remote sensing can provide the key to scaling up our measurements of plot-scale water partitioning and energy balance to the basin scale. During the first phase of SAHRA, the SEBAL (Surface Energy Balance Algorithms for Land) [*Bastiaanssen et al.(a&b),* 1998] model was tested, with generally favorable results. This will be continued in the intervening period and results evaluated against alternative approaches. We will produce basin-scale maps of ET at the 1-km^2 scale using MODIS imagery and these will serve as key tests of the adequacy of the conceptual approaches and numerical models to scale-up the results from task 1.1.

Task 1.2c. ***Recharge revealed through isotope geochemistry*** (*Ekwurzel, Phillips, Eastoe, Hogan):* Sustainable management of groundwater resources to meet increasing human demands while sustaining groundwater-fed riparian ecosystems is predicated on knowing natural recharge rates. SAHRA has focused on developing and employing new isotopic methods that will result in independent estimates of recharge rates, provide information about recharge mechanisms, and determine recharge source regions within the basin. Stable isotopes and noble gases may be employed to determine recharge source regions. Recharge rates can be constrained from residence time information determined through tritium, ^{3}He, radiocarbon and ^{32}Si isotopes. Recharge investigations are currently focused in three crucial areas: 1) mountain block (noble gases, stable isotopes, radiocarbon), 2) alluvial channels (noble gases, stable isotopes, tritium), and 3) valley floor (^{32}Si).

Explicit Linkages. In addition to the tasks enumerated under section A.1, the landscape-scale water-balance analysis will also explicitly include work described in other sections of this proposal. These include section A.2, which deals with water and salt balance in the river and riparian environments. Upland (watershed) and river water balances must ultimately be linked in order to quantify the water balance at the basin scale. Another explicit linkage is with section A.4 (Integrated Modeling), because basin-scale models are not only the goal of this research thrust; they are also indispensable tools in developing our understanding of that balance.

Task 1.3. Linkages between scales

Task 1.3a. Investigate vadose zone water partitioning across climatic and vegetation gradients *(Phillips):* We have found that net water fluxes through the vadose zone are actually upward rather than downward over much of the landscape. The critical questions then become: where are the boundaries of regions of differing flux, and what controls the position of these boundaries? We will analyze water potential and environmental tracers in shallow (5- to 10-m deep) vadose-zone boreholes to distinguish regions of upward from downward fluxes, and to quantify the magnitude of those fluxes. The boreholes will be in linear arrays that cross both climatic gradients and ecotones, and will link the plot-scale study sites. When combined with the insights from plant-scale process studies and regional-scale ET analysis these data should enable ecohydrological controls to be scaled up to the landscape unit.

Task 1.3b. Investigate temporal variations of partitioning across a range of scales using nonlinear dynamics *(Duffy):* The ability to predict effects of long-term perturbations to the Rio Grande (e.g., response of river baseflow to drought, land-use change, salinization, etc.) requires an understanding of nonlinear linkages between components of the system. Work under the first phase of SAHRA has focused on decomposition of recharge from historical hydroclimatic, soil moisture, groundwater levels, spring flow and runoff time series [*Newman et al.,* 2001]. Future work will be directed toward establishing the physical basis [*Duffy,* 2003] and implementing the experimental and conceptual advances of the first 5 years into the dynamical model (e.g., tasks 1.2a,b and 1.3a). In particular we will focus on the degree to which recharge/evapotranspiration to/from the water table produces low-frequency, nonlinear responses in the Rio Grande surface-groundwater system, and how these processes can properly be represented in the Rio Grande dynamical model. The experimental test beds and partners are the Sevilleta LTER (Phillips), the Pajarito Plateau (Springer), Mesilla Valley (Phillips, Hogan) and the Great Sand Dunes National Monument (Wilson).

Task 1.3c. Investigate dynamic vegetation transitions across upland ecosystems *(Huxman, Scott, Martens, Lin, Williams, Archer, Goodrich):* We will investigate how natural and human-induced transitions between different vegetation structures in upland ecosystems influence hydrological, ecological and biogeochemical processes, and how historical and on-going woody plant encroachment alters water, carbon and nutrient cycling. Flux measurements and other ecophysiological and soil measurements will be provided by four existing ARS/DOE flux sites in various upland ecosystems, the Mt. Bigelow site, and additional flux sites to be established oak woodland and piñon-juniper. The goal is to develop fine-scale vegetation succession/transition simulation models and biogeochemical models that describe fluxes and pools of C, N, and H_2O across vegetation transitions/states. Complementary work will be conducted for areas of riparian vegetation (section A.2). The vegetation change models will enable the effects of long-term perturbations to the system, such as drought or changes in grazing, to be linked to changes in the water balance through the ecohydrological studies described above.

Task 1.4. Human effects on the water balance

Task 1.4a. Quantify basin water demand *(Woodard, Brookshire, Chermak, Krause):* Significant categories of basin-scale water demand, such as groundwater pumping and its sensitivity to climate variability, production costs, and other factors remain poorly known due to poor metering. Estimates based on utility records or outputs from an agricultural or industrial process are unreliable. To better understand basin scale demand, a representative sample of five to ten non-municipal wells in the San Pedro will be specially metered and logged using modified personal digital assistants. Meter traces will be analyzed to understand the key factors determining usage. Historical pumping records will be reconstructed using, for example, utility records and acres of crops planted. Complementary funding by Cochise County will support metering of 20 homes with private wells. Findings will be integrated into the modeling effort.

Synthesis
The first goal of the individual components listed above will be to develop an understanding of the water balance over semi-arid basins, with a primary focus on the Rio Grande basin, that is physically based and founded on process studies conducted at the actual scale of the processes. The next is to identify methods (again, physically based) to parameterize these processes at the scale of the landscape unit. Once this is accomplished, the conceptual models and parameters can be incorporated in to numerical models that can be tested against the actual historical behavior of the integrating system outputs. Finally, these results can be integrated into a model, or series of linked models, that will incorporate human interactions and be employed to predict responses of the system under a variety of imposed stresses and management responses.

A2. River Systems

River systems integrate the hydrologic and biogeochemical processes that occur in a basin. In semi-arid areas, river valleys are the major location of human settlements and irrigated agriculture. Water resource decisions often directly impact streamflows, and may result in unexpected impacts on water quality, the socio-economic value of the river system, and the structure and diversity of the riparian ecosystem. These decisions are particularly challenging because the water needed to sustain riparian areas, home to much of the regional biodiversity, is the same water needed for urban and agricultural growth.

In the first three years SAHRA river system research has focused on developing fundamental processes-level understanding in three areas: 1) riparian water balance, 2) nutrient and solute sources and cycling, and 3) ecosystem dynamics and value. To date, research has been conducted on the San Pedro, an unmanaged river with an intact native riparian ecosystem, and the Rio Grande, a highly regulated river with large urban areas and extensive irrigated agriculture.

Specific questions included: 1) What are the controls on riparian evapotranspiration? 2) How are plant water sources partitioned between groundwater, precipitation, soil moisture, and stream flow? 3) What hydrologic and biologic factors control nutrient cycling in riparian ecosystems at the gravel bar and kilometer-reach scales? 4) What are the sources of salinity and how are they partitioned between natural and anthropogenic sources? 5) What hydrologic factors control the structure and function of riparian ecosystems?

Achievements
Considerable progress has been made, as documented in the publications listed in section IX. Some noteworthy achievements/findings follow.

Riparian Water Balance

- Eddy covariance measurements of riparian ET show tight coupling between understory ET and monsoon precipitation, whereas mesquite tree transpiration does not show significant change with the arrival of monsoon moisture and is closely related to diurnal water table fluctuations (implying a groundwater source) [*Scott et al.,* 2003]. Isotopic analysis of sap water has revealed that mesquite trees actually transpire a mixture of two-thirds groundwater and one-third precipitation/soil moisture [*Ellsworth and Williams,* in preparation; *Hultine et al.,* forthcoming].
- Through SAHRA efforts in technology development (section A.7), we have made fundamental improvements in the understanding of the spatial sensitivity of electrical resistance tomography (ERT) [*Furman et al.,* 2002*; Furman et al.,* forthcoming]. These results indicate that ERT will enable quantitative monitoring of transient hydrologic processes with immediate application to groundwater-surface water interactions in ephemeral channels and streambed sediments.

Nutrient and Solute Sources and Cycling

- Multiple isotopic and chemical tracers show that local discharge of saline groundwater is a significant source of salinity to the Rio Grande, whereas agricultural return flows add little salt (Figure 2.1) [*Phillips,* forthcoming*; Phillips et al.,* forthcoming]. This suggests that water quality improvements can be achieved through interception of saline groundwater or by changes in river management practices. Contrary to popular opinion, changes in irrigated agricultural practices may do little to decrease salt input to the river.
- Nutrients in the Rio Grande, in contrast to salinity, come mainly from anthropogenic sources including sewage treatment plants and agricultural return flows (Figure 2.1). These inputs are local, however their effects can extend for long distances with minimal biological cycling, ultimately impacting the aquatic and riparian ecosystems far from the original source [*Villinski et al*., in preparation].
- Hydrologic exchanges across riparian system interfaces result in extremely localized zones of rapid nutrient transformation and retention. However, the overall hydrologic flux across these interfaces is very low at baseflow [*Schade et al*., in preparation]. Thus biogeochemical connectivity is limited, both between the riparian zone and the stream, and between upstream and downstream reaches during baseflow [*Brooks, et al*., in preparation]. Consequently, water quality at any location is quite variable and strongly related to local sources and sinks of solutes [*Lewis et al.,* in preparation]. This changes during storm events when large amounts of carbon and nitrogen solutes are flushed from the vadose zone into the stream/hyporheic zone [*Huth et al.(b)*, in preparation]. Elevated baseflow, due to monsoon storm events, results in downstream transport of these solutes, resulting in little variability in surface water carbon and nutrient concentrations, in contrast to low baseflow conditions [*Lemon et al.,* in preparation]
- Continuously recording sediment load sensors indicate that scour and fill can result in highly variable respiration rates for microbial communities in stream sediments. Measurement of respiration potentials showed that the zone for aerobic biological activity extends to at least 80 cm, far deeper than previously thought. Dissolved organic carbon appears to be the most important variable controlling microbial respiration, implying carbon limitation [*Hamblen et al.*, in preparation].

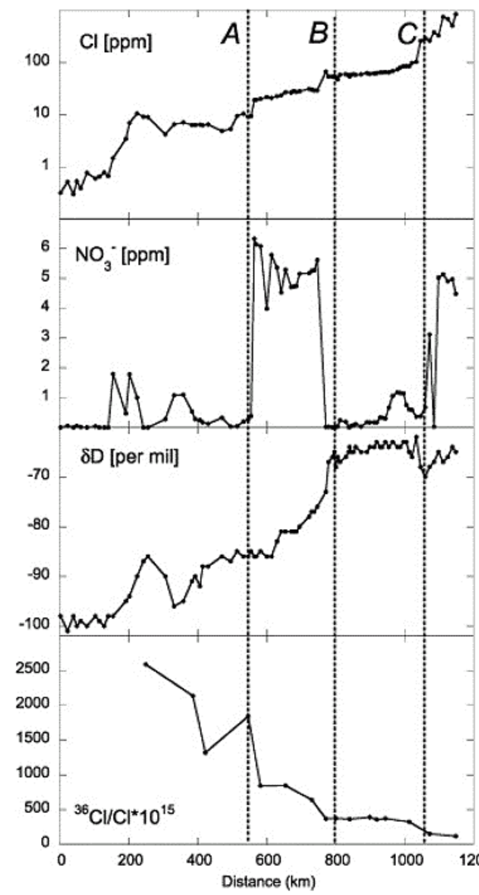

Figure 2.1 – Chemical and isotopic results of the August 2001 synoptic sampling of the Rio Grande. (A) Marks the location of Albuquerque NM, (B) Elephant Butte Reservoir and (C) El Paso TX. Note the stepwise increases in chloride whereas nitrate is marked by local sources followed by eventual removal. Changes in hydrogen isotopes (δD) are indicative of evaporation whereas decreasing ^{36}Cl

Ecosystem Dynamics and Value

- Groundwater depth, flood disturbance intensity, and rainfall quantity exert strong controls on the structure and diversity of riparian vegetation [*Stromberg et al*., in preparation]. These results have important implications for riparian restoration and conservation; riparian managers who wish to restore native broadleaf cottonwood-willow forests to riparian corridors dominated by exotic saltcedar now have guidance on the ranges of groundwater depth and flood inundation frequency needed to adopt a flow-management approach to riparian forest restoration.

Plans for ongoing research

The findings summarized above constitute significant advances in our fundamental understanding of semi-arid and arid river systems. Continuing research is aimed at understanding and evaluating the impacts of natural and anthropogenic changes to support scenario analysis (task 4.3). Fundamental process-level research is required, particularly for riparian biogeochemistry and to understand the causes and feedbacks of dynamic vegetation transitions. However, scaling, integration with economic valuation, and the development of tools for water management will also be a focus of the river systems research.

Additional research questions to be addressed in years 6 to 10: 1) How will vegetation change affect the riparian water balance and nutrient dynamics? 2) How do we scale our process-level understanding of nutrient sources and sinks to the length of the river? 3) What are the management options to decrease salinity? 4) What is the value of a native or restored riparian ecosystem in terms of ecosystem services and non-market value?

Riparian Water-Balance

Task 2.1. ***Quantify components of riparian water use*** *(Goodrich, Scott, Williams, Huxman, Stromberg):* Significant progress has been made in quantifying and modeling water use by the major riparian tree species. This research will focus on understanding phreatophytic understory species (sacaton and seep willow) transpiration and quantifying open water and wetted channel evaporation. Eddy flux measurements will be collected over sacaton stands with varying depths to the water table. Sap flux and scaling techniques will be used to quantify seep willow transpiration and simple open chamber methods will be used to address open water evaporation. Results will be used to evaluate the impact that vegetation change will have on the riparian water balance (e.g., changes resulting from beaver impoundments). We will work closely with BLM scientists who are monitoring vegetation change to quantify associated water use changes.

Task 2.2. ***Investigate applications of ERT to recharge and water flow in riparian areas*** (*Ferre, Goodrich, Maddock):* We will investigate coupling of hydrologic and geophysical models using real-time, automated (genetic algorithm) optimization of ERT measurement systems to monitor flow and transport with high spatial and temporal resolution. We will apply the technique to the monitoring and study of infiltration and recharge beneath ephemeral channels, groundwater-surface water interactions in perennial riparian streams, and solute transport through streambed sediments.

Nutrient and Solute Sources and Cycling

Task 2.3. ***Spatiotemporal characterization of riparian biogeochemical processes*** *(Conklin, Grimm, Martens, Brooks):* Previous SAHRA research has focused on nutrient dynamics in the stream channel/ hyporheic zone. Our continued process-level research will focus on quantifying the *spatial and temporal exchange* of water, energy, and nutrients between upstream-downstream reaches, and between ecosystem components. We will undertake intensive, process-based studies at hillslope, terrace, riparian, and channel sites to quantify both the degree of connectivity between these components, spatial variability, and the mechanisms that control biogeochemical cycling. A nested set of consistently applied measurements will focus on the export and/or delivery of water, sediment, and solutes and how these source-sink relationships respond to changing conditions at each site. Measurements will include hydrologic flux, solute and sediment pool size, isotopic and chemical measurements of mobile solutes, biomarkers, and structural and mineralogical characteristics of transported sediments. Novel techniques employed will include development of wireless chemical and sediment load cells (see also task 7.1). Complementary bench-scale experiments will be conducted to elucidate the time scales and reactive substrates.

***Task 2.4.* Investigate scaling of riparian biogeochemical processes** *(Brooks, Conklin, van Genuchten, Schaap, Bales, Grimm, Maddock):* Our previous SAHRA research has helped us develop a conceptual model about the spatial and temporal variability of nutrients in the riparian corridor. The challenge is to upscale our process-level understanding. A coupled water/biogeochemical/sediment model of the riparian corridor will be developed on a 1-10 km scale. The model will represent how land use change and climate variability perturb water, sediment, and solute/nutrient delivery to (and transport in) the stream-riparian system. Biogeochemical and ecological measurements of dynamic vegetation transitions will provide data for predicting how fluxes will respond to changes in land cover. GIS coverage of the catchment and distributed rainfall from radar measurements will be used to scale plot research (task 2.3) to the catchment. This effort can then be coupled to vegetation structure/succession models (see task 2.6) providing a tool for decision makers to evaluate riparian management options.

***Task 2.5.* Investigate management strategies to control salinity** *(Hogan, Phillips, Hendrickx):* We have demonstrated the importance of local saline groundwater on solute balance of the Rio Grande above El Paso. We will investigate strategies for mitigation of high salinity levels. The first strategy is improved river management practices to limit low-flow/high-salinity periods. We will analyze historical and current water quality data and model past conditions to understand how solute balances respond to climate variability and changing land use. A second strategy is interception of local saline groundwater discharge. Site selection will be based on preliminary hydrogeological analysis. At the selected site we will conduct a feasibility study using limited brine interception, geochemical analyses and modeling. We will also conduct socioeconomic and hydrologic analyses of brine disposal strategies.

Ecosystem Dynamics and Value

***Task 2.6.* Investigate dynamic vegetation transitions in riparian ecosystems** *(Huxman, Scott, Martens, Lin, Williams, Archer, Goodrich, Stromberg, Grimm, Conklin, Brooks):* We will investigate how natural and human-induced transitions between different riparian vegetation structures influence hydrological, ecological, and biogeochemical processes. Measurements of sap flow, carbon/water isotopes, vadose zone water content, soil nutrients, vegetation tissue chemistry, and trace gas fluxes will be taken to complement ongoing micrometeorological flux measurements in grassland and mixed grassland/mesquite ecosystems in the riparian corridor. Supplemental irrigation experiments will be conducted to investigate how precipitation may be utilized differently across this vegetation gradient. This effort will build on the SAHRA riparian mesquite tower and leverage towers provided by T. Huxman. The goal is to develop fine-scale vegetation succession/transition simulation models and biogeochemical models that describe fluxes and pools of C, N, and H_2O across vegetation transitions/states. Riparian vegetation cover maps produced by the Army from 2000 through 2008 will document the extent of riparian-area vegetation changes. Complementary work will be conducted for the basin floor (see task 1.3c).

***Task 2.7.* Investigate non-market value of riparian ecosystems** *(Brookshire, Stewart, Stromberg, Goodrich, Brand, Maddock):* Value estimates of riparian ecosystems are lacking and demand-side management models typically do not include non-market components. Building on ongoing collaborative research involving economists and physical scientists, we will examine the multi-attribute nature of riparian ecosystems in the presence of significant spatiotemporal feedbacks with other system components. A disaggregated non-market demand model for water will be constructed (using choice-based conjoint analysis) to account for natural system changes resulting from economic actions, and integrated into the river system model. A bird diversity/population production function will be developed and coupled with a behavioral model to determine aesthetic, recreation, and existence values, given alternative mixes of riparian characteristics. The commodity to be valued for different user groups will be defined through focus group participation. Ground-based measurements of riparian area quality will be linked with remote sensing data to provide GIS-referenced maps. Econometric models will estimate impacts of riparian proximity and quality to home values. Extensions to the Mexican side of the border will also be pursued (tasks 5.2 and 5.6).

A3. Regional Scale Hydrometeorology

Regional water resources planning requires estimates of the regional water budget and prediction of the natural system's responses to water balance perturbations, along with assessments of the uncertainty in such estimates. Critical elements in such assessments are precipitation (rain and snow) and evapotranspiration. However, in the mountainous SW U.S., surface-based observations are limited by spatial heterogeneity and by topographic blockage of rainfall radar. SAHRA has prioritized the development of satellite remotely sensed methods and regional modeling approaches for estimating these variables by addressing three main science questions:

- To what extent can satellite-based precipitation estimation meet the spatial/temporal resolution requirement for hydrologic applications in the semi-arid regions?
- To what degree can one achieve a higher level of accuracy as compared to the current techniques, in estimating snow accumulation in high elevations of SW U.S. using satellite-based data in conjunction with surface measurements?
- To what extent will the use of satellite-based information results improve the ability of regional climate models to simulate precipitation anomalies in semi-arid region?

Given the relative complexity and large size of the problem, resources are being leveraged from a number of other projects supported by NASA and NOAA.

Achievements
Ongoing research has emphasized: a) developing the means to estimate the quantity and spatial distribution of rainfall using satellite data, radar, and ground measurements; b) developing tools for estimating spatially distributed snow accumulation and snow melt in seasonally snow-covered catchments; and c) adapting a regional climate modeling system to synoptic and climatological characteristics of the SW U.S. Progress to date is documented in the publications listed in section IX. Two noteworthy achievements are:

- Near real-time estimates of precipitation at 6-hourly and 0.25° resolution are being produced over the SW U.S. using infrared and microwave data from 11 satellites processed by the PERSIANN algorithm (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Network) [*Sorooshian et al.,* 2000; *Gupta et al.,* 2002*; Hsu et al.,* 2002]. A pilot study showed that the precipitation product is approaching levels of accuracy suitable for driving a distributed land surface water and energy balance model.
- A real-time global-to-regional climate modeling system, the Global Spectral Model-Regional Spectral Model-Variable Infiltration Capacity (GSM-RSM-VIC) macroscale model is under development [*Han and Roads,* in review; *Roads,* in review; *Chen and Roads,* in preparation]. The output data are routinely archived and continually re-analyzed. The modeling system simulates and predicts synoptic and climatological characteristics of the SW U.S. for use in scenario analyses.
- A strategy has been implemented for improving SWE estimates and modeled streamflow using an 8-year data set of 1 km^2 gridded SCA that we developed from remote sensing data for the SW U.S. [*Bales, et al.,* in preparation]. Methods for assimilating this spatial data into hydrologic models have been tasked in the Rio Grande headwaters.

Plans for ongoing research
SAHRA research priorities related to this section for the renewal phase will continue to benefit from substantial leveraging with other funded projects.
***Task 3.1.* Improve spatiotemporal resolution of precipitation estimates using remote sensing and climate modeling** *(Hsu, Gao, Imam, Sorooshian, Gupta):* Multiple sources of remotely sensed information will be integrated to compensate for high spatiotemporal variability, and processed using cloud classification techniques to improve the current 12 × 12 km and hourly estimates. Information from surface sources (rain gauges, radars) will be assimilated to develop a 4 x 4 km product. Product evaluation will be done using independent test regions containing dense networks of rainfall gauges. We will also aim to separate rain from snow. This data will be used to investigate (for the SW U.S.) the adequacy of model cloud microphysics to represent cloud thermodynamics and radio-transfer processes detectable by multi-channel remote sensing. While satellite-based estimates interpret cloud spectral images using regression or simplified radio-transfer models, cloud microphysics is based on dynamic, thermodynamic, and radio-transfer conditions. By investigating this gap, we will seek insights into the cloud microphysics of semi-arid region precipitation, improved ways to model precipitation, and methods to assimilate remotely sensed data.

***Task 3.2.* Improve modeling of SW U.S. regional climate** *(Roads, Gao, Hsu):* We will continue development and refinement of the GSM-RSM-VIC global-to-regional climate modeling system, for simulating and predicting synoptic and climatological characteristics of the SW U.S. PERSIANN estimates of precipitations (task 3.1) will be used to guide model improvements. This research will also take advantage of the North American Monsoon Experiment (NAME) of the CLIVAR program that is currently being conducted.

***Task 3.3.* Estimate regional snow properties** *(Bales, Miller, Fassnacht, Hsu):* We will develop improved estimates of snow cover properties in mountain areas of the SW U.S. using a combination of remote sensing and ground-based data. SCA time series will be developed from MODIS products, and combined with energy balance modeling to estimate spatial SWE. Canopy corrections will be based on vegetation classification from remote sensing (MODIS and ETM) and spot checks on the ground. ETM data will be used to validate SCA. SWE will be validated using permanent measurement networks at test basins and in campaigns.

