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# I. GENERAL INFORMATION

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<tr>
<td>Name of the Center</td>
<td>Sustainability of semi-Arid Hydrology and Riparian Areas</td>
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<tr>
<td>Name of the Center Director</td>
<td>Soroosh Sorooshian</td>
</tr>
<tr>
<td><strong>Lead University</strong></td>
<td><strong>University of Arizona</strong></td>
</tr>
<tr>
<td><strong>Contact information</strong></td>
<td></td>
</tr>
</tbody>
</table>
| Address | University of Arizona  
Hydrology & Water Resources  
PO Box 210011  
Tucson, AZ 85721-0011 |
| Phone Number | 520-626-6974 |
| Fax Number | 520-626-7770 |
| Email Address of Center Director | soroosh@sahra.arizona.edu |
| Center URL | www.sahra.arizona.edu |
| **Participating Institutions** | |
| **Institution 1 Name** | **Arizona State University** |
| Address | Nancy Grimm  
Arizona State University  
Department of Biology  
Box 871501  
Tempe, AZ 85287-1501 |
| Phone Number | 480-965-4735 |
| Fax Number | 480-965-2519 |
| Email Address of Center Director | nbgrimm@asu.edu |
| Role of Institution at Center | Partner in scientific research and education |
| **Institution 2 Name** | **Columbia University Biosphere 2** |
| Address | Steve Russell  
Biosphere 2 Center  
P.O. Box 689  
32540 S. Biosphere Rd  
Oracle, AZ 85623 |
| Phone Number | 520-896-5005 |
| Fax Number | 520-896-6383 |
| Email Address of Center Director | srussell@bio2.edu |
| Role of Institution at Center | Partner in development of educational systems and knowledge transfer |
| **Institution 3 Name** | **Desert Research Institute** |
| Address | Joseph R. McConnell  
2215 Raggio Parkway  
Reno, NV 89512 |
<table>
<thead>
<tr>
<th>Phone Number</th>
<th>775-673-7348</th>
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<tbody>
<tr>
<td>Fax Number</td>
<td>775-673-7363</td>
</tr>
<tr>
<td>Email Address of Center Director</td>
<td><a href="mailto:jmcconn@dri.edu">jmcconn@dri.edu</a></td>
</tr>
<tr>
<td>Role of Institution at Center</td>
<td>Partner in scientific research and education</td>
</tr>
</tbody>
</table>

**Institution 4 Name** New Mexico Institute of Mining and Technology

| Address | Fred Phillips  
New Mexico Institute of Mining and Technology  
Department of Earth & Environmental Science  
801 Leroy Place, Room 208 MSEC Bldg  
Socorro, NM 87801 |
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Phone Number</td>
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</tr>
<tr>
<td>Fax Number</td>
<td>505-835-6436</td>
</tr>
<tr>
<td>Email Address of Center Director</td>
<td><a href="mailto:phillips@nmt.edu">phillips@nmt.edu</a></td>
</tr>
<tr>
<td>Role of Institution at Center</td>
<td>Partner in scientific research and education</td>
</tr>
</tbody>
</table>

**Institution 5 Name** Northern Arizona University

| Address | Mansel Nelson  
Northern Arizona University  
ITEP  
P.O. Box 5697  
Flagstaff, AZ 86011-5697 |
<table>
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<tr>
<td>Phone Number</td>
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</tr>
<tr>
<td>Fax Number</td>
<td>928-523-1266</td>
</tr>
<tr>
<td>Email Address of Center Director</td>
<td><a href="mailto:mansel.nelson@nau.edu">mansel.nelson@nau.edu</a></td>
</tr>
<tr>
<td>Role of Institution at Center</td>
<td>Partner in education and outreach to Native Americans</td>
</tr>
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**Institution 6 Name** Pennsylvania State University

| Address | Chris Duffy  
Pennsylvania State University  
212 Sacket Building  
University Park, PA 16802 |
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<tr>
<td>Phone Number</td>
<td>814-863-4384</td>
</tr>
<tr>
<td>Fax Number</td>
<td>814-863-7304</td>
</tr>
<tr>
<td>Email Address of Center Director</td>
<td><a href="mailto:cxd11@psu.edu">cxd11@psu.edu</a></td>
</tr>
<tr>
<td>Role of Institution at Center</td>
<td>Partner in scientific research and education</td>
</tr>
</tbody>
</table>

**Institution 7 Name** University of California, Los Angeles

| Address | William Yeh  
University of California, Los Angeles  
5732B Boelter Hall  
Mail Code 159310  
Los Angeles, CA 90095-1593 |
<table>
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<tbody>
<tr>
<td>Phone Number</td>
<td>310-825-2300</td>
</tr>
<tr>
<td>Fax Number</td>
<td>310-825-7581</td>
</tr>
<tr>
<td>Email Address of Center Director</td>
<td><a href="mailto:williamy@seas.ucla.edu">williamy@seas.ucla.edu</a></td>
</tr>
<tr>
<td>Role of Institution at Center</td>
<td>Partner in scientific research and education</td>
</tr>
</tbody>
</table>

**Institution 8 Name** University of California, Riverside

| Address | Feike Leij  
University of California, Riverside  
U.S. Salinity Laboratory  
450 W. Big Springs Road  
Riverside, CA 92507 |
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Phone Number</td>
<td>909-369-4851</td>
</tr>
<tr>
<td>Institution 9 Name</td>
<td>University of California, San Diego</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------------------------------</td>
</tr>
</tbody>
</table>
| Address           | John Roads  
Scripps Inst. of Oceanography  
UC-San Diego  
Geosciences Research Div., 0244  
La Jolla, CA 92093-0224 |
| Phone Number      | 858-534-2099 |
| Fax Number        | 858-534-8561 |
| Email Address of Center Director | jroads@ucsd.edu |
| Role of Institution at Center Partner in scientific research and education |