***Task 3.4*. Study the regional feedbacks between soil-moisture, precipitation and evapotranspiration** *(Sorooshian, Hsu, Gao, Hendrickx, Roads, Gupta):* MODIS daily cloud free images (1 x 1 km resolution) will be processed using appropriate algorithms (e.g. SEBAL) to estimate the spatial distribution of components of the energy balance (latent heat, sensible heat and net radiation) and used to correlate the evaporation fraction with the effective soil moisture in the root zone. The ET estimates will be used to estimate regional and basin scale water balances (see also task 1.2b). The regional distribution of effective root zone soil moisture will be used to study the feedback mechanism between soil moisture and precipitation distribution at regional and basin scales. This task will also benefit from leveraged interactions with NAME and the GEWEX Americas Prediction Project (GAPP).

A4. Integrated Basin Modeling

The primary functions of integrative modeling are to provide a formal framework for integrating the research findings of SAHRA investigators and to evaluate scenarios that describe potential future changes in the Rio Grande, San Pedro, and other basins. These scenarios project physical (including climatic), socio-economic, and/or institutional stresses and prescribe changes in model boundary conditions. Given the complexity and multidisciplinary nature of SAHRA and the scope of the modeling endeavor, considerable dialogue has been required to arrive at a workable structure for coordinating model development. A series of workshops and meetings has resulted in a consensual framework, and a core modeling team now provides leadership and structure. Novel elements include a unique multi-resolution approach, models specifically suited for semi-arid areas, and integration between the physical and behavioral models at different scales.

Achievements to date

Considerable progress has been made, as described below. Publications are listed in section IX. Some noteworthy achievements include:

- A scenario-driven approach has been adopted for design of the integrated modeling, to ensure that the models include the important processes. Each scenario generates a series of questions that must be answered, thereby defining the requirements for model structure and content. The initial scenario selected for integrated model development is a 1950's-style drought, given current demographics and use within the Rio Grande from its headwaters to the Texas – New Mexico border.
- In response to community debate regarding appropriate spatiotemporal resolutions for basin-scale integrated models, a three-resolution approach has been adopted. A set of complementary models is being developed and will be evaluated against a predefined set of benchmarks to provide insight into this issue. At "coarse resolution," a systems model will represent the river basin as a linkage of lumped features with uniform properties. The "medium resolution" (1-12 km/sub-daily) and "high-resolution" (~100 m/sub-hourly) models are both grid-based with spatially distributed model parameters and model forcing. The initial focus of the integrated modeling will be the Rio Grande basin.
- All the models will be based on the same general conceptual (perceptual) framework representing the important interactions to be included for the Rio Grande (Figure 4.1). This framework allows the physical system and human behavior components to be developed in parallel, with clear agreement on linkages through land use, engineering, and monitoring.

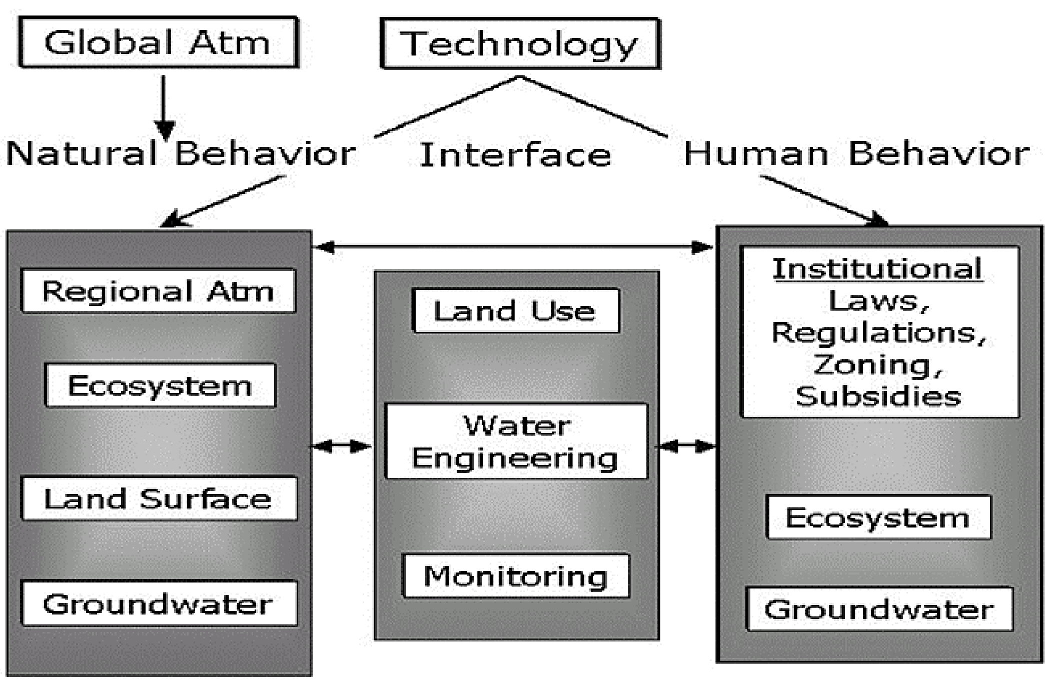

Figure 4.1 – Conceptual model of the Rio Grande for SAHRA integrated model development.

• Discussions among SAHRA social scientists, economists and hydrologists have shown clearly that a common list of definitions is critical to communication. The slow process of arriving at a consensus on conceptual model structure has resulted in considerable cross-disciplinary education of all parties involved. Also, a review of integrated modeling systems under development internationally is being undertaken to ensure best possible use of existing research into the linking of model structures from different disciplines.

• The MMS/PRMS modular hydrologic model produced stream discharge forecasts in 21 headwater basins of the Rio Grande that were significantly better than empirical forecasts currently used by water resource managers [*Gorham,* 2002]. Inclusion of spatial snow information [*Bardsley,* 2002] and multi-criteria optimization also provided significant improvements [*Boyle et al.,* 2002]. A 10-year pilot study on vegetation representations in MMS/PRMS applied to snow-covered headwater areas yielded significantly different streamflow estimates, with a reclassified 30-m product giving the best model result [*Dressler et al.,* 2001].

• A dynamic simulation water resources planning model of water supply and demand in the Albuquerque region through the year 2040 has been developed in collaboration with Sandia National Labs. (Figure 4.2). The Middle Rio Grande Water Assembly intends to use this model to evaluate and compare management and conservation options for achieving sustainable water use.

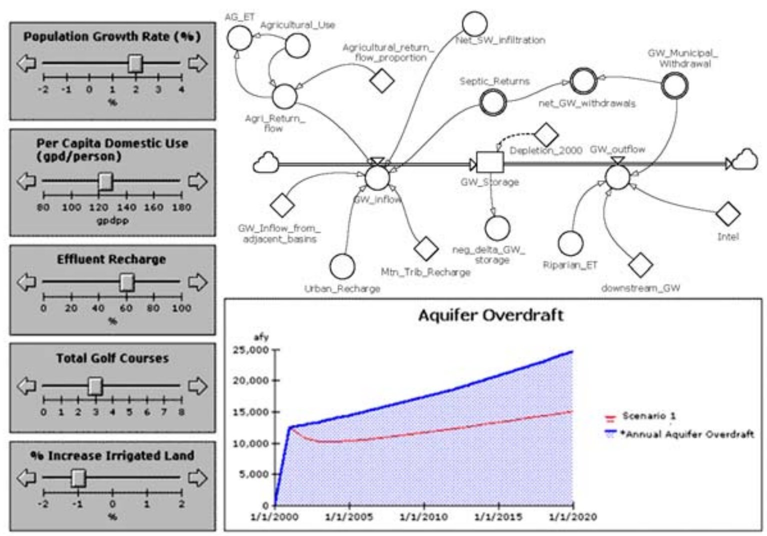

Figure 4.2 – Dynamic simulation model of the Albuquerque water system. Shown are examples of user-controlled variables (left), graphical relationship between model variables (top) and model output comparing different scenarios.

• A NOAH land surface model of the San Pedro river basin (at ~12 km and ~4 km spatial resolutions) has been implemented on a parallel computing machine to evaluate model sensitivity to grid size, temporal resolution, and parameter estimation, using MM5 forcing and remotely sensed data including SAHRA satellite-based precipitation [*Yatheendradas,* in preparation].

• The Los Alamos Distributed Hydrologic System (LADHS) surface hydrology model has been coupled with the Finite Element Heat and Mass (FEHM) variably saturated multiphase code and the RAMS Model [*Pielke et al.,* 1992] and implemented using the LANL PAWS (Parallel Application Workspace) linking software to run on massively parallel computers. Initial simulations for the Rio Grande using nested RAMS grids sizes of 80, 20, and 5 km show increased precipitation accuracy as grid cell size is decreased [*Costigan et al.,* 2000].

• A rigorous, novel approach has been developed to quantify uncertainty in stochastic partial differential equations that depend on the nonstationary random fields that appear in simulations of physical systems. This approach will lead to improved estimators and tighter bounds on uncertainty arising from stochastic simulations of systems states and parameters [*Winter and Tartakovsky*, 2001; *Tartakovsky and Winter*, 2001].

• A physics-based approach has been developed to couple between hydrologic regimes for the stream aquifer interface [*Murray and Winter,* 2003]. Boundary conditions applicable for any stream-aquifer interface have been derived from first principles, and can be simplified based on the Reynolds and Froude numbers. In special cases the boundary conditions reduce to a simple difference between pressures in the steam and aquifer, which is the current approach used in most models. The coupling approach has application to other interfaces such as land surface and atmosphere.

- *Parameter estimation tools:* Previous work on multi-criteria parameter estimation under uncertainty is being extended to distributed and coupled model environments [*Khodatalab et al.,* in review]. Testing of a land-atmosphere model shows increased parameter sensitivity in coupled mode and significant potential for enhanced model accuracy [*Liu,* in preparation]. Testing has shown that the commonly used carbon exchange model needs correcting to work in semi-arid mixed C3/C4 environments [*Hogue*, in preparation]. New optimization algorithms, Shuffled Complex Evolution Metropolis (SCEM) and Multi-objective Shuffled Complex Evolution Metropolis (MOSCEM) have been developed for probabilistic parameter estimation [*Vrugt et al. (a&b),* in review]. These tools are recently finding wide acceptance at the international level through GEWEX and other organizations.

Plans for ongoing research

Major gaps currently limit our ability to integrate feedbacks between physical and behavioral models (including proper representation of vegetation dynamics in semi-arid conditions), which are important to predict and understand river basin changes in energy and water balances across a river basin. Algorithms and tests to compare the three model resolutions are needed to assist both users and scientists in understanding the value of the different resolutions in solving their problems. The initial scenario selected for integrated model development is a 1950's-style drought, given current demographics and use within the Rio Grande from its headwaters to the Texas-New Mexico border.

***Task 4.1.* Improved operational forecasting in the upper Rio Grande** *(McConnell, Boyle, Leavesley, Markstrom, Bales, Gao, Sorooshian, Gupta):* This task will focus on precipitation distribution issues, snowmelt processes, surface water studies, and linkages to water resource management models. PRMS and MODFLOW will be coupled by leveraged USGS activities to provide a semi-physical, distributed hydrologic model calibrated and operating in the Rio Grande headwater basins. This model will be used: a) as a test bed for new modules obtained from other SAHRA process studies; b) to evaluate climate and management scenarios; c) to assimilate the spatial data products into the model and evaluate the impact of this assimilation on predicted streamflow; and d) provide current state-of-the-art model results to evaluate the multi-resolution models that are being developed in Tasks 4.4, 4.5 and 4.6.

***Task 4.2.* Couple behavioral and physical models** *(Nijssen, Brookshire, Chermak, Stewart, Bastidas, Gupta, Woodard, Wagener):* The "medium resolution" model will be coupled with an engineering module and the behavioral/institutional model and applied to scenario analysis (Figure 4.1). Coupling will occur at designated locations along the Rio Grande. Water flows and groundwater pumping will be supplied by the physical/engineering module to the behavioral/institutional model. The latter will then determine water uses and transfers to be fed back to the physical model. This integration of physical and social sciences into a single model represents a significant step for water resources systems, and the experience gained is expected to guide development of more robust interfaces.

***Task 4.3.* Perform scenario evaluation** *(Springer, Nijssen, Bales, Wagener, Gupta, Bastidas, Gao, Winter, Brookshire, Chermak, Sorooshian, Duffy, Costigan, Woodard, Roads):* Initially, the medium and fine resolution models will be compared using weather data for 1998 to 2000 derived from remote sensing products and the *Mauer et al.* [2002] data set to assess performance against observations of stream discharge, groundwater levels, snow cover (section A.1) and evapotranspiration (section A.1), providing indications of the ability to reproduce spatial and temporal patterns of behavior. Model evaluation and improvements will be assessed using a variety of scalar and multi-criteria methods [*Gupta et al.,* 1999]. The approach will be designed to enable comparisons of results from models of widely differing complexity and data and computational requirements. The scenario evaluation will simulate the Rio

Grande for a 1950's-style drought for all three model resolutions. Land conditions will be current (late 1990's) and basin-wide, model-forcing data will be from *Mauer et al.* [2002] for the 1950's period. Results from the three models will be compared and contrasted to look for trends in the response of the Rio Grande basin to the scenario. These results will provide SAHRA with a first look at how integrated research and modeling can be used to diagnose the future of a large river basin. A critical process that has been identified by SAHRA research is vegetation shifts (see sections A.1 and A.2). A study of available dynamic vegetation models such as MAPSS [*Neilson, 1995*] will identify a model and determine the logical approach to bring the important process of vegetation change into the integrated models.

<u>Task 4.4.</u> Enhance the medium-resolution model *(Nijssen, Bastidas, Gupta, Sorooshian):* Three activities comprise this task: 1) mesoscale moisture redistribution, 2) variable-resolution implementation of the medium resolution model, and 3) methods for parameter and uncertainty estimation. In the mesoscale moisture redistribution activity, an improved mesoscale flow routing model will be developed such that: river flows can be routed on a sub-daily time step; withdrawals and diversions can be specified for each reach; dams and reservoir operations can be specified for network nodes and reaches; and streamflow hydrographs can be obtained at all nodes and for all reaches in the river network. We will investigate the importance of representing lateral moisture distribution through the subsurface by interfacing a regional groundwater model (MODFLOW) with the NOAH and/or CLM land surface model. SAHRA research (section A.1) suggests that cell size in land surface models of the semi-arid SW U.S. should be of variable size, linked to the inherent heterogeneity and scale of terrain, vegetation, and hydrologic processes. The variable-resolution implementation of the medium resolution model activity will investigate a model structure that represents more detail in areas of hydrologic activity (e.g., groundwater recharge along the mountain front, and surface-groundwater interactions along the riparian corridor) while preserving mass and momentum exchanges across the grids. The methods for parameter and uncertainty estimation activity will explore issues related to parameter estimation for land surface models in coupled mode at local and regional scales. The SCEM and MOSCEM algorithms that provide simultaneous estimates of model parameters and their uncertainty will be adapted and applied to coupled distributed environment.

<u>Task 4.5.</u> Enhance the fine-resolution model *(Winter, Wilson, Phillips, Springer, Costigan, Fasel, Mnewski, Zyvoloski):* This task will consist of two activities: 1) vadose representation for high-resolution models and 2) high-resolution representation on parallel computers. SAHRA has identified the importance of two-phase flow in determining recharge in semi-arid areas and the desert floor in particular (section A.1). In the vadose zone representation activity, FEHM will be evaluated for its ability to represent deep vadose zones in the Rio Grande basin by: a) complete representation by FEHM; b) development of a parametric relationship using FEHM; and c) one-dimensional vertical columns. Computation demand for a), and the scale and spatial representation for b) and c) will be evaluated in coordination with tasks under section A.1. Use of massively parallel architectures involves a balance between the domain size placed on each processor and the amount of message passing between processors. Processor use can be maximized and calculation speed enhanced by sequencing operations based on topography. The high-resolution representation on parallel computers activity will investigate the optimal number of grid points that a single processor can accommodate without passing messages for solution and an efficient approach for implementing the model for an entire basin, thereby gaining insight into the optimal implementation of hydrology on high performance computers.

<u>Task 4.6.</u> Coarse resolution/dynamic simulation modeling for decision support *(Tidwell, Woodard, Lansey, Valdés, Yeh, Gupta, Brookshire, Chermak, Goodrich, Duffy, Wagener, Hogan, Valdés):* SAHRA will develop dynamic simulation models (DSMs) for the Rio Grande and San Pedro basins that integrate key aspects of water supply and demand, water quality, and economic costs and values to evaluate scenarios as outlined above. This modeling effort serves to integrate SAHRA science findings, especially those related to water quality and socio-economic factors, and provide an effective means for sharing scientific understanding of basin behavior with stakeholders and decision-makers. The integrated model will be developed in a series of stages as knowledge gaps are filled. Initial development is focused on two efforts: a) a water resources planning model for the city of Albuquerque that incorporates our understanding of water demand for the region; and b) a salinity model for the Rio Grande basin above El Paso that incorporates our understanding of salinity sources and riparian water balance. By focusing first on these efforts we will be able to evaluate how potential scenarios may affect salinity levels or whether proposed water conservation measures will result in actual water savings. As experience and knowledge are gained, the differing perspectives/modules will be integrated into a model that reflects the multiple perspectives. Anticipated stages of model development involve integrating nutrient dynamics (task 2.4), controls on riparian ET (task 2.1), market and non-market economic valuation (task 2.7), socio-demographic trends (tasks 1.4a and 5.2), optimal allocation models, improved understanding of groundwater-surface water interaction (task 5.4), and a physically based dynamical model (linked to GIS) to evaluate basin-wide changes (e.g., vegetation change impact on water balance and groundwater recharge) (see also task 5.6). This task is also related to task 5.3.

A5. International Collaboration

Rapid growth along the U.S.-Mexico border is increasing demands on the region's already limited surface and groundwater supplies. Mexico also reflects a worldwide trend in the privatization, decentralization, and restructuring of water management that is providing many new challenges and opportunities for sustainable water management in semi-arid environments. Improved management of shared binational water resources requires a multidisciplinary and multinational research effort. This effort aims to promote an integrated binational water management policy that takes into consideration the issues and concerns of stakeholders and fills critical knowledge gaps among scientists and stakeholders, including information about climate variability and change, and water quality. This work will a) increase access to hydrologic and policy information on both sides of the border to improve decision-making related to sustainable development of water resources, and b) conduct focused research projects to develop tools that address surface water and groundwater sustainability across the border region.

Achievements to date

Results to date are modest and partly reflect our desire to engage in projects where we have developed strong collaborations with Mexican researchers and have secured funding for their participation.

- An NSF "Glue Grant" is supporting collaboration between researchers from SAHRA, the CREST center at California State University, Los Angeles, and Universidad Autónoma de Ciudad Juárez. A variety of isotopic tracers were used to study recharge rates, groundwater flowpaths and mechanisms of salinization of the Hueco Bolson aquifer, which serves the binational El Paso - Ciudad Juarez area. Recent analyses unexpectedly revealed that Juárez and El Paso have distinct recharge sources and appear to link predevelopment recharge in Mexico to an extra-basinal source of water, a result with important implications for the sustainability and management of the aquifer and the water supplies of the two cities [*Eastoe et al*., 2002; *Hibbs et al.,* 2002].
- SAHRA sponsored and participated in the Scientific Committee of the First International Symposium on Transboundary Water Management (http://www.transboundarywatersmexico.org/congress.htm), held in November 2002 in Monterrey, Mexico, through several invited presentations and panels. The proceedings [*Aldama, et al., eds.,* 2002] contain more than 65 papers.
- SAHRA played a major role in fostering the formation of the Asociación Ambiental de Sonora-Arizona (ARASA) stakeholder organization in the Mexican portion of the San Pedro and aided in organizing and facilitating several binational meetings of U.S. and Mexican stakeholders.

• SAHRA lobbied for designation of the San Pedro as one of the first four (and the only binational) UNESCO HELP (Hydrology for the Environment, Life, and Policy) pilot basins. This designation recognizes effective integration of science with policy and decision makers for watershed management.

• SAHRA researchers and collaborators have completed a preliminary analysis of the implications of the restructuring of water management in Mexico that demonstrates how water users in urban and rural areas are responding to the changed environment for decision making [*Wilder,* 2002].

Plans for ongoing research

***Task 5.1.* Promote binational basin coordination** *(Varady, Browning-Aiken, Romero, Liverman, Goodrich, Woodard, Sorooshian, Bales, Brookshire, Chermak):* To encourage adoption of an integrated binational water management policy, we will develop three activities that foster increased dialogue between water stakeholders and increased integration between scientific researchers on the Mexican and U.S. portions of shared water resources.

1) Survey rural and domestic water users and water managers about current water management practices and economic valuation of water use in the Mexican portion of the San Pedro and assess the need for additional climate and water information.

2) Promote further collaboration between Mexican and SAHRA scientists regarding water policy and hydrologic research. In particular, develop a community forum and conduct four to five binational dialogues (workshops) on water and climate issues with San Pedro basin watershed groups (Upper San Pedro Partnership [USPP] and ARASA).

3) Investigate Mexican water policy changes and their potential impacts on binational basin management and on supply and demand in the Mexican portion of the San Pedro Basin with a policy paper as a product.

***Task 5.2.* Characterize water demand for Mexico** *(Brookshire, Valdés, Varady, Stewart, Browning-Aiken, Aparicio, Hidalgo, Velasco, Chermak):* The IMPLAN input-output model will be used to calculate regional economic effects of changes in water allocation in the lower Rio Grande/Rio Bravo. We will investigate how water deliveries to the agricultural and manufacturing sectors affect the level of output, employment, and wages in those sectors (primary effects) and in other sectors of the economy (secondary effects). The model will build on disaggregated market demand work conducted in the Albuquerque region, modified based on surveys to identify the unique nature of the border region economy. The primary and secondary effects coefficients from the input-output model will be incorporated into the joint IMTA (Instituto Mexicano de Tecnología del Agua)/SAHRA dynamic simulation model for the Rio Grande/Rio Bravo/Rio Conchos. Non-market demands for ecosystem values developed for the Rio Grande and San Pedro river systems will also be adapted using benefit transfer techniques.

***Task 5.3.* Develop a drought management model** *(Valdés, Aparicio, Stewart, Hidalgo, Velasco, Chermak):* SAHRA will collaborate with IMTA to develop a cross-border decision support tool for drought management in the Rio Conchos and Rio Bravo/Rio Grande basins. An existing system dynamics model, developed by IMTA for the National Water Commission of Mexico, simulates hydrologic/climatic, technological, demographic, normative and infrastructural scenarios for the Mexican portion of the Bravo/Grande basin. It will now be extended into the U.S. and enhanced in terms of hydro-climatology, additional detail in the economic component, and addition of incentive-based components such as water banking and trading. Simulations including hydrologic profiles, ecosystem variability, changes in irrigation technology, and changes in management regimes within the basin will inform decision makers of changes that could increase water supply or manage demand for water in the short- and long-term for the whole watershed on either side of the border. The model will also help Mexican decision makers address water deficits due to drought conditions under the International Treaty of 1944.

***Task 5.4.* Investigate recharge, groundwater flowpaths and salinization of the Hueco Bolson aquifer** *(Hibbs, Eastoe, Granados, Ekwurzel, Hogan):* A number of routine and cutting edge isotopic and geochemical tracers will be used to investigate recharge rates, groundwater flowpaths and mechanisms of salinization to develop a better conceptual understanding of the binational Hueco Bolson aquifer which serves El Paso, Texas, and Juárez, Chihuahua. Specifically, oxygen, hydrogen and noble gas isotopes will determine recharge sources; tritium and carbon-14 will determine residence times and constrain recharge rates; and sulfur, strontium, and chlorine isotopes will identify salinity sources and potential mechanisms of salinization. Of particular interest is the dynamic role of the Rio Grande as a source of recharge to the aquifer and the Hueco Bolson as a source of salinity to the river system. Isotopic and geochemical results will be used to constrain and improve existing groundwater models of the Hueco Bolson.

Task 5.5. ***Investigate salinity sources in the Rio Grande/Rio Bravo*** *(Hogan, Phillips, Hendrickx):* As an extension of our salinity research, we will investigate the cause of the recent 10 to 40 ppm/yr increase in TDS on the Rio Grande/Rio Bravo below El Paso/Juárez [*Miyamoto et al.,* 1995]. In conjunction with the USGS-NASQAN program and Mexican universities, we will collect limited geochemical data to constrain potential salinity sources. We will then develop (in collaboration with task 5.3) a dynamic simulation model using the geochemical data and existing hydrologic data, in order to investigate the cause of the recent salinity increase and to evaluate potential management options. The results will be relevant to improved management of this shared U.S. - Mexico water resource and will be used in the model developed in task 5.3.

Task 5.6. ***Develop an evolving basin assessment tool for water management*** *(Goodrich, Woodard, Yeh, Lansey, Maddock, Gupta, Bastidas, Stromberg, Dixon, Huxman, Archer, Schaap, Brookshire, Conklin, Shuttleworth, Chermak, Sorooshian):* We will continue to develop a multi-use bilingual integrated basin assessment tool to meet the needs of water planners, policy makers and educators throughout the San Pedro basin (in both the U.S. and Mexico). The foundation for this long-term effort will be four models of various components of basin hydrology that are relatively mature and have been specifically parameterized for the San Pedro: MODFLOW for groundwater, AGWA for surface water, a riparian ET model, and HYDRUS-2D for the vadose zone. As other components under development by SAHRA become mature, they will be integrated. Works in progress include a dynamic simulation model of the Sierra Vista sub-basin, a multi-objective optimization of the groundwater model, a model of riparian vegetation condition as a function of hydrologic characteristics, biogeochemistry and nutrient cycling, societal valuation of the physical system, and inputs and constraints on the basin system resulting from legal or institutional rules; see sections A.1 and A.2. Work will initially focus on coupling the physical and ecological models at basin locations where natural coupling is strongest (riparian corridor and secondarily in ephemeral channels).

Task 5.7**.** ***Pursue relevant education and knowledge transfer activities*** *(Woodard, Valdés, Sorooshian):* Education and knowledge transfer activities that currently support international collaboration include Water News Watch (www.sahra.arizona.edu/newswatch), which summarizes global water stories in seven languages. SAHRA will work with UNESCO and other organizations to add more languages and otherwise enhance this service. Relationships with research centers in North Africa (Morocco and Egypt) will be actively developed. We also plan to adapt the Masters of Engineering degree for practicing water professionals developed by SAHRA for the Army Corps of Engineers (www.iwr.usace.army.mil/iwr/planningcapabilities/arizona.htm) to meet the needs of junior faculty from Universidad Autónoma de Nuevo Leon and Universidad de Sonora–Hermosillo.

A.6. Data and Information System

Archiving the large amounts of data produced by SAHRA research and making that data available in appropriate forms requires an investment well beyond what was conceived and budgeted in the original proposal. However, we find it imperative to develop an online data archive to serve this immediate need.

In the future, the same system may also serve as a clearinghouse for the sharing of software tools, algorithms, tutorials and other knowledge relevant to SAHRA participants. We also plan to seek leveraged funding to develop a Web interface that will provide one-stop access for others interested in SAHRA scientific products and knowledge transfer activities.

Achievements to date

- System design and resource needs have been identified, and implementation will begin in 2003.
- Prototype tools for a Web interface have been developed, with leveraged funding (http://hydis.hwr.arizona.edu/).
- A prototype Web portal for serving software and algorithms to the scientific community has been developed (http://www.sahra.arizona.edu/software).

Plans for ongoing research

Task 6.1. ***Data archive*** *(Gupta, Bales, Imam, Sorooshian):* An online archive of data and model results for SAHRA investigators and other scientists will be maintained, similar to archives set up as part of other NSF projects (e.g., LTERs). Both point and spatial data will be included. The archive will include Federal Geographic Data Committee (FGDC) compliant metadata for every data set. We will aim to make metadata consistent with the Earth Science Markup Language (ESML) when the ESML schema version 1.0 is released.

Task 6.2. ***Database and web site for visualization and knowledge exchange*** *(Imam, Woodard):* Through leveraged funding, we will continue to develop a Web-based mapping application for display and distribution of spatial data. An ArcIMS (Internet map server) application will be developed to visualize essential spatial data sets (e.g., elevation, hydrography, soils, hydrologic response units) for SAHRA researchers. It will be supported by an ArcSDE (spatial database engine)/Oracle database. The system will also feature a "data-to-knowledge" system in support of local to regional interpretation and synthesis, hypothesis testing, and modeling. This will include online tutorials, algorithms and critical papers on the role of the conceptual model, model calibration strategies and forecasting, as well as data mining. Links and guidance for tools such as neural networks, principal components analysis, signal processing, genetic algorithms, optimization, and high performance computing for large-scale modeling will be provided.

Task 6.3. ***3-D hydrostratigraphic model*** *(Duffy, Springer):* Seed money will initiate the construction of a 3-D hydrostratigraphic model for the Rio Grande basin, and an external proposal submitted for full model development. The geologic framework model will be constructed using measured stratigraphic sections, new and existing borehole data, cuttings and cores. It will also incorporate topographic, soil, and geologic maps. This geologic framework model will provide important geometric, stratigraphic, and hydrologic controls for computational meshes for the surface and groundwater flow and transport modeling efforts, and for the development and refinement of the basin perceptual model (section A.4).

A7. Technology and Equipment

SAHRA aims to further the development, adaptation, and improvement of technologies that advance the study of water, energy, and nutrient exchanges. Key efforts that address technology development can be grouped into five categories: 1) investment in necessary capital equipment; 2) development of new technologies or techniques; 3) adaptation of existing technologies; 4) provision of continuity of expertise for the use of advanced technologies; and 5) identification of unfulfilled measurement needs.

Achievements to date

- An eddy covariance tower and micrometeorological network have been installed and are currently operational in a sky island subalpine forest. Tower data will be integrated with that from flux towers at complementary regions to understand and expand the impact and the utility of our data [*Brown-Mitic et al.(a&b),* in preparation].
- SAHRA researchers have developed a new method of quantifying infiltration and recharge in deep arid vadose zones using the cosmogenic isotope ^{32}Si [*Einloth, et al.,* 2002]. This isotope has a 140-year half life and thus is a potentially useful tracer for processes on the 100 to 1000 year time scale, a time scale for which there are few other available tracers [*Ekwurzel*, 2003].
- Self-contained temperature loggers (e.g., TidbiTs, Onset Corporation) have been successfully adapted to monitor the timing and duration of streamflow in ephemeral channels in the SW U.S. Due to their low cost, durability, and high data storage capacities, these devices are an excellent augmentation to stream gauging by traditional methods [*Lawler et al.,* in review].
- A low cost flowmeter/datalogger system was developed through hardware and software modification of consumer handheld computers (PDAs) connected to reed switch flow meters. The PDA loggers are planned to be used for representative time-usage sampling of production wells in the upper San Pedro basin.
- The combined use of stream gauge measurements, auto-samplers, and novel pressure sensors measuring sediment scour and fill integrated through a datalogger, allows researchers to record biogeochemical and morphological characterization of flow events at the reach scale [*Huth et al.(a&b)*, in preparation; *Hamblen et al.,* in preparation].
- Borehole ground penetrating radar (BGPR) has shown promise as a method for monitoring water content changes with high temporal and spatial resolution to great depths. SAHRA researchers [*Ferre et al*., in review; *Rucker and Ferré*, in review] have advanced the application of BGPR to water content monitoring under highly transient conditions. This will allow for direct monitoring of water storage changes due to groundwater-surface water interaction and plant root uptake.

Plans for ongoing research

Advances in remote sensing technologies have revolutionized our understanding of water exchange at the basin scale. Similar advances are needed at scales relevant to the description of physical and chemical processes that control the interaction of surface and subsurface water bodies or the movement of water through deep vadose zones. Ongoing research within SAHRA has demonstrated the need for methods that will provide measurements of: water pressure in the vadose zone; water flux throughout the subsurface; direction and magnitude of water flux between the surface and the subsurface; and chemical transport into and out of gravel bars.

Task 7.1. ***Continue testing and development of automated hydrologic measurement and data collection system*** *(Conklin, Bales):* The application of technological advances to measurements at the river reach scale is emergent. We will continue the integration of separate hydrologic chemical and sediment sensors into a self-contained, self-triggering, wireless network that can continuously and adaptively monitor water storage, sediment scour/fill, nitrate, dissolved organic carbon, pH, conductivity, dissolved oxygen and other conditions at the reach scale. Particular emphasis will be given to biogeochemically active stream locations (e.g., gravel bars).

Task 7.2. ***Methods for determining infiltration in rocky soils*** *(Ferré):* Conventional time-domain reflectometry and water content reflectometry are inadequate for accurate measurement of infiltration in mountainous rocky soil. We will investigate semi-empirical tools/methodologies to resolve this problem.

Task 7.3. ***Deployment of a micro-hydrometeorological network in the upper Rio Grande*** *(Small, Springer, Shuttleworth, Bales, Brown, Petti):* Using seed money from SAHRA and by seeking leveraged funding, we will seek to deploy a dense network of hydro-micrometeorological stations in a small watershed in the headwaters of the Rio Grande. The network will be located in representative vegetative cover and operate in conjunction with intensive snow and soil surveys. The network is intended to provide validation for spatially distributed modeling efforts in the basin.

***Task 7.4.* Acquisition of scintillometer equipment** (*Hendrickx, Petti):* Leveraged funding will be sought for the acquisition and installation of scintillometers at three sites (wet, dry, and intermediate), in conjunction with eddy covariance and Bowen ratio equipment. The equipment will be used to assess SEBAL over large areas, including large irrigated sites.

***Task 7.5* Automated, real-time optimization of infiltration monitoring** *(Ferre, Warrick):* Electrical resistance tomography instrumentation continues to advance rapidly, offering the possibility of monitoring transient processes such as infiltration and solute transport into gravel bars. Ongoing research within SAHRA [*Furman et al.,* 2002; *Furman et al.,* forthcoming] has shown that fundamental improvements to the design and interpretation of ERT surveys are necessary to make full use of this technology. We will extend this research leading to optimal application of this technology through expert systems.

B. Education

Issues
There is an urgent need for water literacy among all citizens [*National Research Council*, 1993], especially in the SW U.S. As described above, semi-arid regions of the U.S. are experiencing above-average rates of population growth and development, and are therefore faced with the critical problem of how to support sustainable development and, in particular, how to provide sustainable water resources. Key issues faced by such regions include managing the water supply (quantity and quality) and protecting ecosystem health. Achieving sustainability of water resources in semi-arid regions depends on optimal management of water resources and the rational implementation of public policy. Such efforts cannot come to fruition without educating all stakeholders, especially those from underrepresented groups, about the science of semi-arid hydrology.

Achieving SAHRA's vision of developing and implementing an integrated, multidisciplinary understanding of the hydrology of semi-arid regions requires a broader public comprehension and consensus on the critical issues before us. Thus, SAHRA's educational programs are focused on developing hydrologic literacy among many stakeholder groups. Fully realized, greater literacy will result in the application of sound hydrologic principles to water management problems and wider participation of both individuals and communities in water-related issues (e.g., conservation and growth). Additionally, SAHRA is committed to reaching a diverse audience and thus to increasing the participation of underrepresented groups in science and policy. We anticipate that women, Hispanics, and Native Americans will be key players in our effort to improve the current state of water management and operations throughout the SW U.S. and Mexico. Thus, many of our efforts seek to improve the hydrologic literacy and technical capabilities of regional high school students, who are predominately Hispanic, and of tribal members.

In order to attract capable and motivated students, SAHRA is actively promoting hydrologic literacy among precollege teachers and students. To be most effective with this audience, the content and instruction of SAHRA's educational efforts are aligned with the recommendations of the National Science Education Standards [*National Research Council,* 1996] and the Benchmarks for Scientific Literacy [*American Association for the Advancement of Science*, 1993]. These documents guide our emphasis on interdisciplinary understandings of science and inquiry learning.

Achievements
In pursuit of these goals, we have initiated an ambitious, multifaceted approach to educational outreach with the help of numerous collaborators and by successfully leveraging resources. Our initial plan was divided into three primary client/user groups: undergraduates, graduates, and teachers. This plan has evolved over the last three years into the SAHRA Education Matrix (see Figure B.1) of five user/stakeholder groups in four program themes. The four themes were defined early during our first year to help describe and organize the common characteristics among our efforts. While many of these initiatives clearly link a given user with a theme, they cannot begin to show the many secondary connections to a broader audience of users or to the many themes each is capable of expressing. Each of these programs is described below with the approximate numbers of participants impacted per year indicated in parentheses.

Who / What	Graduate Students	Undergrad Students	K-12 Teachers	High School Students	K-8 Students
New Curricula	Grad. Seminar	Arizona Water Issues		SPLASH	Biosphere 2 Passport to Learning
	Hot Topics				
	Neoliberalism Seminar				
Professional Growth	*MSEng*	*CREST Centers**	Inquiry and Water Issues	SACNAS*	AZ Prop 301
	Tribal Watershed Workshop*				NAU Tribal Education*
Research Experiences	Research Assistantships*	Research Experience for Undergraduates*	**Teacher Research**	HS Interns	*Data Networks*
					GLOBE
Extended Learning	Outreach Opportunities		*Web site*	Res. Mentors ------------ CATTS	*Flandrau Science Camp**
			ECOSTART*		

Figure B1. Matrix of Educational Activities (interactive version at www.sahra.arizona.edu/education/) (dark background = leveraged; *italics* = new programs; underline = past programs; **bold** = future programs; * = programs specifically targeting diversity)

New Curricula allow us to take Center-related education and research findings or ideas and present them to appropriate audiences. State-of-the-art science and policy ideas are incorporated in several all-new courses taught by our researchers. In some cases, not all the material is new but the courses materially benefit from Center activities, discoveries, or collaborations. Overall, approximately 20 graduate students and 100 undergraduate students (taught by 8 SAHRA-related faculty members), and 100 to 200 high school students (taught by 6 to 10 SAHRA-affiliate teachers) benefit from these curricula. Evaluation of these courses indicates that undergraduate students are developing a multidisciplinary understanding of semi-arid water issues with an orientation toward action [*Hancock (b),* in preparation] and that teachers develop more sophisticated conceptions of scientific activity [*Hancock (a),* in preparation].

- *Graduate/SAHRA Seminar (HWR696L)* (8 students/yr.) – This seminar has been offered at UA annually since 2001.
- *Hot Topics in Surface Water Hydrology (HWR696F)* (12) – This seminar is being offered at UA beginning in the spring 2003 semester.

- *Arizona Water Issues (HWR203)* (100) – This course for undergraduate non-science majors has been offered at UA two times each year since 2000.
- *SPLASH (Student-centric Program for Learning About Semi-arid Hydrology)* (5 teachers, 150 students) – This modular high school water curriculum is in the developmental phase with five teachers working on the development team. Pilots and implementation will begin during the 2003/04 school year.
- *Neoliberalism and Globalization of the Environment (LAS 595)* (15) – This new seminar explores the impacts of economic restructuring and new policies on environmental management in Latin America with a particular focus on water.
- *Biosphere 2 Passport to Learning (2000)* – SAHRA supported Biosphere 2's development of middle school water science curricular materials.

Professional Growth programs develop career pathways or stakeholder "pipelines" from one educational or knowledge level to the next. For example, water resource professionals gain new knowledge while completing advanced degrees and teachers develop updated content knowledge. Most of these career pathway projects are designed to help "prime the pump" by developing water science graduate study or career awareness.

- *M.S.Eng. (Masters of Engineering in Water Resources Management* (10) – This tri-University, M.E. program is intended for professional practitioners. It is offered at all three Arizona universities (UA, ASU, and NAU) but has minimal enrollment in Water Resources. Beginning in August 2003 we expect a major increase in enrollment as the Army Corps of Engineers has signed a letter of intent to initiate a professional development effort for many of their mid-level managers.
- *The Tribal Watershed Workshop* (8) – This workshop was a great success for the land-use managers who completed the course in its first year. A major wildfire season and changes among our collaborators' job responsibilities has sidelined this effort temporarily. The course focused on integrating aspects of watersheds to ecology and land use, and started to build tribal capacity in terms of water resource management.
- *CREST (Centers for Research Excellence in Science and Technology)* (1) –We have an NSF "Glue Grant" with the CEA program at California State University, Los Angeles and are exploring other collaborations with the new RESACCA at TAMU-Kingsville. We have implemented some research exchanges with CEA and are interested in recruiting Ph.D. candidates at both locations. The number of anticipated participants is low because we do not want to undercut the CREST Centers' advanced degree programs.
- *Integrating Inquiry with Water Issues* (5 teachers, 150 students) – Formerly known as 'Water Science' or 'Literacy Workshop', this 2-week summer workshop has been offered at UA and NMT. Mansel Nelson at NAU has also expressed an interest in hosting this course. Evaluation indicates that participants have an increased interest in using inquiry-learning and integrating hydrology in standard content [*Uyeda et al.,* in review].
- *SACNAS (Society for the Advancement of Chicanos and Native Americans in Science)* (many contacts) – We have begun to participate in the SACNAS annual meeting in an effort to communicate career information and to advertise research assistantships to these underserved communities. In particular, we are coordinating a special workshop, "Opportunities for Interdisciplinary Science at NSF's Environmental Research Centers," at the October 2003 annual meeting.
- *AZ Prop 301* (100 teachers) – SAHRA leverages funding for a water education specialist in Maricopa Co. (Phoenix; Dana Flowers) from Arizona's Prop. 301 funding and provides additional infrastructure support to the nationally recognized Project WET (Water Education for Teachers) program. Through this K-8 project, our goals are to build an early appreciation of water issues and to expose large numbers of students to water careers.
- *NAU's K-8 Tribal Water Education Programs* (30 teachers, 300 students) – SAHRA provides support for NAU's effort to reach tens of teachers and hundreds of Native American students each year. The

programs include Project WET and GLOBE materials. The summer scholars program at NAU will be expanded this summer to include more water content.

Research Experiences are among the best motivational tools for getting stakeholders from one level of knowledge to the next higher level. Research experiences tend to be personnel- and resource-intensive so participants must be selected carefully. NSF supplemental funding has allowed us to support at least a dozen REU students each year. In keeping with SAHRA's multidisciplinary efforts, these projects range from formal empirical research to data collection and analysis to technology development to innovations in water conservation. An in-progress study of SAHRA undergraduates involved in research experiences suggests that these students develop more realistic images of science research and greater enthusiasm for continuing work in their fields of study [*Austin,* in preparation].

- *Research Assistantships* (60) – Significant NSF and matching funds are distributed to M.S. and Ph.D. candidates through this mechanism, which helps support the student's academic and research interests during graduate school. There are about 60 RAs throughout SAHRA and the annual production rate should approach 8 M.S. and 3 Ph.D. degrees/yr. See SAHRA annual meeting abstracts for a sample of on-going research efforts by these students. Table B1 summarizes demographic and completion time information for SAHRA graduates.

Table B1. Years to completion of degree for graduates supervised by SAHRA researchers

			M.S.					*Ph.D.*				
			Minority, Y/N					Minority, Y/N				
	Citizenship		Male		Female			Male		Female		
Name	US	other	N	Y	N	Y	Yrs	N	Y	N	Y	Yrs
Brookshire	2	0	0	0	0	0	0	1	0	1	0	4
Ferre	2	1	3	0	0	0	3	0	0	0	0	0
Gupta	0	2	2	0	0	0	3	0	0	0	0	0
Hendrickx	0	1	1	0	0	0	2	0	0	0	0	0
Liverman	1	0	0	0	0	0	0	0	0	1	0	5
Luft	1	0	0	0	0	0	0	0	0	1	0	5
McConnell	2	0	1	0	1	0	2.5	0	0	0	0	0
Phillips	1	0	0	0	0	0	0	0	0	1	0	5
Sorooshian	2	1	0	0	1	0	2	1	0	1	0	5
Stromberg	1	0	1	0	0	0	3	0	0	0	0	0
Varady	2	0	0	0	1	0	4	0	0	1	0	5
Winter	1	0	0	0	0	0	0	0	0	1	0	5
Total	15	5	8	0	3	0	2.8 avg	2	0	7	0	4.8 avg

Note: An additional 9 students (2 Ph.D., 7 M.S.) will graduate in May 2003.

- *Research Experiences for Undergraduates* (15) – SAHRA has leveraged additional funds to support local undergraduates' participation in summer research projects. We also provide support for non-hydrology students, as many other members of our student body have creative ideas, penetrating insights, and serious questions about sustainable water resource management.
- *Teacher Research* (5) – This new effort for Summer 2003 is intended to attract a few teachers to the UA Hydrology Department's annual snow and summer field camps. Participants will complete projects on using research skills in the classroom.
- *High School Interns* (7) – We select local high school students to help support various research efforts

using leveraged funds. Projects are related to SAHRA research and have included programming PDAs and field testing an innovative household water data logging system. Most interns have enrolled at the UA upon high school graduation and are majoring in science or engineering disciplines.

- *Data Networks and GLOBE, Global Observations to Benefit the Environment* (25 teachers, 325 students) – The Center is leveraging considerable resources here because both Washburne and Bales are also GLOBE science PIs. Our strategy is to develop GLOBE school networks in SAHRA research basins to collect baseline and background environmental data that can be integrated into our research. The first network was set up along the Rio Grande (9 schools measuring salinity); networks are currently being developed in the San Pedro and in the cross-border region (with ECOSTART).

Extended Learning and Community Service Opportunities allow our students to interact with a wider community of stakeholders than is typically possible on a college campus.

- *Outreach Opportunities* (20) – This informal and voluntary community service effort allows SAHRA-supported students to experience outreach through a range of structured activities. These include mentoring science fair students, supporting all-day school field trips, and simple demonstrations for a Daughters on Campus day event.
- *Web site* (www.sahra.arizona.edu/education/main/) – Our education web site has been redesigned to meet the needs of our various education audiences. Key features of the site are information on programs for teachers and students, and links to interactive Web pages created for knowledge transfer.
- *ECOSTART* (20 teachers) – In collaboration with the Udall Center, we have supported this cross-border environmental education and capacity building effort. Most funding for this is leveraged from other sources. Both GLOBE and Project WET materials are being made available to border (mostly Mexican) schools. Approximately six other organizations are involved in this collaboration, including Hands Across the Border and the Arizona-Sonora Desert Museum.
- *Research Mentors and CATTS, Collaboration to Advance Teaching Technology and Science* (6 teachers, 120 students) – As opportunities arise, SAHRA scientists and students mentor high school students working on individual research projects. SAHRA participates in the University of Arizona's CATTS program, which is funded by the NSF GK-12 program. CATTS Fellows work closely with teachers and classes implementing water science education.

Diversity and International Development are critical elements of many of these programs. While many of SAHRA's educational efforts were developed with the aim of expanding or improving the Center's impact on all members of our community, there are several focused efforts that address diversity issues directly. *NAU's K-8 Tribal Water Education Programs*, which are funded in part by SAHRA, provide training and support for environmental education in tribal schools throughout Arizona. Our involvement supports the dual goals of advancing hydrologic literacy among all stakeholder and increasing the participation of underrepresented groups in science. The *Tribal Watershed Workshop* takes SAHRA research to a different group of stakeholders: tribal water and land use managers. By integrating aspects of watersheds to ecology and land use, the workshop builds tribal capacity in terms of water resource management. *ECOSTART* addresses the needs of residents (mostly Hispanic) of the U.S.-Mexico border region, educating local adult and student communities about environmental issues and the critical role water plays in the environment. *SPLASH* will introduce the 25% Hispanic student population in Arizona to career opportunities in hydrology and water resource management. *Fellowships and exchanges* are available for Mexican graduates and professionals for pursuit of advanced degrees or training. The *World Laboratory Fellowship* provides funds for 3 to 4 exceptional candidates each year from developing countries to initiate their degree programs. After a year, we develop follow-on funding. This is a significant and successful international professional development/KT program.

Plans
During SAHRA's second five years, our primary goal is to refine and broaden or extend the delivery of these programs with special consideration of three key issues: high quality professional development for teachers, increasing attention to water science in high school curricula, and diversity.

An important part of SAHRA's work will continue to be with K-12 teachers. Any effort to provide professional development for teachers must be guided by high quality models, which emphasize projects that are long-term, collaborative, and linked to practice [*Darling-Hammond,* 1997]. Professional development for science teachers must also include the nature of science, knowledge of content, and professional social interaction [*Rhoton and Bowers,* 2001]. Beyond the professional development experience, we have found that providing teachers with support for implementation is critical. For these reasons SAHRA's continued interaction with teachers will incorporate more of these principles with emphasis on maintaining supportive relationships with teachers.

As we have pursued educational projects during SAHRA's early years, the critical need for inclusion of hydrologic literacy and water science in high school courses has become apparent. Achieving this is especially difficult because of the current pressures on schools from state and national accountability efforts. In the SW U.S., these efforts involve high-stakes tests that currently emphasize mathematics and language skills to the exclusion of earth and social sciences. Another challenge to the inclusion of water issues in high schools is the traditional curriculum structure, which emphasizes specific content areas such as physics or chemistry with little interdisciplinary work. This situation subsequently makes it difficult to recruit high school students into undergraduate hydrologic sciences programs. Awareness of these challenges will guide future efforts to have a greater impact on high school curricula and students.

Another educational challenge SAHRA faces is increasing the diversity of participants at all levels, especially in undergraduate and graduate enrollment. We are in the process of critically reviewing our impact in diversity against disciplinary and industry trends and best practices. The outcome of this review will be a comprehensive self-assessment and set of diversity challenges to all levels of our organization. So far, more resources have been allocated to developing career pathways for area minorities (Hispanics and Native Americans) and to increasing the number of women in our graduate programs.

Programs for Graduate Students – We plan to expand our offerings for graduate students to include a course that emphasizes the complexity of the San Pedro basin. That complexity moves beyond basic hydrology to include natural, social, economic, and institutional considerations. The course will produce a more interdisciplinary understanding of the San Pedro basin that will ideally be applied to research in the San Pedro and similar semi-arid basins. Approximately 10 graduate students are expected to take this course.

Programs for Undergraduate Students – Arizona Water Issues (HWR203), a general education course for non-science majors, will be improved based on the findings of ongoing evaluation. We are expanding our collaboration with NAU and CREST centers at California State University, L.A. (CEA) and at Texas A&M in Kingsville (RESACCA) to attract more undergraduate minority students to SAHRA. Our REU program will be modified to actively recruit minority students and students from local community colleges. Based on early findings of research on our REU program [*Austin,* in preparation], we will institute monthly colloquia meetings for students and mentors so that they may more clearly articulate hydrologic content and science research culture. We anticipate continuing to support 15 REU students annually.

Programs for K-12 Teachers – Most of our teacher workshops have been in a development mode but are now ready for wider distribution and greater enrollments. This will be achieved through better advertising, presentations at teacher conferences, and a greater emphasis on how inquiry and hydrologic science can be integrated into existing physics, chemistry, biology, and environmental science and mathematics courses. Our goal is to achieve annual attendance of 15 teachers per workshop, reaching a minimum of 450 students. A new SPLASH workshop will reach 5 to 10 teachers and 150 to 300 students annually. Considering the guidelines for teacher professional development, we will be adding follow-up components to all teacher workshops with stipend money attached to monthly meetings during the school year following workshop participation. In future years, we plan to expand our offerings by making the Inquiry and Waters Issues and SPLASH workshops available throughout Arizona and in parts of New Mexico and by developing advanced versions of the workshops for previous participants. To support this effort we will recruit education personnel support in New Mexico. SAHRA researchers at UNM are already engaged in professional development activities in collaboration with the Albuquerque Public Schools. We will expand our new teacher research program to include five preservice and early service science teachers annually. We also plan to hire a preservice or early-service teacher to run the summer camp for middle school students described below.

Programs for High School Students – As mentioned, we face challenges in making water science part of high school curricula. In order to meet this challenge, we will facilitate the inclusion of water in high school science curricula collaboratively with high school teachers by making presentations at teacher meetings, networking with teachers, modifying our programs to meet the needs identified by teachers, advertising more widely, and updating our education web site. Members of SAHRA's educational team are building networks to become more actively involved in district and state level decision-making about science education. Our plans to offer Research Experiences for Teachers (RET) for preservice and early service teachers is designed to work around the traditional science structures in schools by fostering recognition of, and experience with, water science in new teachers. We plan to continue our high school internship program at UA and to expand its implementation at SAHRA's partner institutions, roughly doubling its annual impact. We are also continuing our involvement with UA's CATTS Fellows Program (GK-12 grant) to increase the direct involvement of undergraduate and graduate science students in high school science classrooms to facilitate implementation of water science. While none of SAHRA's partners have GK-12 funds, we plan to support similar fellowships at partner institutions to provide the human resources needed to sustain the teaching of hydrologic literacy in high school classrooms in the SW U.S.

Programs for Elementary and Middle School Students – Much of SAHRA's early efforts with students in grades K-12 have been with pre-existing programs such as GLOBE and Project WET, which both have quality materials and lengthy track records of success. We are pursuing additional funding in collaboration with other water education projects from Arizona's Proposition 301. Current options include creating permanent exhibits in public places with field trip support and mobile exhibits that can be used in schools, and providing human and material support for the implementation of GLOBE and Project WET. These efforts will increase our collaboration with state water agencies and Arizona Cooperative Extension. SAHRA researchers at UNM have begun developing and testing protocols for hands-on water demand simulations (closely linked to SAHRA research) that elementary and middle school teachers can use in their classrooms. Combined, these projects have the potential of impacting hundreds of students. New Mexico Tech currently supports a network of schools on the Rio Grande collecting water quality data. This network will be expanded in size and scope to be more useful to SAHRA scientists. At the UA, we are collaborating with the Udall Center and the Bureau of Applied Research in Anthropology to leverage funds for the development of similar networks on the Santa Cruz and San Pedro Rivers. Our plans for these networks include working with 10-20 teachers and 300-600 students on the development and implementation of student inquiry. During the summer of 2003 we will initiate the first summer camp for middle school students on the hydrology of the Tucson Basin, with an emphasis on the summer monsoon. This leveraged activity is a collaborative project with UA's Flandrau Science Center. Current plans are to provide partial scholarships and transportation for low-income minority students. Future camps will facilitate student development of research projects for science and engineering fairs that continue beyond the camp experience. We anticipate the camp will impact 45 students annually.

All Educational Audiences – We are improving and expanding our educational web site to reach a wider audience and support implementation of water education programs. Future improvements will include refined lesson plans and the addition of hydrologic data that can be used by students and other stakeholders. As SAHRA's relationship with stakeholder groups has grown, it has become apparent that our educational activities must address specific knowledge gaps and misconceptions. We will use surveys to identify these needs in guiding the content of our educational and knowledge transfer activities.

Diversity – Meeting our diversity goals of encouraging the enrollment of underrepresented groups in postsecondary science degrees and advancing the hydrologic literacy of all stakeholders has been a challenge. We are currently developing a diversity plan to guide and strengthen our efforts. That plan will include targeted recruiting and scholarships for graduate enrollment, sepecific undergraduate REU opportunities, greater involvement with CREST centers, greater participation with other university minority programs, and encouraging tribal participation in watershed cooperative groups. Many tribes in the Southwest employ water and natural resource scientists who are graduates of the institutions involved in SAHRA. We will formalize our relations with these individuals to increase recruitment of tribal students into our programs.

Education and SAHRA Science – The need to extend education to the public and policy makers in order to fill knowledge gaps and dispel misconceptions is apparent to SAHRA scientists. To facilitate integration of cutting edge SAHRA science with decision-making, four specific education/knowledge transfer activities will be developed. They are: 1) creation of a San Pedro Seminar that helps graduate students to understand the complexity of the San Pedro River basin, moving beyond basic hydrology to include natural, social, economic, management, and institutional considerations; 2) creation of interactive educational kiosks that educate the public about water science, semi-arid hydrology, and riparian systems in SAHRA's research basins. These will be created and installed in Arizona and the Rio Grande in New Mexico; 3) continuation and expansion of SAHRA interactions with San Pedro and Rio Grande stakeholders and decision-makers such as the Upper San Pedro Partnership, to refine the bi-directional interaction between stakeholder needs and SAHRA research. The dialogue will be linked with efforts to engage ARASA and other Mexican stakeholders to participate in and understand the research on both sides of the border on the San Pedro; and 4) application of SAHRA's dynamic simulation modeling efforts for education.

Evaluation and Research – We have used surveys of teachers participating in workshops, interviews with undergraduates participating in research experiences, and qualitative accounts accompanying requests from stakeholders for educational support to evaluate and improve our programs. We recently completed and began implementing a comprehensive evaluation plan for SAHRA's education and knowledge transfer programs. This primarily involves identification of baseline knowledge and learning outcomes through a survey instrument administered to participants in SAHRA's education and knowledge transfer programs. The instrument includes items to assist in formative evaluation to guide future program implementation. Another feature of the evaluation program is the use of qualitative and interpretive tools such as interviews to achieve greater depth in our understanding and to consider our education and knowledge transfer programs through the lenses of quality educational practices (such as inquiry-learning) [*Hancock and Washburne,* in preparation]. Protocols articulate data collection, analysis, and communication procedures. The evaluation plan is an integral part of SAHRA's overall strategic plan.

C. Knowledge Transfer

Achievements
In its first three years, KT activities have evolved from a focus on sharing information among SAHRA's geographically dispersed, multidisciplinary PIs, students, partners and cooperators to providing a growing set of services to a wide range of regional and global audiences. See Figure 1 below:

With Whom / What	SAHRA & Partners	Water Professionals	Basin-Based Public	National/Int'l. Public
Web Resources	Intranet Project management	News Watch Water Quotes	Bibliographies Documents	Conservation Hse Glossary services
Informal/ Experiential		Mobile Display & Kiosks	Sabino Kiosk Rural WRCs	Biosphere 2 Disp. Tohono Chul Park
Skills Development	Workshops	M.Eng. (described in Education)	Conflict Resol. Training	
Pubs, Confs, Broadcasts	Annual Meeting	Indian Water Rights Book	Newsletter Media Briefs	AAAS SoundPrint

Figure 1. Knowledge Transfer Activities matrix (shaded area represents shared resources)
An interactive version is at http://www.sahra.arizona.edu/kt/.

SAHRA's Intranet contains many Web-based data management tools that are used extensively to facilitate communication and reduce time spent on reporting and other management tasks. Each SAHRA participant is assigned an appropriate level of access to a variety of administrative and database utilities. The appearance of the main Intranet page accordingly varies by user, based on the assigned administrative level or responsibilities. An example is the *Research Projects Management* system, initially developed for streamlining annual reporting, which provides PIs and individual researchers an interface to document research progress, submit timely reports, manage project participant information, and upload project presentations and publications. Other data management tools on SAHRA's Intranet include Web-based forms for a growing number of databases, including the *Water News Watch* submission software, a directory of contacts, calendar manager, photo database utility, PowerPoint slides gallery, quotes manager, glossary, sound catalog, and bibliographies. The Intranet also includes tools for tracking real-time usage for the web site, Sabino Canyon Kiosk, and Rural Water Resource Centers. We also monitor real-time data flows from instrument towers (e.g., Mt. Bigelow) and joint SAHRA/USGS/Forest Service data for the Sabino Canyon Kiosk and Web site. *'Workgroups'* is a set of software tools developed to facilitate research projects by groups of geographically scattered researchers. The hardware side to this includes a network of videoconferencing rooms, now at UA, ASU, New Mexico Tech and UNM.

Web-based resources for broader audiences, including regional, national and international, attract over 10,000 web site visitors per month, more than double a year ago. A major resource is *Water News Watch* (www.sahra.arizona.edu/newswatch), which now covers seven languages (English, Spanish, French, Italian, Portuguese, Farsi and Greek), and includes summaries of over 4,000 articles in 13 categories from 136 countries. The home page highlights high-profile stories and recent developments. Other services for broad audiences include glossary services and water quotes. Some Web content targets particular audiences. The *Isotopes in Hydrology* site contains information for those interested in applying isotopes to hydrologic studies; the new education site meets the needs of K-12 educators; the *Residential Water Conservation* house has information for homeowners looking to reduce water consumption; *Basin Bibliographies* are for those interested in water issues in particular river basins. The *Calendar and Directory* are for persons searching for particular SAHRA events or people.

Displays and electronic kiosks at various public venues provide numerous informal, experiential education opportunities. In addition to SAHRA's traveling displays, touch-screen kiosks and posters, we have supported development of a riparian display at *Tohono Chul Botanical Park* (300,000 visits/yr.) and a large sand tank aquifer model at *Biosphere 2* (20,000 visitors/year). *New Rural Water Resource Centers* have been established in Cochise County (Upper San Pedro River) and Yavapai County (Verde River). Two more are being developed. Displays, kiosk, and web site for *Sabino Canyon* represents our most ambitious effort to date, integrating research and KT through the use of real-time data and live video. By sharing resources with the Forest Service and USGS, we have the opportunity to increase the hydrologic literacy for 1.4 million visits per year. See www.sabinocanyon.arizona.edu/.

Media briefings and science radio have reached even wider audiences. SAHRA is co-hosting with UA's Institute for the Study of Planet Earth a series of targeted media briefings on drought-related issues, including: Tucson, July 22, '02; Phoenix, Aug. 26, '02; Albuquerque, Sep. 26, '02; and Tucson, Jan. 9, '03. SAHRA also joined with USGS, the US Forest Service, and several state and local water agencies for a media briefing on National Water Monitoring Day (Oct. 18, '02). These briefings generated numerous stories and articles in newspapers and on TV and radio. See www.sahra.arizona.edu/kt/media.

The AAAS recorded a series of interviews with SAHRA researchers that were broadcast as part of their Science Updates series on NPR: *Water in Plants*, Jan. 25, '02; *Low-Flush Toilets*, March 18, '02; *Salty River*, April 3, '02; *Tree Torture Research*, April 19, '02; and *Snow Mapping*, May 29, '02. See http://www.scienceupdate.com. SoundPrint's NSF-funded series on Models and Forecasting on NPR stations aired *Water is Gold* on November 25, '02. In addition to providing interviews of researchers, SAHRA developed a special web site for KJZZ - Phoenix. See http://water.soundprint.org/

Professional workshops and seminars are a key KT mechanism. SAHRA has a regular seminar series for UA researchers, and conducted a State Department Senior Seminar. Short courses and symposia have covered ModFlow 2000, the North American Monsoon Experiment, and the ecohydrology of semi-arid landscapes. Workshops have been held for Indian natural resource and watershed managers, modelers, K-12 teachers, and other groups. Topics include groundwater recharge; dynamic simulation modeling of semi-arid basins; satellite-based precipitation estimates, and hydrologic modeling.

Leveraging resources with other groups gives SAHRA access to more venues, new audiences, and better displays. We have worked with the USGS, US Forest Service, SoundPrint, Tohono Chul Park, Institute for the Study of Planet Earth, Cooperative Extension, Arizona Water Resources Research Center, and a variety of cosponsors for workshops and seminars. We now receive State of Arizona Prop. 301 sales tax revenues to fund an outreach and education program with three other UA water centers.

Recruiting a Knowledge Transfer Team with complimentary skills and interests is a final achievement worth noting. Kyle Carpenter, Web designer/marketer has been joined by: Louise Shaler, polylingual Water News Watch editor (June '01); Steve Schroeder, database and PERL programmer (Nov. '01); Brad James, graphic artist and Web animator (May '02); and Mary Black, editor/technical writer (July '02). In addition, SAHRA's External Advisory Board has been strengthened by the addition of Bonnie Van Dorn, Executive Director of the Association of Science-Technology Centers (Nov. '02).

Plans

Our goals are to assure that SAHRA research is relevant to stakeholders, greatly increase the rate at which research results are made available to water managers, and raise the hydrologic literacy of policy makers and the general public. Achieving this ambitious agenda requires efficient, timely production of high-quality, reusable content delivered in multiple formats. Key to this strategy are a set of related approaches: automated gathering, processing and dissemination of data; modular construction and use of visual displays; continuous gathering and analysis of user feedback; integrating science data and results into KT content; identifying or creating venues that provide large, motivated audiences for informal experiential education; keeping water professionals current with expanded workshop opportunities; and leveraging resources.

Intranet enhancements planned or underway include *Basin Portals* containing relevant links, current projects, maps, photos, virtual field trips, bibliographies, digital books, map layering tools, and publications relevant to the basins. The capability for online *Indicators Tracking* is being developed and will be tested in early February, 2003. *Educational tools* for teachers and students will be enhanced considerably over the next few years. A *Hydrologic Software Utilities and Algorithm Archive* is nearly complete and will be used to share useful software tools with researchers globally. Automated data gathering and dissemination will be enhanced through efforts to minimize ongoing maintenance and increase sustainability through automation, appropriate tasking, and database management.

Modularity is a key concept for future KT work. Database-linked modules provide dynamic Web pages and kiosks and create strong synergies among components that facilitate the rapid combining of Web services to quickly create sites that are fresh and current. An example is our nearly complete glossary. It can be used like a conventional print glossary, to look up the definitions of terms. However, this database has additional fields that greatly increase functionality. For example, terms will have both full technical definitions and more comprehensible definitions for the general public. They also contain synonyms that are used to make keyword searches more intelligent (e.g., searches on "groundwater" also return items containing "ground water"). Automatic generation of pop-up definitions is planned. We also plan to use push, not just pull, in delivering Web content; e.g., subscribers to Water News Watch will be able to indicate topic and geographic interests and receive customized newsletters via email on a schedule of their choosing. Another example of modularity is KT/educational display modules. Self-contained hands-on displays and electronic kiosks will be used individually in some settings, in small sets as exhibits in other venues, and in larger sets as exhibitions in major science museums and visitor centers.

Feedback and monitoring of impacts will expand with more sophisticated Web and kiosk monitoring, and pre- and post-testing of seminar and workshop participants.

Science ties to KT activities are being strengthened. With more automated data collection and research results available, we will increase linkages to KT and education efforts. Examples include mountain block recharge work in Cochise County tied to displays at nearby Kartchner Caverns, isotopic work leading to a web site and featured articles in *Southwest Hydrology* [*Eastoe,* 2003; *Ekwurzel,* 2003; *Hogan*, 2003], and DSMs producing content for conservation tools and interactive models for KT activities.

Reaching large audiences with more accessible, relevant information will receive even more emphasis. Content and presentation will be attractive, eye-catching, even entertaining, through use of high-quality graphics, animation, video, sound, and real-time data. We plan to follow our Sabino Canyon displays with a larger-scale effort at the Grand Canyon (5 million visitors/yr.) with the USGS and the National Park Service. We are investigating opportunities with the Arizona-Sonoran Desert Museum (500,000 visits/year) and Kartchner Caverns (200,000 visits/yr.). We will continue media briefings in Tucson, Phoenix, and Albuquerque and improve them as we better understand reporters' interests and information and scheduling needs. We will attempt to add Arabic and Mandarin sources to Water News Watch.

The KT Team may expand slightly to handle the growing workload. New State of Arizona funding may support hiring a KT equivalent to the postdocs in other Thrust Areas; state funds may also support a stakeholder development person for Maricopa County to be shared with three other UA water centers.

Workshops and short courses will continue to meet the needs of technical groups, but also will reach broader audiences of decision makers, such as state legislators, city councils, ranchers, etc. Short courses are being planned on the topics of Indian Water Rights and Surface Water/Groundwater Interactions. In addition, SAHRA is working with the U.S. Army Corps of Engineers and three other universities to offer an accelerated professional degree in water resources planning beginning Fall 2003. Similar discussions are taking place with two Mexican universities.

Leveraging resources will be even more important as SAHRA's KT activities evolve and expand. Arizona Prop. 301 funds are anticipated to increase substantially over the next three years and beyond. Support from the USGS, National Park Service, Arizona State Parks and other agencies will be necessary to put compelling displays in venues such as the Grand Canyon. We anticipate more activities with Cooperative Extension offices. Grant proposals have been written, alone and with organizations such as SoundPrint. Emphasis must be placed on leveraging outside Arizona. We have prototyped a number of activities in Tucson, with plans to expand to Phoenix, Albuquerque, rural Arizona/New Mexico, and beyond. International opportunities are also being explored. The UN has launched the International Year of Fresh Water for 2003, and UNESCO has made water resources and supporting ecosystems its highest priority for 2002-2007. SAHRA is involved in a proposed global information network for arid lands.

D. Rationale for the Center Concept

Why is a Center necessary? The issues and factors affecting water resources in arid and semi-arid regions are very complex. To understand a river system one must integrate a great number of scientific disciplines, to study key basin processes that govern water and energy fluxes, soil moisture partitioning, river system dynamics, climate and weather, and human impacts. The scope of this effort dictates a coordinated, integrated, multidisciplinary and sustained effort by leading researchers, rather than uncoordinated, individual and independent research efforts. SAHRA has been created to rapidly synthesize and translate the current state of scientific knowledge for water resource managers by closing the loop of measurement→understanding→education/knowledge transfer→decision-making→ intervention→new measurement, etc. (Figure D.1). Our experiences will clearly have considerable influence on the way hydrologic science and water resources management are conducted in the U.S. and elsewhere.

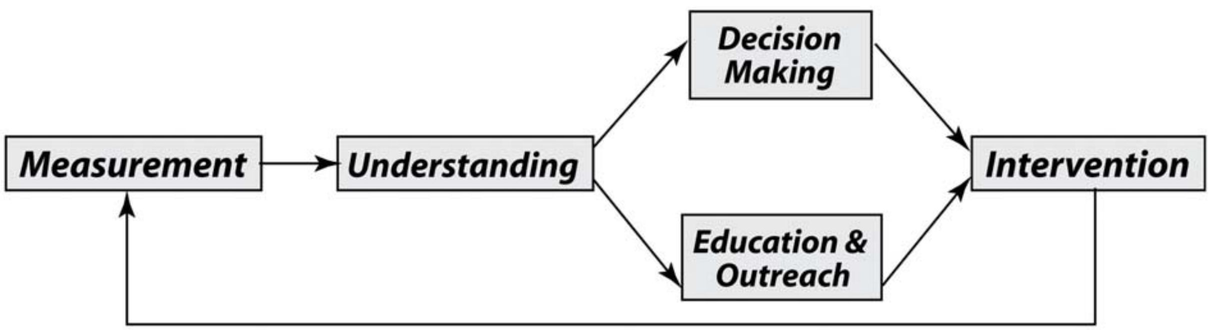

Figure D.1 – A model of science and sustainability.

What unique opportunities are provided by the Center? By virtue of its stable, long-term funding, SAHRA is able to develop and enable multidisciplinary and multi-year research efforts at the basin scale that involve the close cooperation of natural and social scientists and educators. Stakeholder input is integrated into the design of the research plan and stakeholder issues are captured in scenarios that drive research and modeling. Synergies are created when outputs from some projects serve as key inputs to other projects, resulting in a whole that far exceeds the sum of the individual parts.

What has been achieved that could not be accomplished through individual awards? The pursuit of efficient water management practices is made difficult by the highly dispersed responsibility for water resources. Such practices currently do not fully appreciate the interconnections, feedbacks, and time delays among watershed subsystems that operate over the relevant range of spatial and temporal scales. The Center concept has allowed a holistic, systems-level approach by a multidisciplinary, multi-institutional team with participants from 17 universities in the U.S. and 6 in Mexico (see section F), researchers from national labs, the USGS, ARS, and other agencies. Our integrated approach to research includes: joint definition and development of the research agenda by researchers and stakeholders; multidisciplinary teams; end-to-end integration of causes, impacts, and responses; and integration of research with education and knowledge transfer efforts.

Knowledge transfer thrives in the Center environment, in contrast with most individual research projects where KT is often an afterthought. Research results leveraged through KT efforts benefit many groups. The Center concept facilitates communication and is bringing about a truly interdisciplinary perspective among the emerging generation of researchers. Students and postdoctoral research associates enjoy unique opportunities to engage in cutting-edge research and to interact with peers at multiple institutions and organizations. New courses, career pathways, research experiences, and extended learning opportunities are attracting new talent and underrepresented populations into water -related fields.

How do SAHRA's efforts complement those at other national laboratories? ***Los Alamos Labs*** and SAHRA have several joint studies: 1) SAHRA data provide essential input to, and help validate the LANL Rio Grande Basin hydrologic model; and 2) fine-resolution integrated modeling of the Rio Grande Basin benefits science-based decision making by water managers/policy makers, supported by a $500,000/yr. match from LANL. ***Sandia National Labs*** and SAHRA continue to develop a dynamic simulation model (DSM) for water supply and demand in the Albuquerque region. Shared resources include Ph.D. fellowships and internships. The disaggregated behavioral market model is being used by the Middle Rio Grande Water Assembly to evaluate alternative water conservation and basin management strategies. The broader goal of increasing the use of DSMs for water resource management is being pursued through joint efforts such as a recent workshop for researchers using DSMs to model environmental resources, which attracted 35 scientists from 15 institutions.

E. Management Plan

Structure

The basic structure and management of the Center are as follows. The PI and Director (*Soroosh Sorooshian*) carries overall responsibility for the Center, assisted by co-PI/co-Director (*Roger Bales*) and co-PIs *(Juan Valdés*, *Diana Liverman, and W. James Shuttleworth)*. A 12-member Executive Committee (EC) (listed below) is responsible for overall planning. The EC will continue to meet at least monthly to set the vision and goals of SAHRA and oversee planning and coordination of the science, education and knowledge transfer activities. Decision-making is largely by consensus with ultimate authority and responsibility carried by the Director and co-Director. The EC will also continue to coordinate and integrate science activities, assisted by a team of full-time postdoctoral research associates (PDRAs).

The nine-member External Advisory Board (EAB, see below) will continue to provide external advice and oversight. The EAB meets at least once a year to provide feedback to the executive committee. Changes from the original EAB are as follows: *John Bredehoeft* (Hydrodynamics Group, Story, WY), *William Harris* (Biosphere 2/U. South Carolina), *Ken Schmidt* (Ken D. Schmidt and Associates, Phoenix), and *Peggy Woods* (Science Department, Amphitheatre High School, Tucson) resigned at different times during the past three years due to other commitments. *John Schaake* (NWS), *Julie Luft* (UT, Austin) and *Bonnie VanDorn* (ASTC) have joined.

The PDRAs (see below) constitute a "shadow" executive committee, and are extremely important in planning, critical self-review, cross-disciplinary integration, and coordination with other non-SAHRA funded projects and activities. They will continue to meet weekly as a group with senior researchers, to discuss ongoing science activities. Major ideas and initiatives that emerge will be presented before the EC for discussion and approval. PDRAs will change over time as individuals are promoted or move on to other jobs.

Day-to-day administrative affairs will primarily be managed by the Associate Director (*Hoshin Gupta*), two Assistant Directors (*Gary Woodard* and *Jim Washburne*) and a 10-person administrative support staff. Weekly meetings ensure communication and coordination.

SAHRA investigators will participate in several SAHRA-wide workshops and meetings each year. All SAHRA scientists, students and stakeholders will gather at the annual meeting in Tucson to meet, share and discuss scientific results, provide feedback, and conduct center-wide discussion and planning.

One of the challenges for large and sustained research programs such as SAHRA is to design a management structure that is resilient yet flexible when faced with changes in personnel and professional commitments. For example, several SAHRA researchers have moved on to other institutions or taken temporary positions of administrative leadership during our first 3 years of operation. New faculty hires and shifting faculty interests and availabilities at UA and other institutions also create new opportunities for SAHRA activities, collaborations, and partnerships. When faced with such changes, the SAHRA Executive Committee convenes with the full support of university administrators, to discuss what changes in researchers and management structure allow continuity, smooth transitions, and the best use of new personnel and linkages.

Executive Committee: *Soroosh Sorooshian* (UA, Director), *Roger Bales* (UA, co-Director, Thrust Area Leader), *Hoshin Gupta,* (UA, Associate Director, Science & Administration), *Gary Woodard* (UA, Assistant Director, Knowledge Transfer), *James Washburne* (UA, Assistant Director, Education), *Fred Phillips* (NMT, Thrust Area Leader), *David Goodrich* (USDA-ARS/UA, Thrust Area Leader), *Larry*

Winter (LANL, Thrust Area Leader), *Juan Valdes* (UA, Thrust Area Leader), *David Brookshire* (UNM, Thrust Area Leader), *Diana Liverman* (UA, International Cooperation), and *Stan Leake* (USGS).

Post-Doctoral Research Associates: *Constance Brown* (natural science), *James Hogan* (natural science), *John Villinski* (natural science), *Thorsten Wagener* (modeling), *Steven Stewart* (behavioral science), *Elizabeth Hancock* (education).

External Advisory Board: *Susan Avery* (CIRES, Univ. of Colorado), *John Bernal* (Pima County Public Works), *Peter Eagleson* (MIT), *Julie Luft* (Univ. of Texas, Austin), *Charles Howe* (Univ. of Colorado), *Devendra Lal* (Scripps Institute of Oceanography), *Harold Mooney* (Stanford University), *John Schaake* (National Weather Service), and *Bonnie VanDorn* (Assn. of Science and Technology Centers).
Center Administrative Staff: *Rannie Fox* (Program Coordinator), *Jill Gibson* (Business Manager Senior), *Kyle Carpenter* (Communications Specialist), Gabriel Lopez (Accountant), *John Petti* (Research Specialist), *Steven Schroeder* (Support Systems Analyst), *Dean Jones* (Support Systems Analyst), *Brad James* (Graphic Designer), *Mary Black* (Associate Editor), *Louise Shaler* (part-time News Watch Editor), and two work-study student assistants. Additional administrative support is provided by *Corrie Thies* (Administrative Associate to the Director) and *Cas Sprout* (Administrative Assistant to the Co-Director).

Goals of SAHRA Management
The goals of management (EC and senior staff) are to: a) implement the strategic plan developed by the EC to carry out SAHRA's mission; b) support SAHRA research, knowledge transfer and education activities; c) meet the contractual obligations to NSF; d) promote Center activities at local, regional, national, and international levels; and e) work toward post-NSF sustainability.

We will continue to update and implement our strategic plan to carry out the mission of the Center, integrating recommendations from the EAB, SAHRA science teams, SAHRA stakeholders, and the NSF oversight team. We will also implement project selection and performance evaluation procedures, continue to pursue integration of projects across disciplines and institutions, reallocate resources as needed, organize and conduct science, education and knowledge transfer workshops, and plan and conduct the Center-wide annual meeting.

We will support and facilitate SAHRA research, education, and knowledge transfer activities in several ways. This includes activities to: acquire, manage and maintain infrastructure (space, furnishings, computer systems, communication network, equipment, supplies, laboratories and field sites); recruit and maintain scientific, technical, and administrative staff; create and maintain a stimulating and rewarding work environment so stability is maintained and turnover is minimized; manage finances (budgeting, accounting, disbursement); support preparation of grant proposals to NSF and other funding sources; shift resources among partners and between research areas, based on performance and relevance of scientific issues; manage communication; manage information (collecting, organizing, disseminating); coordinate activities (meetings, workshops, report preparation, project reviews); coordinate and prepare documentation; and recruit and support students in achieving their educational and professional goals. Each year, several SAHRA-wide workshops and meetings will be held to bring researchers together across disciplines. An annual meeting in Tucson will bring all SAHRA scientists, students and stakeholders together to share and discuss scientific results, and conduct center-wide planning.

We will ensure contractual obligations to NSF are met by: coordinating and preparing reports (work plan, annual reports, continuation proposal); responding to requests for information; coordinating and conducting site visits; promoting a diverse staff and student population; and developing and maintaining necessary databases. Beyond that, we will continue to manage in a highly efficient manner the activities of over 200 people involved in dozens of projects, by: streamlining and automating processes through online forms for updating and linking databases and reimbursing expenses; expanding our intranet and improving services such as directory, calendar, and automatic tracking; utilizing performance and management indicators; and integrating and developing hardware and software to create better facilities for remote teleconferencing.

We will promote the activities of the Center at local, regional, national, and international levels, by: updating and improving our web site; providing information to the public, professionals, and the media; representing the Center at conferences, meetings, and through visits to other organizations/institutions; and participating in key local, national and international committees and research initiatives. We will also hold meetings and press conferences to disseminate information on SAHRA activities.

Finally, we will continue to work toward post-NSF sustainability by supporting proposal preparation, developing collaborative relationships with other groups, building a useful infrastructure, and developing activities that are considered valuable by the water resources community.

Proposed Plans and Explanation of Changes

The EC and management will continue to steer the Center toward bridging the gap between the current and developing scientific understanding and the tools used by water resources practitioners. We will continue to: a) pursue an integrated, multidisciplinary understanding of the hydrology of semi-arid regions, including both the demand and supply aspects of water resources and their linkages; b) build partnerships with a broad spectrum of stakeholders (public and private organizations) so that this understanding is effectively and rapidly brought to bear on the management of water resources and rational implementation of public policy; and c) develop strategies for implementing scientific understanding on a practical level through aggressive knowledge transfer and strong education initiatives (K-16 and public).

This renewal proposal reflects one important logical and evolutionary change to the SAHRA strategic plan. The original research agenda involved five loosely integrated (primarily science-focused) thrust areas and a large variety of research tasks in disparate and somewhat uncoordinated geographical locations. A thorough process, including evaluation of SAHRA activities by an "integration subcommittee," regular meetings of the EC and staff scientists, a series of workshops, and a comprehensive internal review of all science tasks, led us to conclude that a river basin/river systems focus can provide the necessary context and motivation to help identify knowledge gaps and drive the integration process. Therefore, while SAHRA scientists will continue to organize many activities around science themes, overall project coordination and budgetary decisions will be strongly coordinated around the selected river basins (Rio Grande/Rio Bravo/Rio Conchos and San Pedro/Gila) and at the scale of the regional SW U.S., to achieve stronger integration of the science. This flexible strategy, including both a "science" dimension and the emergent "river basin" dimension, already is having positive impacts on the development of SAHRA science as reflected in section III.A. Note that this strategy also promotes closer connections between the science and educational/knowledge transfer activities (as reflected in sections III.B and III.C).

We will continue to build on our successes and to learn from our difficulties, bringing creativity, maturity, leadership and integration to our activities. We will hold our staff and participants to consistently high standards and reward them for performance and teamwork, thereby maintaining a high level of morale. By insisting on a high degree of communication, coordination and co-location of research activities (responsibility for each task to be borne by multiple investigators), by directing research toward major knowledge gaps, by supporting calculated risk-taking, by promoting a diverse workforce, and by giving individual investigators sufficient responsibility and ownership for their part in the research effort, we will continue to ensure that the Center's impact far exceeds the sum of its individual parts. We believe that these experiences and successes will have considerable and lasting influence on the way hydrologic science is conducted in the U.S. and elsewhere.

F. List of Academic Participants, Industrial, and Other Partners

U.S. University Participants

1. University of Arizona

- Dept. of Hydrology and Water Resources: Roger Bales, Professor and Co-Director, SAHRA; Paul Brooks, Assistant Professor; Constance Brown, Research Associate; Martha Conklin, Professor; Brenda Ekwurzel, Assistant Professor; Paul Ferré, Assistant Professor; Xiaogang Gao, Adjunct Assistant Professor; Hoshin Gupta, Adjunct Professor and Associate Director, SAHRA; Elizabeth Hancock, Research Associate; James Hogan, Research Associate; Thomas Maddock III, Professor; Bart Nijssen, Assistant Professor; James Shuttleworth, Professor; Soroosh Sorooshian, Regents Professor and Director, SAHRA; Steven Stewart, Research Associate; John Villinski, Research Associate; Thorsten Wagener, Research Associate; James Washburne, Adjunct Assistant Professor and Assistant Director, SAHRA; Gary Woodard, Assistant Director, SAHRA
- Cooperative Extension: Deborah Young, Associate Director; Susan Pater, Director, County Extension, Cochise County; Jeff Schalau, Director, County Extension, Yavapai County
- Dept. of Agricultural and Resource Economics: Bonnie Colby, Professor; Daniel Osgood, Assistant Professor; Paul Wilson, Professor
- Dept. of Civil Engineering and Engineering Mechanics: Kevin Lansey, Professor; Juan Valdés, Professor and Head
- Dept. of Geosciences: Christopher Eastoe, Staff Scientist; Austin Long, Professor
- Dept. of Soil, Water, and Environmental Sciences: Arthur Warrick, Professor
- Flandrau Science Center: Debra Colodner, Associate Director, Education
- Institute for the Study of Planet Earth: Gregg Garfin, Assistant Staff Scientist; Barbara Morehouse, Associate Research Scientist; Jonathan Overpeck, Director
- Latin American Area Center: Diana Liverman, Professor and Director; Margaret Wilder, Assistant Research Social Scientist
- Udall Center for Studies in Public Policy: Anne Browning-Aiken, Program Manager, Environmental Policy and Community Collaboration; Robert Varady, Research Professor and Deputy Director
- Water Resources Research Center: Kerry Schwartz, Water Education Program Director

2. Arizona State University

- Center for Environmental Studies: David Lewis, Research Associate
- Dept. of Biology: Nancy Grimm, Professor and Co-director of the Central Arizona-Phoenix Long-term Ecological Research Project; John Schade, Research Associate
- Dept. of Plant Biology: Mark Dixon, Research Associate; Gabrielle Katz, Research Associate; Juliet Stromberg, Associate Professor

3. California State University, Los Angeles:

- Dept. of Biology and Microbiology: Carlos Robles, Director, CEA-CREST
- Dept. of Geological Sciences: Barry Hibbs, Associate Professor

4. Columbia University Biosphere 2: Guanghui Lin, Associate Research Scientist

5. Desert Research Institute: Douglas Boyle, Assistant Research Professor; Joseph McConnell, Associate Research Professor

6. New Mexico Institute of Mining and Technology

- Earth and Environmental Sciences Hydrology Program: Fred Phillips, Professor; Jan Hendrickx, Professor; John Wilson, Professor
- Master of Science Teaching Program, Marisa Wolfe, Coordinator

7. Northern Arizona University

- Institute for Tribal Environmental Professionals: Mansel Nelson, Senior Program Coordinator
- School of Forestry: Aregai Tecle, Professor

8. Penn State University, Dept. of Civil and Environmental Engineering: Christopher Duffy, Professor

9. Texas A&M, Dept. of Biological and Agricultural Engineering: Binayak Mohanty, Associate Professor
10. University of California, Berkeley, Dept. of Civil and Environmental Engineering: John Dracup, Professor
11. University of California, Los Angeles: Dept. of Civil and Environmental Engineering: William Yeh, Professor and Chair
12. University of California, Riverside, Dept. of Soil and Environmental Sciences: F. Leij, Associate Research Soil Physicist; Marcel Schaap, Assistant Research Soil Scientist
13. University of California, San Diego, Scripps Institute of Oceanography, John Roads, Director, Experimental Climate Prediction Center
14. University of Colorado, Dept. of Geological Sciences: Eric Small, Assistant Professor
15. University of New Mexico, Dept. of Economics: David Brookshire, Professor; Stuart Burness, Professor; Janie Chermak, Associate Professor; Kate Krause, Associate Professor
16. University of Wyoming, Dept. of Renewable Resources: David Williams, Instructor
17. Utah St. University, Dept. of Civil and Environmental Engineering: Luis Bastidas, Assistant Professor

Mexican Institutions
1. Instituto del Medio Ambiente y Desarrollo Sustenable del Estado de Sonora (IMADES): Hector Arias, Director; Christopher Watts, Professor
2. Instituto Mexicano de Tecnología del Agua (IMTA): Javier Aparicio, Head, Hydrologic Technology Coordination
3. Instituto Tecnológico de Sonora (ITSON): Jaime Garatuza, Professor of Hydrology
4. Universidad Autónoma de Ciudad Juarez:
- Secretaria General: Alfredo Granados Olivas, Coordinator of the Center of Geographic Information
- Laboratorio Ambiental: Thomas Kretzschmar, Coordinator of Special Projects

5. Universidad Autónoma Metropolitana, Campus Xochimilco: Patricia Romero Lankao, Profesora de Política y Cultura and Visiting Scholar, Center for Latin American Studies,
6. Universidad de Sonora – Hermosillo (UniSON): Alejandro Castellanos, Visiting Scientist at UA

Governmental Research Organizations
1. Army Corps of Engineers:
- Cold Regions Research and Engineering Laboratory: Robert Davis, Research Scientist
- Engineer Institute for Water Resources: C. Mark Dunning, Chief, Programs Analysis Division
- Continuing Education: Duayne Baumann, Consultant

2. Lawrence Berkeley National Laboratory, Earth Sciences Division: Norm Miller, Director
3. Los Alamos National Laboratory
- Mathematical Modeling and Analysis Group: Larry Winter, Technical Staff Member
- Atmospheric, Climate and Environmental Dynamics Group: Everett Springer, Technical Staff Member

Other Research Scientists: Keely Costigan, Patricia Fasel, Susan Mniszewski, G. Zyvoloski
4. Sandia National Laboratory, Dept. of Geohydrology: Vincent Tidwell, Senior Member, Technical Staff; Erik Webb, Manager
5. U.S. Geological Survey
- Denver: George Leavesley, Research Hydrologist; Steven Markstrom, Hydrologist; Roland Viger, Physical Scientist
- Tucson: Kyle Blasch, Hydrologist; Michael Carpenter, Hydrologist; John Hoffmann, Hydrologist; Stan Leake, Research Hydrologist; James Leenhouts, Hydrologist; Christopher Smith, Hydrologist

6. USDA Agricultural Research Service

- Tucson: David Goodrich, Research Hydraulic Engineer and SALSA Program Co-leader; Dean Martens, Soil Scientist; Russell Scott, Hydrologist
- **7. U.S. Salinity Laboratory, Riverside**: Rien van Genuchten, Research Leader; Peter Shouse, Soil Scientist; Jirka Simunek, Assistant Research Scientist

Advisory Board

- Susan Avery, Director, Cooperative Institute for Research in Environmental Sciences (CIRES)
- John Bernal, Deputy County Administrator, Pima County Public Works Dept.
- Peter Eagleson, Professor Emeritus, Water Resources Program, Massachusetts Institute of Technology
- Julie Luft, Senior Director-at-Large AETS, Associate Professor, University of Texas
- Charles Howe, Professor of Economics, Institute of Behavioral Science, University of Colorado at Boulder
- Devendra Lal (Chair), Professor of Oceanography, Scripps Institute of Oceanography
- Harold Mooney, Professor of Biology, Stanford University
- Bonnie VanDorn, Executive Director, Association of Science-Technology Centers

Industrial and Other Partners

1. Arizona Dept. of Water Resources - Kathy Jacobs and Ken Seasholes, Tucson Active Management Area
2. Arizona Hydrologic Society (AHS) - Mike Block, President of Tucson Chapter
3. Arizona Prop 301 Water Centers: Engineering Research Center for the Environmentally Benign Semiconductor Manufacturing (ERC-EBSM) (Farhang Shadman, Director), the Water Resources Research Center (Peter Wierenga, Director; Sharon Megdal, Associate Director), and the Water Quality Center (Ian Pepper, Director)
4. Arizona Project WET - Kerry Schwartz, Tucson Area Coordinator
5. Arizona White River Apache Tribe - Laurel Larcher, Tribal Hydrologist
6. Asociación Ambiental de Sonora-Arizona/Sonora-Arizona Regional Environmental Association (ARASA) - Ana Lilia Ross, Director
7. Audubon Society's Appleton-Whittell Research Ranch - Bill Branan, Director
8. Bureau of Applied Research in Anthropology, UA - Diane Austin, Assistant Professor
9. Bureau of Reclamation: Jim Cherry, Lower Colorado Office, Leslie Meyers, Arizona Projects Office
10. Central Arizona-Phoenix LTER - Nancy Grimm, Project Director
11. Cochise County, Arizona - Mark Apel, Senior Planner
12. Collaborative for the Advancement of Teaching Technology and Science - Michelle Hall-Wallace, Director
13. ECOSTART - Rene Cordova, Acting Director
14. El Paso Water Utilities - William Hutchison, Geohydrologist
15. Elephant Butte Irrigation District (EBID), Las Cruces, NM - Gary Esslinger, District Manager
16. GEWEX-CEOP - Rick Lawford, Project Manager, GCIP, NOAA Office of Global Programs
17. GLOBE - Dixon Butler, Chief Scientist
18. IAEA - Pradeep Aggarwal, Head, Isotope Hydrology Section
19. International Boundary and Water Commission (IBWC), Debra Little, Principal Engineer; Rong Kuo, Civil Engineer
20. Nature Conservancy - Holly Richter, Upper San Pedro Project Manager; David Harris, Dave Gori, Tucson Office
21. New Mexico State Engineer Office - Nabil Shafike, Interstate Stream Technologist

22. New Mexico Interstate Stream Commission - Rolf Schmidt-Peterson, Chief, Rio Grande Basin Bureau
23. Pima Association of Governments - Claire Zucker, Senior Water Quality Planner
24. Salt River Project – John Sullivan, Associate General Manager for Water; Dallas Riegle, Senior Hydrologist
25. Science and Math Education Center, UA (SAMEC) - Tim Slater, Director
26. Science Teachers and Reformed Teaching (START) - Steve Uyeda, Steve Fletcher
27. Sevilleta Long-term Ecological Research (LTER) site - Cliff Dahm, Interim Director
28. Tucson Unified School District - Barry Roth, High School Science Curriculum Specialist
29. U.S. Army, Ft. Bliss - Paul Raisch, SDWA Program Manager
30. U.S. Army, Ft. Huachuca - Gretchen Kent, Physical Scientist, NEPA Coordinator
31. U.S. Forest Service - Ron Senn, Santa Catalina District Ranger; Sarah Davis, Interpretive Staff Officer
32. Upper San Pedro Partnership - Bob Strain, Chair, Partnership Advisory Commission

G. Intellectual Property Rights

SAHRA is developing new tools for use in water resources management that will find application in both the public and private sectors. These tools include measurement methods, field equipment, computer models, and new ways of applying emerging technology; several are described in section III.A.7. Project teams developing these new tools are from multiple academic institutions and governmental research organizations. All intellectual property will be protected through patents, copyrights, and trademarks to the extent allowed by law. This does not mean that SAHRA will attempt to limit its use; to the contrary, some of it will be freely distributed, and we will work to have all of it widely disseminated and used.

Intellectual property is defined as any and all inventions, devices, processes (including without limitation processes of using devices or of manufacturing such devices), methods, compositions or products or software, whether patentable or unpatentable, and works of authorship, and related know-how conceived or first actually reduced to practice in the course of research conducted by or at the Center by its participants.

Intellectual property shall be allocated according by applicable employment contracts and U. S. Patent Law (Title 35 U. S. Code) and U.S. Copyright Law (Title 17 U.S. Code) in effect at the time the intellectual property was created. Federal agency participants' rights to intellectual property are governed by the Bayh-Dole Act. The U.S. Government has rights to intellectual property developed all or in part in the Center with the use of federal funds.

Protection and transfer of Center intellectual property shall be managed by The University of Arizona in consultation with the Center's participants. Any income to the Center, less costs to protect Intellectual property, shall be shared with inventors and developers of works of authorship according to the policies of their employers.

The Center invites participation by industry. The gateway for such participation is membership in the Center as a Collaborating Corporation. To become a Collaborating Corporation, the only requisite is to express interest in the Center by attending annual meetings. A company may become an Active Collaborating Corporation in one of the several ways listed below:

1. If a company wants to make, use, or sell intellectual property resulting from the work conducted under Center funding, it may negotiate a royalty-bearing license to do so.

2. If a company wants to support the general development of work in one of the Center's research thrusts, it may provide gift funds to support a summer student and provide a summer internship.

3. If a company wants to support a specific line of work in the Center, perhaps by working collaboratively with Center researchers, it can negotiate a research contract and acquire an exclusive option to license the Center's interests in the intellectual property that results from that research.

Any commercial license to intellectual property resulting from work conducted under Center funding is, of course, subject to the rights of the federal government.

H. Projected Funding by Source

Information is available from Jill Gibson at **jill@sahra.arizona.edu**

I. Institutional and Other Sector Support

Information is available from Jill Gibson at jill@sahra.arizona.edu

J. Shared Experimental Facilities

SAHRA makes maximum use of existing experimental facilities, making incremental additions where needed to accommodate research associated with the Center. These include computing facilities at Los Alamos National Laboratory and a dedicated cluster of shared workstation computing facilities at the University of Arizona, as well as experimental facilities at the Agricultural Research Service's Walnut Gulch Experimental Watershed, the Arizona District of the United States Geological Survey, the University of Arizona's Laboratory of Isotope Geochemistry, the Sevilleta LTER, the Center for Environmental Analysis at California State University, and the Noble Gas Laboratory at the UA.

1. Los Alamos National Laboratory
The Los Alamos National Laboratory (LANL) is well known for its expertise in advanced computing and numerical simulation of physical phenomena. The capabilities of the Los Alamos computers allow very highly resolved simulations to be performed, based on which up-scaling schemes can be designed through sensitivity experiments. The new computer at Los Alamos, built by Silicon Graphics, is capable of 10^{12} operations per second and is based on 2,048 R10K processors running at a rate of 250 MHz each. Memory consists of 512 Gbytes of RAM and 5 terabytes of local disk. Later generations of this machine will be capable of 10-100 teraflops with correspondingly larger numbers

Research at LANL includes the development of high-resolution computer models of coupled hydrologic systems, with Department of Energy funding at the level of $900K/year for 5 years. The study is designed to provide insight into how the discrete physical components of coupled hydrologic/environmental systems (e.g., atmosphere and land surface) interact nonlinearly and operate at different time and space scales. In particular, the current research emphasizes the importance of inter-domain exchanges of mass and energy, which have not previously been represented with enough detail because adequate computational resources and physical models have been unavailable. The goal is to develop a new generation of modeling tools that can be used to assess, manage, and eventually predict, the evolution of regional catchments. These tools will facilitate the study of a large variety of future environmental security issues ranging from global challenges such as CO_2 and water cycles, to local and regional problems such as fresh water supply, agriculture, and flooding.

The research at LANL addresses advances in both the computer and physical sciences, for efficient parallelization (development of a new communicating asynchronous processes alternative to the standard massively parallel computing method), data mining, numerical schemes capable of accurately representing large gradients, gridding methods capable of representing highly variable geologic media (such as those found in groundwater basins), new turbulence schemes to support high-resolution modeling, methods of scaling to assure commensurability of data passed among individual physical components, and upscaling through averaging techniques, scaling laws, and sensitivity analysis.

2. USDA-ARS Walnut Gulch Experimental Watershed
The Walnut Gulch Experimental Watershed operated by the Southwest Watershed Research Center of USDA-Agricultural Research Service in Tucson, Arizona is a premiere semi-arid experimental watershed. The watershed (roughly an 80 minute drive from Tucson) drains 150 square kilometers in southeastern Arizona and is representative of the approximately 60 million hectares of grass- and brush-covered rangeland found throughout the semi-arid southwest and northern Mexico. It lies in a transition zone between the Chihuahuan and Sonoran Deserts. The scientific instrumentation and research infrastructure at Walnut Gulch are unparalleled. Detailed experiments and long-term observations are conducted to improve understanding of semi-arid rangeland hydrology and erosion. No comparable semi-arid hydrologic database exists in the world (see http://www.tucson.ars.ag.gov).

The Walnut Gulch facility consists of 29 nested watersheds that range in drainage area from 0.002 to 150 square kilometers. Rainfall and runoff instrumentation (including 85 recording rain gauges) has been in place since 1964. Eleven of the nested watersheds are gauged for runoff with concrete supercritical flumes that are specially designed to give very accurate estimates of runoff (notoriously difficult to obtain in semi-arid regions). Extensive monitoring of erosion and sediment transport is conducted on eight of the smaller sub-watersheds. Hydro-meteorological instrumentation at two locations, one grass dominated and the other brush dominated, provide measurements of the energy balance, soil temperature, soil moisture and CO_2 fluxes. Biotic characterization has been ongoing. A high-resolution GIS database for the watershed has been created. All of the recording instrumentation is currently undergoing conversion to digital systems with telemetry for remote data transfer. The NEXRAD radar system installed by the National Weather Service at Tucson provides radar coverage. The ARS Walnut Gulch headquarters facilities outside Tombstone include soils and sediment laboratories, and workshops for electronics, machine and welding/fabrication. The facilities and instrumentation are maintained by four full-time support staff, and on-site lodging is available for up to six visiting scientists.

The Walnut Gulch watershed and the containing San Pedro basin continue to be a venue for highly instrumented large-scale multidisciplinary research and watershed characterization conducted by a variety of agencies, universities, and members of the Upper San Pedro Partnership to more accurately estimate the semi-arid water balance and understand the water needs of the first Congressionally designated Riparian National Conservation Area. Ongoing ground, aircraft and satellite data remote sensing collections continue as these watersheds serve as the primary semi-arid validation site for NASA's Earth Observing System. SPOT and LANDSAT images are being routinely archived.

3. University of Arizona, Laboratory of Isotope Geochemistry
Using isotopic tools in concert with conceptual and computer flow models, the Laboratory of Isotope Geochemistry conducts research to develop a quantitative understanding of aquifer hydrodynamics. The lab, led by Austin Long, has five full-time staff and receives funding through sample analysis in conjunction with numerous projects. At least seven SAHRA research projects currently utilize this facility at a reduced sample cost. A low level 1220 Quantulus liquid scintillation spectrometer was purchased in 2002 through funds from the NSF "Glue Grant" matched by the UA and SAHRA. This dedicated instrument gives SAHRA full-time access to investigate the use of ^{32}Si as a tracer of long-term recharge rates in semi-arid regions. The Lab's instrumentation includes six additional low-level liquid scintillation spectrometers for radiocarbon and tritium measurements, three isotope ratio mass spectrometers for measurements of the stable isotopes of carbon, hydrogen, oxygen, sulfur and chlorine, and an automated device for detecting O and H isotopes in water.

4. Arizona District of the United States Geological Survey
The U.S. Geological Survey conducts extensive research on the groundwater resources of the southwestern U.S. Many of the projects conducted by the Arizona district programs have great relevance to SAHRA's effort. In addition, scientists in the USGS National Research Program provide research tools and models that are standard to groundwater analysis and research in the United States.

The Arizona District of the USGS located in Tucson is leading a multidisciplinary groundwater project called the Southwestern Groundwater Project that is highly relevant to SAHRA. The project involves research and evaluation of the spatial and temporal variability of groundwater recharge and outflow in shallow aquifer systems. It consists of five parts: a) a regional synthesis and review of existing groundwater models, particularly those related to surface water/groundwater interactions; b) an evaluation of the effects of climatic variability on groundwater recharge and outflow; c) development of new geophysical and geochemical techniques for identifying and quantifying the spatial and temporal variability of groundwater recharge; d) development of techniques for using riparian vegetation as a tool for assessing the long term stability of shallow groundwater systems; and e) development of new tools to more realistically model the temporal and spatial variability of groundwater recharge and outflow. The 5-year project began October 1, 1998 and was funded at $1-2 million per year, in addition to existing USGS projects with state and local cooperators. The project provides several opportunities for collaboration SAHRA, including studies of ephemeral wash recharge and groundwater outflow in the middle Rio Grande basin near Albuquerque, New Mexico, and the San Pedro River National Conservation Area in southern Arizona. These investigations provide important research opportunities for students in the hydrology and ecology programs. Additionally, the USGS Arizona District office is conducting a detailed investigation of groundwater resources of the upper San Pedro River Basin. That project and SAHRA have continuing collaboration on data collection and analysis relating to the groundwater flow system.

USGS also operates the most extensive set of streamflow gauging stations in the U.S., providing an essential long-term database from which to evaluate outflow from shallow groundwater systems such as the San Pedro River. The USGS also has geophysical tools for assessing characteristics of aquifer systems. A drill rig is maintained in Menlo Park, CA, and is available to the Arizona District for drilling high-quality monitoring wells. A national database system maintains information on wells and groundwater geochemistry.

5. University of Arizona Workstation Computing Facilities
Two four-processor Sun Microsystems computers with four gigabytes of RAM, 500 gigabytes of disk space and tape changer are dedicated for use by SAHRA staff and students for modeling, data analysis, data storage, database, web and file serving. All UA SAHRA members have a Windows or Unix based desktop computer. All desktop computers are connected to the local are network at 100mb/s; servers are connected with gigabit Ethernet. The UA and HWR hold software site licenses for ESRI products (arcinfo, arcview, arcims), ERDAS imagine, Matlab, Oracle, Sun Solaris, Sun Microsystems Compilers and other scientific and utility software. These are available for SAHRA to purchase at discount rates. HWR has a PC laboratory that is available for all students to use and can be scheduled for workshops and special events. The University of Arizona provides the use of a Silicon Graphics Origin 3000 parallel processing supercomputer for numerical modeling.

6. Sevilleta LTER
This Long Term Ecological Research site (LTER) in New Mexico is used for watershed-scale and riparian research. Given its history of biological and other research, the Sevilleta has been an excellent resource for SAHRA. Major advantages to conducting research on the LTER include: a) security, since it is fenced and patrolled, b) existing instrumentation networks for measuring rainfall, solar radiation, soil temperature and moisture, wind speed and direction, and other climate variables, c) ongoing hydrologic studies, and d) available satellite data. Eric Small (University of Colorado) and Will Pockman (UNM) have obtained additional funding from DOE ($290,000 over 3 years, beginning June 2003) for water addition experiments to parallel their SAHRA-sponsored drought experiments here.

7. CEA-CREST (Center for Environmental Analysis at California State University-Los Angeles
CEA-CREST promotes the development and testing of theories predicting natural and anthropogenic changes in ecosystems, with an emphasis on southern California and the southwestern U.S. NSF, through a "Glue Grant", has recently funded a joint research program between SAHRA and CEA-CREST.

SAW Group Laboratories and Field Equipment, California State University-Los Angeles
Dr. Barry Hibbs' wet chemistry lab in the Dept. of Geological Sciences is equipped to measure the full suite of standard inorganic constituents and many trace elements. Analytical equipment includes a new Dionex DX600 Ion Chromatograph with UV detector, a Perkin-Elmer 5000 Atomic Absorption Spectrophotometer, and a Hach DR/4000 UV-VIS spectrophotometer. He also has standard hydrogeological field equipment for student use.

Geographical Information Systems, California State University-Los Angeles

The Center for Spatial Analysis and Remote Sensing (CSARS) has a total of twenty-five Pentium PCs that run Windows NT versions of GIS software with all key extensions, and various types of image processing software. Installed software packages that can be accessed from CSARS PC's through X-Windows include ArcView, Arc/Info, ENVI/IDL, Fortran, C, and JAVA compilers. The Virtual Center for Spatial Analysis and Remote Sensing (VCASRS) is a second distributed computing facility linked with CSARS. It includes numerous workstations for spatial analysis, and instrumentation devoted to remote and close-up sensing of landscapes.

8. Noble Gas Laboratory – UA

Beginning in 2003, SAHRA researchers have at-cost, priority access to a new noble gas laboratory for water samples. Housed in the Dept. of Geosciences at the UA, the lab measures noble gas isotopes, which can be used in groundwater analysis to map basin regions in terms of dominant recharge characteristics (because of the variability in noble gas signatures caused by elevation and temperature differences). Additionally, helium isotopes (^{3}He and ^{4}He) can be used to calculate water residence times for both the short term (the past several decades) and long term (thousands of years ago to extreme antiquity). These methods are currently available in only a few labs worldwide.

IV. References Cited

Albuquerque Journal, 2002*:* Dec. 6, 2002, “State drought task force urges preservation methods;” Sept. 6, 2002, “Monsoons don’t dent drought,” June 7, 2002, “Break hydro-illogical cycle.”

Albuquerque Journal, 2003: “On their minds: Business folks tell the chamber what the big problems are,” Jan. 27, 2003; “Creation of State Water Plan in Works," Jan. 28, 2003.

Aldama, A., J. Aparicio and R. Equihua, eds., Proceedings of the 1st International Symposium on Transboundary Waters Management, *Avances in Hidráulica 10*, 646 pp., 2002.

American Association for the Advancement of Science, *Benchmarks for scientific literacy,* Oxford University Press, New York, 1993.

Arizona Daily Star: Jan. 11, 2003, “Arizona looks OK for now with CAP,” by M. Tobin; July 26, 2002, “This drought’s persistent,” by M. Tobin.

The Arizona Republic: Jan. 1, 2003, “SRP cuts ‘03 water deliveries,” by S. McKinnon; Dec. 18, 2002, “Winter storm little help for water-starved West,” by S. McKinnon; Nov. 22, 2002, “Report paints dire picture of state’s future water supply,” by S. McKinnon; Sept. 9, 2002, “Colorado River not doing job: Brought just one-eighth of water needed,” by S. McKinnon

Austin, B., Challenging assumptions about scientific and hydrologic literacy: How the research experience affects undergraduates, in preparation.

Bales, R.C., B. Imam, D. Lampkin, S.R. Helfrich, and S.R. Fassnacht, Fractional snow cover in the Colorado River and Rio Grande basins, 1995-2002, in preparation.

Bardsley, T., Investigations toward understanding the spatial representativeness of SNOTEL measurements of snow water equivalence, MS Thesis, Hydrologic Sciences, University of Nevada, Reno, 2002.

Bastiaanssen, W.G.M., M. Menenti, R.A. Feddes, and A.A. M. Holtslag. A remote sensing surface energy balance algortithm for land (SEBAL). Part 1: Formulation, *J. Hydrology 212-213*(1-4), 198-212, 1998a.

Bastiaanssen, W.G.M., H. Pelgrum, J. Wang, Y. Ma, J.F. Moreno, G.J. Roerink, R.A. Roebeling, and T. van der Wal, A remote sensing surface energy balance algortithm for land (SEBAL). Part 2: Validation, *J. Hydrology 212-213*(1-4): 213-229, 1998b.

Bhark, E., and E. Small, The relationship between plant canopies and the spatial variability of infiltration in grassland and shrubland of the northern Chihuahuan desert, NM, submitted to *Ecosystems.*

Blasch, K.W., T.P.A. Ferré, A.H. Christensen, and J.P. Hoffmann, A new field method to determine streamflow timing using electrical resistance sensors, *Vadose Zone J., 1*: 289-299, 2002.

Boyle, D.P., H.V. Gupta, and S. Sorooshian, Multicriteria calibration of hydrologic models, chapter 8 of *Advances in Calibration of Watershed Models*, edited by Q. Duan, S. Sorooshian, H.V. Gupta, A.N. Rousseau, R. Turcotte, Monograph Series on Water Resources, American Geophysical Union, 2002.

Brooks, P., J. Hogan, J. Villinski, J. Schade, M. Lemon, A.K. Huth, and P. Haas, Scaling biogeochemical processes along rivers in semi-arid regions: How do point-scale processes relate to water quality at larger scales?, in preparation.

Brookshire, D.S., S. Burness, J.M. Chermak, and K. Krause, Western urban water demand, *Nat. Resour. J. 42(4):*1-26, 2002.

Brown-Mitic, C., C. Harlow, J. Shuttleworth, R. Bales, Spatial variabilities in sky island subalpine hydro/micrometeorology, in preparation (a).

Brown-Mitic, C., J. Shuttleworth, C. Harlow, R. Bales, Characterizing water, energy, and CO_2 exchange for a sky island subalpine forest in the southwestern USA, in preparation (b).

Chen, J., and J. Roads, Hydrology forecast skill for southwestern United States, in preparation.

Chermak, J., and K. Krause, Individual response, information, and intergenerational common pool problems, *J. of Environ. Econ. and Management, 43,* 47-70 2002.

Costigan, K.R., J.E. Bossert, and D.L. Langley, Atmospheric/hydrologic models for the Rio Grande Basin: Simulations of precipitation variability, *Global and Planetary Change, 25*:83-110, 2000.

Darling-Hammond, L., *The Right to Learn,* Jossey-Bass, San Francisco, 1997.

Dressler, K.A., S.R. Fassnacht, and R.C. Bales, A comparison of snow telemetry (SNOTEL) and snowcourse measurements in the Colorado River Basin, in preparation.

Dressler, K.A., S.R. Fassnacht, and R.C. Bales, Hydrologic modeling of the Colorado River Basin, Arizona: A water resources management approach, poster presentation at the *6th IAHS Scientific Assembly Symposium S2: Regional Management of Water Resources*, Maastricht, Netherlands, July 18-27, 2001.

Duffy, C.J., A distributed dynamical model for mountain-front recharge and water balance estimation: The Rio Grande of southern Colorado and New Mexico, in *Recharge and Vadose Zone Processes: Alluvial Basins of the Southwestern United States*, ed. by F.M. Phillips, J.F. Hogan, and B. Scanlon, Water Resources Monograph series, Washington, DC, American Geophysical Union, (forthcoming).

Duffy, C.J., A two-state integral-balance model for soil moisture and groundwater dynamics in complex terrain, *Water Resour. Res., 32*(8), 2421-2434, 1996.

Dunne, T., W. Zhang, and B.F. Aubry, Effects of rainfall, vegetation, and microtopography on infiltration and runoff, *Water Resour. Res., 27*(9): 2271-2285, 1991.

Eastoe, C.J., Locating recharge zones with isotopes, *Southwest Hydrology, 2*(1): 22-23, 2003.

Eastoe, C.J., B. Hibbs, A. Granados Olivas, J. Hogan, and J. Hawley, Preliminary O and H isotope data for groundwater from the Hueco Bolson (El Paso, Texas; Cd. Juárez, Chihuahua): Constraints on water sources, *Eos Trans. AGU, 83*(47), H11F-02, 2002.

Einloth, S.L., B. Ekwurzel, C. Eastoe, and D. Lal,, ^{32}Si in Wet and Dry Deposition as an input to the vadose zone, *Eos Trans. AGU, 83*(47), Fall Meet. Suppl., Abstract H21A-0792, 2002.

Ekwurzel, B., Dating groundwater with isotopes, *Southwest Hydrology, 2*(1): 16-18, 2003.

Ellsworth, P.Z., and D.G. Williams, Mesquite water sources in relation to groundwater depth across floodplain habitats in the upper San Pedro River basin, USA, in preparation.

Fassnacht, S.R., K.A. Dressler and R.C. Bales, Geostatistical interpolation of point-measured SWE in the Colorado River basin, submitted to *Water Resour. Res.*

Fassnacht, S.R., and R.C. Bales, Physiographic variables as indicators of snowpack state for the Colorado River Basin from snow telemetry (SNOTEL) data, submitted to *Water Resour. Res.*

Ferré, T.P.A., G. von Glinski, and L.A. Ferré, Monitoring the maximum depth of drainage in response to pumping using borehole ground penetrating radar, submitted to *Vadose Zone J.*

Furman, A., P.A. Ferré, and A.W. Warrick, A sensitivity analysis of electrical-resistance-tomography array types using analytical element modeling, forthcoming in *Vadose Zone Jl.*

Furman, A., A.W. Warrick, and T.P.A. Ferré, Electrical potential distributions in response to applied current in a heterogeneous subsurface: Solution for circular inclusions, *Vadose Zone Journal 1*, pp. 273-280, 2002.

Gonzalez, J., and J.B. Valdés, Bivariate drought recurrence analysis using tree ring reconstructions, forthcoming in *J. of Hydrol. Eng*.

Gorham, T., Application and evaluation of a distributed, physically based hydrologic model to improve streamflow forecasts in the upper Rio Grande basin, MS Thesis, Hydrologic Sciences, University of Nevada, Reno, 2002.

Gupta, H.V., L.A. Bastidas, S. Sorooshian, W.J. Shuttleworth, and Z.L. Yang, Parameter estimation of a land surface scheme using multicriteria methods, *J. Geophys. Res., 104*(D16):19,491–19, 503, 1999.

Gupta, H.V., S. Sorooshian, D.P. Boyle, and T. Hogue, Advances in automatic calibration of watershed models, chapter 1 of *Advances in Calibration of Watershed Models*, edited by Q. Duan, S. Sorooshian, H.V. Gupta, A.N. Rousseau, R. Turcotte, Monograph Series on Water Resources, American Geophysical Union, 2002.

Hamblen, J., I.S. Burns, and M.H. Conklin, Temporal and spatial trends in microbial metabolism and sediment dynamics in the San Pedro River, southeastern Arizona, in preparation.

Han, J., and J. Roads, U.S. climate sensitivity simulated with the NCEP regional spectral model, submitted to *J. Climate Change*.

Hancock, E., Creation of a multidisciplinary curriculum for hydrologic literacy: An applied ethnography, in preparation (a).

Hancock, E., Hydrologic literacy among undergraduate non-science majors, in preparation (b).

Hancock, E., and J. Washburne, Researching the educational activities of a science research center, in preparation.

Hendrickx, J.M.H., S. Hong, T. Miller, E. Small, P. Neville, J. Cleverly, and W.G.M. Bastiaanssen, Test of SEBAL in the Middle Rio Grande Valley. AGU abstract, Winter Meeting, San Francisco, CA, Dec. 2002.

Hibbs, B., F. Phillips, J. Hogan, C. Eastoe, J. Hawley, A. Granados, and B. Hutchison, and T. Kretzschmar, Groundwater resources of the Hueco Bolson-El Paso/Juárez area, forthcoming in *Hydrological Science and Technology.*

Hogue, T.S., Energy, water and carbon parameterizations in hydrometeorological models, with a focus on semi-arid regions. Ph.D. Dissertation, Department of Hydrology and Water Resources, The University of Arizona, Tucson, AZ, in preparation.

Hong, S., Soil salinity in non-flooded arid riparian areas, M.S. Thesis, Hydrology, New Mexico Tech, Socorro, NM, 2002.

Hogan, J.F., Isotope hydrology: Web and print resources, *Southwest Hydrology, 2*(1): 29, 2003.

Hsu, K., H.V. Gupta, X. Gao, S. Sorooshian, and B. Imam, Self-organizing linear output map (SOLO): An artificial neural network suitable for hydrologic modeling and analysis, *Water Resour. Res.* 38(12): 10.1029/2001WR000795, 2002.

Hultine, K.R, D.G. Williams, W.L. Cable, and S.S.O. Burgess, Hydraulic redistribution by deep roots of a Chihuahuan Desert phreatophyte, forthcoming in *Tree Physiology*.

Lemon, M.M., P.D. Brooks, A.K. Huth, Spatial and temporal variability in water chemistry associated with land use and hydrologic flowpaths, in the San Pedro River, AZ, in preparation.

Huth, A.K., R.C. Bales, P.D. Brooks, P.A. Haas, M.H. Conklin, and J.R Petti, A mixing model analysis of solute sources in a semi-arid stream, in preparation (a).

Huth, A.K., P.D. Brooks, R.C. Bales, P.A. Haas, M.H. Conklin, and J.R. Petti, Patterns in NO_3^- and SO_4^{-2} during monsoon floods in a semi-arid stream: Linking hydrologic pathways and nutrient sources, in preparation (b).

Khodatalab, N. Distributed hydrologic modeling for flow forecasting by using high resolution data, M.S. Thesis, Department of Hydrology and Water Resources, The University of Arizona, Tucson, AZ, 2002.

Khodatalab, N., H.V. Gupta, T. Wagener, and S. Sorooshian, Calibration of a semi-distributed hydrologic model for streamflow estimation along a river system, submitted to DMIP Special Issue of *J. of Hydrology*.

Kim, T., and J.B. Valdés, A nonlinear model for drought forecasting based on a conjunction of wavelet transforms and artificial neural networks, submitted to *J. Hydrol. Eng.*

Kim, T., and J.B. Valdés, Long-term forecasts of droughts using a conjunction of wavelet transforms and artificial neural networks, submitted to *Experimental Long-Lead Forecast Bulletin*, 2002.

Kim, T., J.B. Valdés, and J. Aparicio, Frequency and spatial characteristics of droughts in the Conchos River Basin, Mexico, *Water International, IWRA 27*(3): 420-430, 2002.

Kim, T., J.B. Valdés, and C. Yoo, A nonparametric approach for estimating return periods of droughts in arid regions, forthcoming in *ASCE J. Hydrol. Eng.*

Krause, K., J.M. Chermak, and D.S. Brookshire, The demand for water: Consumer response to scarcity, forthcoming in *J. Regul. Econ.*

Kurc, S., and E. Small, Dynamics of evapotranspiration in semiarid shrubland and grassland during the summer monsoon season, central NM, submitted to *Water Resour. Res.*

Lawler, D.S., K. Blasch, T. Ferré, and S.A. Leake, Using streambed temperature to identify perennial, ephemeral, and intermittent reaches in the San Pedro River, Southeastern Arizona, submitted to *J. Hydrol.*

Lewis, D.B., J.D. Schade, A.K. Huth, and N.B. Grimm, Influence of geomorphic type on seasonal variability of nutrient concentrations in an arid-land fluvial ecosystem, in preparation.

Liu, Y. Modeling, calibration, and sensitivity analysis of coupled land surface models, Ph.D. Thesis, Dept. of Hydrology and Water Resources, The University of Arizona, Tucson, AZ, in preparation.

Mauer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen, A long-term hydrologically based dataset of land surface fluxes and states for the conterminous Unites States, *J. Climate, 15*:3237-3251, 2002.

Miyamoto, S., L.B. Fenn, D. Swietlik, Flow, salts and trace elements: A review, Texas Water Resources Institute Report TR-169, 30 pp., 1995.

Molotch, N.P., and R.C. Bales, Estimating the spatial representativeness of the Natural Resource Conservation Service's Snow Telemetry (SNOTEL) network in the Rio Grande headwaters, in preparation.

Molotch, N.P., T.H. Painter, M.T. Colee, R.C. Bales and J. Dozier, Incorporating remotely sensed snow surface grain size data into distributed snowmelt modeling, in preparation.

Murray, R.M. and C.L. Winter, Volume averaged boundary conditions at a stream-aquifer interface: Los Alamos report, in progress (to be submitted to *Water Resour. Res.).*

National Research Council, *National Science Education Standards,* National Academy Press, Washington, D.C., 1996.

National Research Council, Committee on Status and Research Objectives in the Solid-Earth Sciences, *Solid-earth Sciences and Society: A Critical Assessment,* National Academy of Sciences, 1993.

Neilson, R.P., A model for predicting continental-scale vegetation distribution and water balance. *Ecol. Appl.., 5*, 362-385, 1995.

Newman, B.D., C.J. Duffy, and D.D. Hickmott, Evaluating the hydrogeochemical response of springs using singular spectrum analysis and phase-plane plots, in *New Approaches to Characterising Groundwater Flow*, edited by Seiler and Wohnlich, International Assn. of Hydrogeologists, 762-767, 2001.

New York Times, 2002: “Battle brews over Rio Grande water,” Sept. 16, 2002.

New York Times, 2003: "Arizona starts to feel impact of long drought," by M. Janofsky, Jan. 27, 2003.

Phillips, F.M., Salt of the earth: What makes the Rio Grande go saline? in *New Mexico Academy of Science, Centennial Volume*, edited by R. Nygren, New Mexico Academy of Science, Albuquerque, (forthcoming).

Phillips, F.M., J.F. Hogan, S.K. Mills, and J.M.H. Hendrickx, Environmental tracers applied to quantifying causes of salinity in arid-region rivers: Preliminary results from the Rio Grande, Southwestern USA, in *Water Resources Perspectives: Evaluation, Management and Policy,* edited by A.S. Alsharhan and W.W. Wood, Elsevier Science, (forthcoming).

Pielke, R.A., W.R. Cotton, R.L. Walko, C.J. Tremback, M.E. Nicholls, M.D. Moran, D.A. Wesley, T.J. Lee, and J.H. Copeland, A comprehensive meteorological monitoring system – RAMS. *Meteor. Atmos. Physics, 49*:69-91, 1992.

Rhoton, J., and P. Bowers, *Professional Development: Planning and Design,* NSTA Press, Arlington, VA, 2001.

Roads, J., Experimental weekly to seasonal, global to regional U.S. precipitation forecasts, submitted to *J. Hydrology.*

Rucker, D.F., and T.P.A. Ferré, Near-surface water content estimation with borehole ground penetrating radar using critically refracted waves, submitted to *Vadose Zone J.*

Schade, J.D., D.B. Lewis, N.B. Grimm, J.E. Villinski, Hydrologic exchange, boundaries, and nitrogen retention, in preparation.

Scott, R.L., C. Watts, J. Garatuza, E. Edwards, D. Goodrich, D. Williams, and W.J. Shuttleworth, The understory and overstory partitioning of energy and water fluxes in an open canopy, semiarid woodland, *J. Agr. Forest Meteor. 114*: 127-139, 2003.

Shun, T., and C.J. Duffy, Low frequency oscillations in precipitation, temperature and runoff across a west-facing mountain front: A hydrogeologic interpretation, *Water Resour. Res, 35*(1), 191-201, 1998.

Sorooshian, S., K. Hsu, X. Gao, H.V. Gupta, B. Imam, and D. Braithwaite, Evaluation of PERSIANN system satellite-based estimates of tropical rainfall, *Bull. of the Amer. Meteorological Soc., 81*(9): 2035-2046, 2000.

Stromberg, J.C., K. Bagstad, and S.J. Lite, Riparian plant diversity and functional group patterns across lateral, longitudinal, and temporal gradients, San Pedro River, Arizona, USA, in preparation.

Tartakovsky, D.M, and C.L. Winter, Dynamics of free surfaces in random porous media, *SIAM J. Appl. Math. 61*(6), 1857-1876, 2001.

Uyeda, S., J.A. Luft, J. Madden, J. Washburne, and L.A. Brigham, Advancing science literacy through a teacher workshop on hydrology, submitted to *J. of Geoscience Ed.*

Villinski, J.E., J.F. Hogan, and P.D. Brooks, Temporal and spatial variability of nitrogen species and dissolved organic carbon in the Rio Grande, in preparation.

Vrugt, J.A., H.V. Gupta, W. Bouten, S. Sorooshian, A shuffled complex evolution metropolis algorithm for optimization and uncertainty assessment of hydrological model parameters, forthcoming in *Water Resour. Res.*

Vrugt, J.A., H.V. Gupta, L.A. Bastidas, W. Bouten, and S. Sorooshian, Effective and efficient algorithm for multi-objective optimization of hydrologic models, submitted to *Water Resour. Res.*

Vrugt, J.A., H.V. Gupta, W. Bouten, and S. Sorooshian, Application of global optimization and uncertainty assessment to the Sacramento Soil Moisture Accounting model: Parameter stationarity and influence of data length and quality on posterior uncertainty parameters, submitted to *J. of Hydrology*.

Walvoord, M., A unifying conceptual model to describe water, vapor and solute transport in deep arid vadose zones, Ph.D. thesis, New Mexico Institute of Mining and Technology, Socorro, New Mexico, 2002.

Walvoord, M., F.M. Phillips, S.W. Tyler, and P.C. Hartsough, Deep arid system hydrodynamics, part 2: Application to paleohydrologic reconstruction using vadose-zone profiles from the Northern Mojave Desert, *Water Resour. Res.,38*(12): 1291, doi:10.1029/2001WR000825, 2002.

Wilder, M.O., In name only: Water policy, the state, and ejidatario producers in northern Mexico, Ph.D. Dissertation, Geography and Regional Development, University of Arizona, 2002.

Wilson, J.L., and H. Guan, Mountain front recharge and mountain-block hydrology, in *Recharge and Vadose Zone Processes: Alluvial Basins of the Southwestern United States*, ed. by F.M. Phillips, J.F. Hogan, and B. Scanlon, Water Resources Monograph series, Washington, DC, American Geophysical Union, (forthcoming).

Winter, C.L., and D.M. Tartakovsky, A theoretical foundation for conductivity scaling, *Geophysical Research Letters, 28*(23), 4367-4369, 2001.

Yatheendradas, S., Calibration in basin-scale land-surface modeling over the semi-arid Southwest United States. Masters Thesis, Department of Hydrology and Water Resources, The University of Arizona, Tucson, AZ, in preparation.

V. Biographical Sketches

Include a biographical sketch of Key Participants. The Center Director determines who the key participants are (e.g., center director, deputy director, education director, knowledge transfer director, thrust or group leaders, etc.)

Information is available from Rannie Fox at rannie@sahra.arizona.edu

VI. Budget

For years 6-10. To accommodate the specifically planned 2-year phase-out period, the Year 9 budget should be 83% of Year 8, and the Year 10 budget should be 80% of Year 9. Note that the total annual budget for Years 6-8 should be comparable to that for Year 5 of the current award and should not exceed $4 million.

Information is available from Jill Gibson at jill@sahra.arizona.edu.

VII. Current and Pending Support

Current and Pending Support of Key Participants

Information not available.

VIII. Facilities, Equipment, and Other Resources

FACILITIES
Laboratory:

- UA Laboratory of Isotope Geochemistry, 10% access, UA campus -Low level Beta (radiocarbon, tritium), Isotopic ratio mass spectrometer (C, O2, S, Cl), Ion chromatograph, automatic analysis of $\delta^{18}O$ and $\delta^{2}H$, UA campus
- UA-HWR Hydrochemistry Labs, 100% access, 250 m^2, walk-in cold room, 2 ion chromatographs, 2 gas chromatographs with ECDs and FIDs – one with liquid autosampler, microcomputers, graphite furnace/flame atomic absorption spectrophotometer, 2 UV/VIS scanning spectrometers – one with photo-diode array, microcomputers, scanning fluorometer with flow-through option, glove box, floor and table top centrifuges, 2 reagent-grade water systems, 2 chromatography refrigerators, 3 sample refrigerators, 2 freezers, UA campus
- NMT Hydrology Laboratories: ^{36}Cl isotope lab (45 m^2); Vadose zone lab; Hydraulics lab/shop, NMT campus
- UA-HWR Biogeochemical Analytical Laboratory, 100% access, aqueous solution TOC analyzer, aqueous solution trace nitrogen analyzer, soil elemental analyzer, ammonium/nitrate/nitrite/phosphate flow injection analyzer, oven for drying/ashing, 4 sample refrigerators, reagent-grade water system, UA campus
- UA Noble Gas Laboratory (new in 2003), priority access to SAHRA researchers, noble gas mass spectrometers for analysis of Ar, Ni, Xe, and He isotopes, UA campus
- ASU Goldwater Environmental Laboratory encompasses seven laboratories for chromatography, elemental analysis, spectroscopy, and wet chemistry; reduced sample fee, ASU campus
- Biogeochemistry/Ecosystems Laboratory, >85 m^2 laboratory with acid bath, Nanopure® water system, shaker table, two drying ovens, muffle furnace, analytical balances, prep room for soil/sediment sieving, Schimadzu gas chromatograph, and computer lab, ASU campus
- UNM Experimental Economics Laboratory, access available for students and faculty, has 20 workstations plus one experimenter machine, UNM campus
- UNM Economics Computer Lab, 12 workstations available, access available to all UNM faculty and students, serves as an additional experimental lab for research projects, UNM campus

Computer:

- UA optical fiber telecommunication network (Gigabit building connection, FDDI backbone, Internet 2 access, 100 Mb desktop connections)
- UA-HWR Surface Water Research/Computer Lab, 100% access, 80 m^2
- UA-CCIT SGI parallel processing supercomputer, amount of time varies
- LANL computer network backbone, accessed from UA campus
- UA, ASU, UNM, NMT: Conference equipment including computer, projector, and interactive electronic whiteboard

Office:

- UA: new facility under construction to house SAHRA scientists, staff, and affiliated projects, to be completed Dec. 2003, 1161 m^2; 270 m^2 of space will be retained in HWR
- ARS: shared office space for students working on this project.
- NMT: participating faculty and staff occupy 80 m^2
- LANL: shared office space for SAHRA and associated students
- UNM: two shared research office spaces for SAHRA-funded students; one 242 sq.ft.and the other 116 sq.ft.

- UNM: 257 sq.ft. conference room with priority access to SAHRA researchers
- UNM: participating faculty occupy three office spaces with total 524 sq.ft.

Field:

- ARS Walnut Gulch Experimental Watershed, Tombstone, AZ, 100 km SE Tucson, 150 km^2, rain gauges, flumes, data archive, machine shops, and motor pool.
- ARS: 2 eddy covariance sites: one is at the Charleston Mesquite site in the San Pedro Riparian National Conservation Area (SPRNCA), 100 km from Tucson near Charleston, Arizona; the second will be set up in an undetermined mesquite site in spring 2003.
- UA: 2 eddy covariance sites set up in a Sacaton grassland and a mixed mesquite/grassland. The sites are adjacent to each other and located 100 km from Tucson near the crossing of Hwy 90 and the San Pedro River.
- SAHRA's Mt. Bigelow Field Site, 50 km N of Tucson. A 30 m-tall eddy covariance tower, with a supporting spatial network of three micrometeorological stations, located in a sub-alpine Douglas fir forest

MAJOR EQUIPMENT

- LANL: computer resources, 1% access to 100 teraflop, super computer; access to 100 processor LINUX computer; Mobile LIDAR, field time for riparian campaigns; 5 mobile eddy covariance stations
- UA-HWR: 2 multiprocessor Unix servers
- UA-HWR: Research workstation cluster, 5 SUN Ultrasparc desktop computers. Software: Matlab, ArcInfo, Imagine, Oracle, Sun Solaris, Sun Compilers
- UA-HWR: Student PC laboratory, 20 desktop PCs
- NMT: Hydrology/Geophysics computer lab, current NSF upgrade to 7 Sparc Ultras
- UA-HWR and ARS: micrometeorological instrumentation (eddy covariance system, basic met sensors, radiometers, heat flux plates), soil moisture probes.
- UA- 2 eddy covariance systems, 2 basic meteorological stations, 1 portable leaf gas exchange analyzer
- UA-HWR Mt. Bigelow: micrometeorological instrumentation (1 eddy covariance tower system with 4-way radiometer, three levels of met. sensors, soil moisture, soil temperature, soil heat flux, 3 basic met. stations with net radiometers, infrared surface temperature, soil moisture probes, and soil temperature probes)
- UA-HWR: 1220 Quantulus liquid scintillation spectrometer (for ^{32}S, tritium, and radiocarbon analysis), 100% access
- ASU Goldwater Environmental Lab: LACHAT QC8000 and Shimadzu TOC-5000 (wet chemistry analysis); Bran-Luebbe TrAAcs 800 autoanalyzer (chemistry of soil extractions); PDZ-Europa mass spectrometer (plant tissue chemistry), and Dionex 4000i ion chromatograph (bromide for injection experiments)

OTHER RESOURCES

- Remote sensing data: Access to UA Center for Excellence in Remote Sensing, which houses UA images for Arizona and the Southwest (great-sandy.arid.arizona.edu).

IX. Special Information and Supplementary Documentation

1. Publications Originating from SAHRA STC Support, 2000 to Present

1a. Theses and dissertations

Bardsley, T., Investigations toward understanding the spatial representativeness of SNOTEL measurements of snow water equivalence, MS Thesis, Hydrologic Sciences, University of Nevada, Reno, 2002.

Dolmar, D., Modeling unsaturated transport of an anthropogenic solute signal near a prehistoric Native American pueblo, MS Thesis, Hydrology Program, New Mexico Tech, 2001.

Gorham, T., Application and evaluation of a distributed, physically based hydrologic model to improve streamflow forecasts in the upper Rio Grande basin, MS Thesis, Hydrologic Sciences, University of Nevada, Reno, 2002.

Hong, S., Soil salinity in non-flooded arid riparian areas. MS Thesis, Hydrology, New Mexico Tech, Socorro, NM, 2002.

Khodatalab, N. Distributed hydrologic modeling for flow forecasting by using high resolution data. MS Thesis, Department of Hydrology and Water Resources, The University of Arizona, Tucson, AZ, 2002.

Moayyad, B., Importance of groundwater depth, soil texture, and rooting depth on arid riparian evapotranspiration. MS Thesis, Hydrology Program, New Mexico Tech, 2001.

Rodriguez-Marin, G., Water flow through indurated calcic horizons in arid New Mexico, MS Thesis, Hydrology Program, New Mexico Tech, 2001.

Walvoord, M., A unifying conceptual model to describe water, vapor and solute transport in deep arid vadose zones, Ph.D. Thesis, New Mexico Institute of Mining and Technology, Socorro, New Mexico, 2002.

Wilder, M.O., In name only: Water policy, the state, and *ejidatario* producers in northern Mexico, Ph.D. Thesis, Geography and Regional Development, University of Arizona, 2002.

1b. Monographs

Duan, Q., H.V. Gupta, S. Sorooshian, A. Rousseau, and R. Turcotte, editors, *Advances in the Calibration of Watershed Models,* Monograph Series on Water Resources, American Geophysical Union, 2002.

Phillips, F.M., J.F. Hogan, and B. Scanlon, editors, *Groundwater Recharge and Vadose Zone Processes: Alluvial Basins of the Southwestern United States*, Water Resources Monograph series, Washington, DC, American Geophysical Union, (forthcoming).

1c. Articles and book chapters (corresponding to research area descriptions, section III.A).

General:

Sorooshian, S., R. Bales, H. Gupta, G. Woodard, and J. Washburne, A brief history and mission of SAHRA: A National Science Foundation Science and Technology Center on 'Sustainability of semi-arid hydrology and riparian areas' (invited commentary), *Hydrol. Process. 16*: 3293-3295, 2002.

A.1: Basin Scale Water Balance

Boyle, D.P., H.V. Gupta, and S. Sorooshian, Multicriteria calibration of hydrologic models, chapter 8 of *Advances in Calibration of Watershed Models*, edited by Q. Duan, S. Sorooshian, H.V. Gupta, A.N. Rousseau, R. Turcotte, Monograph Series on Water Resources, American Geophysical Union, 2002.

*Brookshire, D.S., S. Burness, J.M. Chermak, and K. Krause, Western urban water demand, *Nat. Resour. J. 42(4):*1-26, 2002.

Brookshire, D.S., and J.M. Chermak, Benefit and informational transfers, in *Environmental Value Transfer: Issues and Methods*, edited by O. Olvar, S. Navrud, and R. Ready, Kluwer Academic Publishers, (forthcoming).

Brookshire, D.S., J.M. Chermak, and R. DeSimone, Uncertainty, benefit transfers, and physical models: a Middle Rio Grande Valley focus, in *Environmental Value Transfer: Issues and Methods,* edited by O. Olvar, S. Navrud, and R. Ready, Kluwer Academic Publishers, (forthcoming).

Burness, S., and J. Little, Municipal water conservation policy: Options and design, submitted to *Land Economics.*

Burness, S., J.M. Chermak, and D. Brookshire, Water use in a mountain front recharge aquifer:Analysis, submitted to *Water Resour. Res.*

Burness, S., and J.M. Chermak, Sustainability, incentives and behavioral models of resource use, submitted to *Nat. Resour. J.*

Chermak, J., and K. Krause, Individual response, information, and intergenerational common pool problems, *J. of Environ. Econ. & Management, 43,* 47-70 2002.

Duffy, C.J., A distributed dynamical model for mountain-front recharge and water balance estimation: The Rio Grande of southern Colorado and New Mexico, in *Recharge and Vadose Zone Processes: Alluvial Basins of the Southwestern United States*, ed. by F.M. Phillips, J.F. Hogan, and B. Scanlon, Water Resources Monograph series, Washington, DC, American Geophysical Union, (forthcoming).

Duffy, C.J., and D. Brandes, Dimension reduction and source identification for multispecies groundwater contamination, *J. Contaminant Hydrology 48*(1-2), 151-165, 2001.

Eastoe, C.J., A. Gu, and A. Long, The origins, ages, and flow paths of groundwater in the Tucson Basin: Results of a study of multiple isotope systems, in *Recharge and Vadose Zone Processes: Alluvial Basins of the Southwestern United States*, ed. by F.M. Phillips, J.F. Hogan, and B. Scanlon, Water Resources Monograph series, Washington, DC, American Geophysical Union, (forthcoming).

Eichinger, W., D.J. Cooper, J. Kao, L.C. Chen, and L. Hipps, Estimation of spatially distributed latent energy flux over complex terrain from a Raman lidar, *Agric. For. Meteorol. 105*(1-3), 145-159, 2000.

Ferré, T.P.A., G. von Glinski, and L.A. Ferré, Monitoring the maximum depth of drainage in response to pumping using borehole ground penetrating radar, submitted to *Vadose Zone J.*

Gibson, J., P. Aggarwal, J. Hogan, C. Kendall, L. Martinelli, W. Stichler, D. Rank, I. Goni, M. Choudhry, J. Gat, S. Bhattacharya, A. Sugimoto, B. Fekete, A. Pietroniro, T. Maurer, H. Panarello, D. Stone, P. Seyler, L.M. Bourgoin, and A. Herczeg, Isotope studies in large river basins: A new global research focus, *Eos, 83*(52), 613-617, 2002.

Hibbs, B., F. Phillips, J. Hogan, C. Eastoe, J. Hawley, A. Granados, and B. Hutchison, and T. Kretzschmar, Groundwater resources of the Hueco Bolson-El Paso/Juárez area, forthcoming in *Hydrol. Sci. and Tech.*

Hogan, J.F., et al., Basin-scale recharge: Introduction and overview, in *Recharge and Vadose Zone Processes: Alluvial Basins of the Southwestern United States*, ed. by F.M. Phillips, J.F. Hogan, and B. Scanlon, Water Resources Monograph series, Washington, DC, American Geophysical Union, (forthcoming).

Hultine, K.R., D.G. Williams, S.S.O. Burgess, and T.O. Keefer, Contrasting patterns of hydraulic redistribution among three desert phreatophytes, forthcoming in *Oecologia*.

Hultine, K.R, D.G. Williams, W.L. Cable, and S.S.O. Burgess, Hydraulic redistribution by deep roots of a Chihuahuan Desert phreatophyte, forthcoming in *Tree Physiology*.

Krause, K., J.M. Chermak, and D.S. Brookshire, The demand for water: Consumer response to scarcity, forthcoming in *J. Regul. Econ.*

*Kurc, S., and E. Small, Dynamics of evapotranspiration in semiarid shrubland and grassland during the summer monsoon season, central NM, submitted to *Water Resour. Res.*

Leij, F.J., T.A. Ghezzehei, and D. Or, Modeling the dynamics of the soil pore-size distribution, *Soil and Tillage Res. 64*(1-2), 61-78, 2002.

Leij, F.J., T.A. Ghezzehei, and D. Or, Analytical models for soil pore-size distribution after tillage, *Soil Sci. Soc. Amer. J.*, *66*(4): 1104-1114, 2002.

Matthews, O.P., L. Scuderi, D. Brookshire, K. Gregory, S. Snell, K. Krause, J. Chermak, B. Cullen, and M. Campana, Marketing western water: Can a process based geographic information system improve reallocation decisions? *Nat. Resour. J. 41*(2): 330-371.

Mohanty, B.P., and T.H. Skaggs, Spatiotemporal evolution and time stable characteristics of soil moisture within remote sensing footprints with varying soil, slope, and vegetation, *Adv. Water Resour. 24*(9/10), 1051-1067, 2001.

Moran, M.S., D.C. Hymer, J. Qi, and E.E. Sano, Soil moisture evaluation using multi-temporal synthetic aperture radar (SAR) in semiarid rangeland, *Agric. For. Meteorol., 105*(1-3), 69-80, 2000.

Newman, B.D., C.J. Duffy, and D.D. Hickmott, Evaluating the hydrogeochemical response of springs using singular spectrum analysis and phase-plane plots, in *New Approaches to Characterising Groundwater Flow*, edited by Seiler and Wohnlich, International Assn. of Hydrogeologists, 762-767, 2001.

Phillips, F., M. Walvoord, and E. Small, Effects of climate change on recharge regime, in *Recharge and Vadose Zone Processes: Alluvial Basins of the Southwestern United States*, ed. by F.M. Phillips, J.F. Hogan, and B. Scanlon, Water Resources Monograph series, Washington, DC, American Geophysical Union, (forthcoming).

Šimůnek, J., N.J. Jarvis, M.T. van Genuchten, A. Gärdenäs, Review and comparison of models for describing non-equilibrium and preferential flow and transport in the vadose zone, forthcoming in *J. Hydrol.*

Small, E.E., and S.A. Kurc, The influence of soil moisture on the surface radiation budget, ground heat flux, and soil temperature in semiarid environments, submitted to *Water Resour. Res.*

Small, E.E., and S.A. Kurc, Tight coupling between soil moisture and the surface radiation budget in semiarid environments: Implications for land-atmosphere interactions, forthcoming in *Water Resour. Res.*

Walvoord M., and F.M. Phillips, Deep arid system hydrodynamics, part 3: Vegetation control on desert-floor recharge, submitted to *J. Hydrol.*

Walvoord, M., F.M. Phillips, S.W. Tyler, and P.C. Hartsough, Deep arid system hydrodynamics, part 2: Application to paleohydrologic reconstruction using vadose-zone profiles from the Northern Mojave Desert, *Water Resour. Res.,38*(12): 1291, doi:10.1029/2001WR000825, 2002.

*Walvoord, M., M.A. Plummer, F.M. Phillips, and A.V. Wolfsberg, Deep arid system hydrodynamics, part 1: Equilibrium states and response times in thick desert vadose zones, *Water Resour. Res. 38*(12): 1308, doi:10.1029/2001WR000824, 2002.

Walvoord, M., and B. Scanlon, Hydrologic processes in deep vadose zones in interdrainage arid environments, in *Recharge and Vadose Zone Processes: Alluvial Basins of the Southwestern United States*, ed. by F.M. Phillips, J.F. Hogan, and B. Scanlon, Water Resources Monograph series, Washington, DC, American Geophysical Union, (forthcoming).

Wang, X.-P., C.M. Brown-Mitic, E.-S Kang, J.-G. Zhang, and X.-R. Li, Evapotranspiration of *Caragana korshinskii* communities in a revegetated desert area, submitted to *Hydrological Processes.*

Wilson, J.L., and H. Guan, Mountain front recharge and mountain-block hydrology, in *Recharge and Vadose Zone Processes: Alluvial Basins of the Southwestern United States*, ed. by F.M. Phillips, J.F. Hogan, and B. Scanlon, Water Resources Monograph series, Washington, DC, American Geophysical Union, (forthcoming).

Yepez, E.A., D.G. Williams, R. Scott, and G. Lin, Partitioning overstory and understory evapotranspiration in a semi-arid savanna ecosystem from the isotopic composition of water vapor, submitted to *J. Agr. Forest Meteor.*

A2: River Systems

Bhark, E., and E. Small. The relationship between plant canopies and the spatial variability of infiltration in grassland and shrubland of the northern Chihuahuan desert, NM, submitted to *Ecosystems.*

Blasch, K., P. Ferré, J. Constantz, J.P. Hoffmann, M.A. Bailey, and J.T. Cordova, Recharge beneath ephemeral streams, in *Recharge and Vadose Zone Processes: Alluvial Basins of the Southwestern United States*, ed. by F.M. Phillips, J.F. Hogan, and B. Scanlon, Water Resources Monograph series, Washington, DC, American Geophysical Union, (forthcoming).

Chehbouni, A., D.C. Goodrich, M.S. Moran, C.J. Watts, Y.H. Kerr, G. Dedieu, W.G. Kepner, W.J. Shuttleworth, and S. Sorooshian, A preliminary synthesis of major scientific results during the SALSA Program, *Agric. For. Meteorol., 105*(1-3), 311-323, 2000.

Cooper, D.I., W.E. Eichinger, J. Kao, L. Hipps, J. Reisner, S. Smith, S.M. Schaeffer, and D.G. Williams, Spatial and temporal properties of water vapor and latent energy flux over a riparian canopy, *Agric. For. Meteorol.., 105*(1-3), 55-68, 2000.

Ferré, T.P.A., H.H. Nissen, and J. Šimůnek, The effect of the spatial sensitivity of TDR on inferring soil hydraulic properties from water content measurements made during the advance of a wetting front, *Vadoze Zone J., 1*, 281-288, 2002.

Furman, A., P.A. Ferré, and A.W. Warrick, A sensitivity analysis of electrical-resistance-tomography array types using analytical element modeling, forthcoming in *Vadose Zone J.*

Furman, A., A.W. Warrick, and P.A. Ferré, Electrical potential distributions in response to applied current in a heterogeneous subsurface: Solution for circular inclusions, *Vadose Zone Journal 1*, pp. 273-280, 2002.

Goodrich, D.C., A. Chehbouni, B. Goff, et al., Preface paper to the Semi-Arid Land-Surface-Atmosphere (SALSA) Program Special Issue, *Agric. For. Meteorol., 105*(1-3), 3-20, 2000.

Goodrich, D.C., R. Scott, C. Unkrich, K. Hultine, and D. Williams, Ephemeral channel recharge and ET in the USDA-ARS Walnut Gulch Experimental Watershed, in *Recharge and Vadose Zone Processes: Alluvial Basins of the Southwestern United States*, ed. by F.M. Phillips, J.F. Hogan, and B. Scanlon, Water Resources Monograph series, Washington, DC, American Geophysical Union, (forthcoming).

IAEA Working Group, Report of a research coordination meeting on design criteria for a network to monitor isotope composition of runoff in large rivers (2002-2006), *IAEA Report*, 26 pages, 2002. (Group includes J. Hogan)

Kao, C.-Y.J., Y.-H. Hang, D.I. Cooper, W.E. Eichinger, W.S. Smith, and J.M. Reisner, High resolution modeling of lidar data: Mechanisms governing surface water vapor variability during SALSA, *Agric. For. Meteorol., 105*(1-3), 185-194, 2000.

Lawler, D.S., K. Blasch, T. Ferré, and S.A. Leake, Using streambed temperature to identify perennial, ephemeral, and intermittent reaches in the San Pedro River, Southeastern Arizona, submitted to *J. Hydrol.*

Paige, G.B., J.J. Stone, J.R. Smith, J.R. Kennedy, The Walnut Gulch rainfall simulator: A computer controlled variable intensity rainfall simulator, submitted to *Trans. ASAE.*

Phillips, F.M., Salt of the earth: What makes the Rio Grande go saline? in *New Mexico Academy of Science, Centennial Volume*, edited by R. Nygren, New Mexico Academy of Science, Albuquerque, (forthcoming).

Phillips, F.M., J.F. Hogan, S.K. Mills, and J.M.H. Hendrickx, Environmental tracers applied to quantifying causes of salinity in arid-region rivers: Preliminary results from the Rio Grande, Southwestern USA, in *Water Resources Perspectives: Evaluation, Management and Policy,* edited by A.S. Alsharhan and W.W. Wood, Elsevier Science, (forthcoming).

Pinker, R.T., I. Laszlo, D. Goodrich, and G. Pandithurai, Satellite estimates of surface radiative fluxes for the extended San Pedro Basin: sensitivity to aerosols, *Agric. For. Meteorol., 105*(1-3), 43-54, 2000.

*Qi, J., R.C. Marsett, M.S. Moran, D.C. Goodrich, P. Heilman, Y.H. Kerr, G. Dedieu, and A. Chehbouni, Spatial and temporal dynamics of vegetation in the San Pedro River Basin Area, *Agric. For. Meteorol., 105*(1-3), 55-68, 2000.

*Scott, R.L., C. Watts, J. Garatuza, E. Edwards, D. Goodrich, D. Williams, and W.J. Shuttleworth, The understory and overstory partitioning of energy and water fluxes in an open canopy, semiarid woodland, *J. Agr. Forest Meteor. 114*: 127-139, 2003.

Sorooshian, S., K. Hsu, X. Gao, H.V. Gupta, B. Imam, and D. Braithwaite, Evaluation of PERSIANN system satellite-based estimates of tropical rainfall, *Bull. of the Amer. Meteorological Soc., 81*(9): 2035-2046, 2000.

Zhu, J., and B.P. Mohanty, Analytical solutions for steady state vertical infiltration, *Water Resour. Res*., *38*(8), 2002.

Zhu, J., and B.P. Mohanty, Effective hydraulic parameters for steady state vertical flow in heterogenous soils, submitted to *Water Resour. Res.*

Zhu, J., and B.P. Mohanty, Upscaling of soil hydraulic properties under steady state evaporation and infiltration, *Water Resour. Res. 38(9),* 10.1029/2001WR000704, 2002.

A3: Regional Hydrology

Brown-Mitic, C., I. Macpherson, P.H. Schuepp, B. Nagrajan, P.M.K. Yau, and R. Bales, Aircraft observations of surface-atmosphere exchange during and after snowmelt for different Arctic environments: MAGS 1999, *Hydrological Processes, 1*(18), 3585-3602, 2001.

Brown-Mitic, C., S. Kaharabata, and R. Bales, Priority parameters and their measurements in ‘atmospheric monitoring,’ in *The Encyclopedia of Life Support Systems (EOLSS) (online)*, edited by H.I. Inyang, UNESCO-EOLSS Publisher Co., Baldwin House, Aldates, Oxford, UK, 2001. http://www.eolss.net/

Fassnacht, S.R., K.A. Dressler, and R.C. Bales, Geostatistical interpolation of point-measured SWE in the Colorado River Basin, submitted to *Water Resour. Res*.

*Fassnacht, S.R., and R.C. Bales, Physiographic variables as indicators of snowpack state for the Colorado River Basin from snow telemetry (SNOTEL) data, submitted to *Water Resour. Res.*

Gonzalez, J., and J.B. Valdés, Bivariate drought recurrence analysis using tree ring reconstructions, forthcoming in *J. of Hydrol. Eng*.

Gupta, H.V., S. Sorooshian, D.P. Boyle, and T. Hogue, Advances in automatic calibration of watershed models, chapter 1 of *Advances in Calibration of Watershed Models*, edited by Q. Duan, S. Sorooshian, H.V. Gupta, A.N. Rousseau, R. Turcotte, Monograph Series on Water Resources, American Geophysical Union, 2002.

Han, J., and J. Roads, U.S. climate sensitivity simulated with the NCEP regional spectral model, submitted to *J. Climate Change*.

*Hsu, K., H.V. Gupta, X. Gao, S. Sorooshian, and B. Imam, Self-organizing linear output map (SOLO): An artificial neural network suitable for hydrologic modeling and analysis, *Water Resour. Res.* 38(12): 10.1029/2001WR000795, 2002.

Huth, A.K., A. Leydecker, J.O. Sickman, and R.C. Bales, A two-component hydrograph separation for three high-elevation catchments in the Sierra Nevada, California, submitted to *Hydrological Processes.*

Li, J., X. Gao, R.A. Maddox, S. Sorooshian, and K. Hsu, Investigation of the storm structure and evolution in the 1999 Las Vegas flooding, submitted to *Monthly Weather Rev.*

Li, J., X. Gao, R.A. Maddox, S. Sorooshian, and K. Hsu, Summer weather simulation for the semiarid Lower Colorado River basin: Case tests, submitted to *Monthly Weather Rev.*

Molotch, N.P., S.R. Fassnacht, S.R. Helfrich, and R.C. Bales, Estimating the extent of snow cover over the Salt-Verde River Basin, Arizona from spatial temperature data, submitted to *Hydrological Processes*.

Roads, J., Experimental weekly to seasonal, global to regional U.S. precipitation forecasts, submitted to *J. Hydrology.*

Roads, J.O., The Fourth International RSM Workshop: Meeting summary, submitted to *Bull. Amer. Meteor. Soc.*

Sorooshian, S., X. Gao, K. Hsu, R.A. Maddox, Y. Hong, B. Imam, and H.V. Gupta, Diurnal variability of tropical rainfall retrieved from combined GOES and TRMM satellite information, *J. of Climate, 15*(9), 983-1001, 2002.

A4: Integrated Basin Modeling

Bastidas, L.A., H.V. Gupta, O.L. Sen, Y. Liu, S. Sorooshian, and W.J. Shuttleworth, Comparative evaluation of land-surface schemes using multi-criteria methods, submitted to *J. Geophys. Res.-Atmos.*

Bastidas, L.A., H.V. Gupta, and S. Sorooshian, Parameter, structure and performance evaluation for land surface models, chapter 7 in *Advances in the Calibration of Watershed Models*, edited by Q. Duan, H.V. Gupta, S. Sorooshian, A. Rousseau, and R. Turcotte, American Geophysical Union, 2002.

Bastidas, L.A., H.V. Gupta, and S. Sorooshian, Emerging paradigms in the calibration of hydrologic models, in *Mathematical Models of Large Watershed Hydrology*, vol. 1, edited by V.P. Singh and D. Frevert, pp. 25-56, Water Resources Publications, LLC, Englewood, Colorado, 2002.

Boyle, D.P., H.V. Gupta, S. Sorooshian, V. Koren, Z. Zhang, and M. Smith, Toward improved streamflow forecasts: The value of semi-distributed modeling, *Water Resour. Res.*, *37*(11), 2749, 2001.

Burke, E.J., L. Bastidas, and W.J. Shuttleworth, Exploring the potential for multipatch soil-moisture retrievals using multiparameter optimization techniques, *IEEE Trans. on Geoscience and Remote Sensing*, 40(5), 1114-1120, 2002.

Gupta, H.V., L.A. Bastidas, J. Vrugt, and S. Sorooshian, Multiple criteria global optimization for watershed model calibrations, chapter 9 in *Advances in the Calibration of Watershed Models,* edited by Q. Duan, H.V. Gupta, S. Sorooshian, A. Rousseau, and R. Turcotte, Monograph Series on Water Resources, American Geophysical Union, 2002.

Gupta, H.V., S. Sorooshian, X. Gao, B. Imam, K. Hsu, L.A. Bastidas, J. Li, and S. Mahani, The challenge of predicting flash floods from thunderstorm rainfall, *Phil. Trans. Royal Soc., 360*, 1-9, 2002.

Khodatalab, N., H.V. Gupta, T. Wagener, and S. Sorooshian, S., Calibration of a semi-distributed hydrologic model for streamflow estimation along a river system, submitted to DMIP Special Issue of *J. of Hydrology*.

McPhee, J., and W.W-G. Yeh, Optimal experimental design for parameter estimation and contaminant plume characterization in groundwater modeling, in *Optimal Design: Their Roles and Applications*, edited by W.K. Wong and M.R.F. Beger, Wiley, New York, forthcoming.

Sen, O., L.A. Bastidas, W.J. Shuttleworth, Z.L. Yang, H.V. Gupta, and S. Sorooshian, Impact of field calibrated vegetation parameters on GCM climate simulations, *Quar. J. Royal Meteor. Soc., 127*(574), 1199-1224, 2001.

Tartakovsky, D.M, and C.L. Winter, Dynamics of free surfaces in random porous media, *SIAM J. Appl. Math. 61*(6), 1857-1876, 2001.

Vrugt, J.A., H.V. Gupta, W. Bouten, S. Sorooshian, A shuffled complex evolution metropolis algorithm for optimization and uncertainty assessment of hydrological model parameters, forthcoming in *Water Resour. Res.*

Vrugt, J.A., H.V. Gupta, L.A. Bastidas, W. Bouten, and S. Sorooshian, Effective and efficient algorithm for multi-objective optimization of hydrologic models, submitted to *Water Resour. Res.*

Vrugt, J.A., H.V. Gupta, W. Bouten, and S. Sorooshian, Application of global optimization and uncertainty assessment to the Sacramento Soil Moisture Accounting model: Parameter stationarity and influence of data length and quality on posterior uncertainty parameters, submitted to *J. of Hydrology*.

Winter, C.L., and D.M. Tartakovsky, Groundwater flow in heterogeneous composite aquifers, *Water Resour. Res.*, *38*(8), 10.1029/2001WR000450, 2002.

*Winter, C.L., and D.M. Tartakovsky, A theoretical foundation for conductivity scaling, *Geophysical Research Letters, 28*(23), 4367-4369, 2001.

Winter, C.L., D.M. Tartakovsky, and A. Guadagnini, Moment equations for flow in highly heterogeneous porous media, forthcoming in *Surveys in Geophysics*.

Winter, C.L., D.M. Tartakovsky, and A. Guadagnini, Numerical solutions of moment equations for flow in heterogeneous composite aquifers, *Water Resour. Res., 38*(5), 13.1-13.8, 2002.

A5: Binational Cooperation

Browning-Aiken, A., R. Varady, and D. Moreno, Water-resources management in the San Pedro Basin: Building binational alliances, forthcoming in *J. of the Southwest.*

Kim, T., and J.B. Valdés, A nonlinear model for drought forecasting based on a conjunction of wavelet transforms and artificial neural networks, submitted to *J. Hydrol. Eng.*

Kim, T., and J.B. Valdés, and J. Aparicio, Long-term forecasts of droughts using a conjunction of wavelet transforms and artificial neural networks, *Experimental Long-Lead Forecast Bulletin*, *11*(13), 2002.

*Kim, T., J.B. Valdés, and J. Aparicio, Frequency and spatial characteristics of droughts in the Conchos River Basin, Mexico, *Water International, IWRA 27*(3): 420-430, 2002.

Kim, T., J.B. Valdés, and C. Yoo, A nonparametric approach for estimating return periods of droughts in arid regions, forthcoming in *ASCE J. Hydrol. Eng.*

Kim, T., C. Yoo and J.B. Valdés, A nonparametric approach for estimating effects of ENSO on return periods of droughts, submitted to *KSCE J. of Civil Eng.*

Varady, R.G. and A. Browning-Aiken, The birth of a Mexican watershed council in the San Pedro Basin in Sonora,in *Planeación y Cooperación en la Frontera Mexico-Estados Unidos (Transboundary Planning and Cooperation in the U.S.-Mexico Border Region),* edited by C. Fuentes and S. Peña, (forthcoming).

Varady, R.G., and B.J. Morehouse, Cuanto cuesta? Development and water in the Ambos Nogales and the Upper San Pedro Basin, in *Social Costs of Industrial and Urban Growth on the U.S.-Mexican Border,* ed. by Kathryn Kopinak, UCSD Center for U.S.-Mexican Studies Book Series, (forthcoming).

Varady, R.G., and B.J. Morehouse, Moving borders from the periphery to the center: River basins, political boundaries, and water management policy, in *Science and Water Resource Issues:Challenges and Opportunities*, edited by D. Fort and R. Lawford, American Geophysical Union Water Resources Monograph Series, Washington, D.C., American Geophysical Union, (forthcoming).

A7: Technology and Equipment

Blasch, K.W., T.P.A. Ferré, A.H. Christensen, and J.P. Hoffmann, A new field method to determine streamflow timing using electrical resistance sensors, *Vadose Zone J., 1*: 289-299, 2002.

Lawler, D.S., K. Blasch, T. Ferré, and S.A. Leake, Using streambed temperature to identify perennial, ephemeral, and intermittent reaches in the San Pedro River, Southeastern Arizona, submitted to *J. Hydrol.*

B: Education

Luft, J.A., S.J. Toffleson, and G. Roehrig, Using an alternative report format in undergraduate hydrology laboratories, *J. of Geoscience Ed., 49*(5), 454-460, 2001.

Uyeda, S., J.A. Luft, J. Madden, J. Washburne, and L.A. Brigham, Advancing science literacy through a teacher workshop on hydrology, submitted to *J. of Geoscience Ed.*

*Uyeda, S., J. Madden, L.A. Brigham, J.A. Luft, and J. Washburne, Solving authentic science problems, *The Science Teacher, 69*(1), 24-29, 2002.

Uyeda, S., J. Madden, J.A. Luft, and J. Washburne, Using PBL to connect school to the real world, submitted to *Science Teacher*.

1d. Technical reports

Henderson, J., and G. Woodard, Functioning of aging low-consumption toilets in Tucson: A follow-up with rebate program participants, Issue Paper #2, Water Resources Research Center, Tucson, Arizona, Oct. 2000.

Moote, A, and M. Gutiérrez, Views from the Upper San Pedro River Basin: Local Perceptions of Water Issues/Opiniones desde la Cuenca Altas del Rio San Pedro: Percepciones Locales Sobre Temas Relacionados con el Agua, Udall Center, 2001.

Moote, A., and M. Gutiérrez, Sustainability of Water Resources in the Upper San Pedro River Basin: Results of a Survey of Mexican Residents/Sustentabilidad de los Recursos del Agua en la Cuenca Alta del Rio San Pedro: Resultados de una Encuesta de Residentes Mexicanos, Udall Center, 2001.

Varady, R.G., and M.A. Moote, *Community Outreach and Capacity-Building in the Upper San Pedro River Basin of Mexico and Arizona*. Final Report to the Ford Foundation, 2001.

2. List of Disclosure of Inventions, Patent Applications, Patents (including patent number), New Software, New Tools

Data needs for understanding hydrologic processes at the basin scale are huge. Therefore, SAHRA researchers actively seek novel ways to more efficiently and cost-effectively gather and analyze data (see III.A.7, Technology and Equipment). These activities are resulting in the creation of intellectual property rights (see III.G. for SAHRA's policies on intellectual property rights). The Center also has recently formed a new group to identify promising areas for developing new technology, lead by Shuttleworth.

This innovative and creative work will be protected by intellectual property rights. Some of it may prove to be marketable or have other economic value. Currently, SAHRA's business manager is establishing a new accounting entity that will be able to receive and disburse revenues from patent licenses, technology sales, tuition for workshops, etc.

However, because of the public goods nature of much of this intellectual property, we do not anticipate substantial revenues or spin-off economic activity. Our goal, and the indicator by which we measure success, is the degree to which these outputs are quickly adopted and used by agencies and other water resource management institutions.

To further this technology adoption, SAHRA has established a modeling software- and algorithm-sharing center on our Web site (www.sahra.arizona.edu/software).

Some areas of technological innovation include:

- field measurements

- isotopic analysis
- numeric methods and modeling
- new uses of remote sensing data

Some specific devices and applications include:

- new application of Electrical Resistance Tomography (ERT) to measure transient processes in vadose zones
- use of borehole ground-penetrating radar (GPR) to monitor water content in vadose zones to great depth
- improved variable intensity rainfall simulator
- application of scour pans to develop real-time scour sensors in active streams during storm events
- automated hydrologic data collection systems to improve data collection in ephemeral channels
- new application of ^{32}Si isotopic work to quantify paleo-recharge of water through soil
- a novel multi-isotope system to "fingerprint" and quantify salinity sources
- application of low-cost disposable temperature sensors to log periods of streamflow in ephemeral channels
- use of modified hand-held computers (PDAs) and original software to create low-cost, high-resolution water meter data loggers to disaggregate residential water demand
- SAHRA's 'Workgroups' project collaboration software, used to facilitate communication among participants and allow for easy file sharing and for group discussion of topics or projects.

We will be requesting patent and copyright protection on a number of these advancements over the next several months.