<table>
<thead>
<tr>
<th>Institution 10 Name</th>
<th>University of New Mexico</th>
</tr>
</thead>
</table>
| Address             | David S. Brookshire  
University of New Mexico  
Dept. of Economics  
Social Sciences Room 1019  
1915 Roma NE  
Albuquerque, NM 87131 |
| Phone Number        | 505-277-1964 |
| Fax Number          | 505-277-9445 |
| Email Address of Center Director | brookshi@unm.edu |
| Role of Institution at Center Partner in scientific research and education |

1b. Biographical Information for New Faculty

The only new faculty added this year is Doug Boyle from Desert Research Institute, Reno, NV, who will be working with Thrust Area 1. His biosketch is in Appendix A.
2. Executive Summary

Vision of the Center

Approximately one-third of the land surface of the Earth, including a quarter of the contiguous U.S., is arid or semi-arid. These regions 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 protecting the water supply (quantity and quality) and ecosystem health. Policy decisions, planning and management are complicated by various factors including a variable and uncertain global climate, strong heterogeneities in ecology and topography, and rapidly changing land uses.

The vision of SAHRA, the NSF Science and Technology Center for Sustainability of semi-Arid Hydrology and Riparian Areas, is developing an integrated, multi-disciplinary understanding of the hydrology of semi-arid regions, and building partnerships with a broad spectrum of stakeholders (public agencies and private organizations) so that this understanding is effectively applied to the optimal management of water resources and to the 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?” This highlights the fact that SAHRA is concerned both with advancing the understanding of fundamental principles in semi-arid hydrology (through stakeholder-driven multi-disciplinary research), and with developing strategies for implementing scientific understanding on a practical level through aggressive knowledge transfer and strong education initiatives (K-16 and public).

Goals

The overarching goals of SAHRA are to make significant advances in the understanding of semi-arid hydrology, and to help bring that understanding rapidly to bear on the practical problems of water resources policy, management and operational decision making. SAHRA’s greatest challenge, therefore, 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. This coordination involves the diverse talents of physical scientists, behavioral scientists (including economists), educators, practicing engineers (from both public agencies and private companies), legal experts, and decision makers. This challenge can be considered met if new technologies, analytical tools and modeling approaches are rapidly assimilated into the understanding and management of water resources. To achieve this overarching goal, the Center seeks to:

1. Promote and conduct large-scale, long-term, societally responsive, high-risk, integrated research (including the social and natural sciences) to understand demand and supply aspects of water resources and how these aspects interact
2. Build understanding of key water issues into K-16 science education
3. Promote hydrologic literacy throughout the population that makes water-use and related political decisions
4. Foster a multi-disciplinary perspective and build technological skills within the professional water resources policy and management communities
5. Promote and conduct successful multi-disciplinary collaborations
6. Promote and conduct successful multi-institutional collaborations
7. Foster collaboration with stakeholder groups
8. Achieve recognition as a leader in semi-arid hydrology
9. Achieve post-NSF sustainability

The overall performance of SAHRA can be assessed and evaluated in terms of progress towards meeting each of these nine major goals (see “Performance and Management Indicators” below).
Plans

SAHRA began its operations as a Center in February 2000. While the first year was dominated by start-up issues, research was also initiated, primarily by students already in our graduate programs. Other researchers were phased in as personnel were recruited. SAHRA’s second year was devoted to developing a better understanding of critical water-related issues in the semi-arid southwestern United States and to strengthening partnerships with stakeholder groups in the region. During this period, recruitment for additional scientific and technical personnel continued, and we began to develop a more strongly integrated program of research, education and knowledge transfer. The Centers’ science-education-knowledge transfer goals were refined based on our early experience and on feedback from the advisory board and stakeholder groups.

The past 10 months of SAHRA (October 1, 2001 – July 31, 2002) have seen even greater activity. Primary objectives during this period have been to: a) refine the science plan and strengthen the integration of our science activities (both across projects and disciplines); b) recruit additional scientific and technical personnel; c) accomplish considerable scientific research; d) continue to strengthen partnerships with stakeholder groups; e) expand and improve educational programs; and f) broaden knowledge transfer activities to better serve stakeholders and the general public, and increase international activities outside of North America.

During the fourth and fifth years of SAHRA we expect to continue working on the primary objectives described above, while increasing international outreach and developing knowledge transfer tools for other semi-arid regions of the world. Three main tasks, however, must be completed during the fall of 2002. The first task is to review all existing science tasks and activities supported by SAHRA to determine what has been learned. Tasks that are failing to integrate well with the developing science goals of SAHRA, or that are nearing completion will be phased out. New tasks will be selected for support. Particular attention will be given to including new and innovative science activities. The second task is to prepare the 5-year renewal proposal (for the second phase of STC support) to be submitted to NSF at the end of January 2003. The groundwork for both of these tasks is in place, and SAHRA participants are already preparing suggestions for SAHRA science activities to be considered for inclusion in the renewal proposal. The third task is to implement the database infrastructure to properly track the performance and management indicators used to assess performance and progress.

At the end of the fourth year, we expect to move into new SAHRA facilities, the entire 5th floor of the new Marshall Foundation building currently under construction by the University of Arizona. This move was originally scheduled for this year, but construction of the building has been delayed.

Performance and Management Indicators

The performance and progress of the science and management of the Center are evaluated in terms of the nine major center-wide goals (see “Goals” above). Each of the major sections of this report (Research, Education, Knowledge Transfer, Partnerships, Diversity, and Management) lists Performance Indicators that are being used to measure and assess progress towards achieving these goals.

Significant Changes from the Original Plans

The activities of the Center are firmly on track. The significant change from our original plan has been an evolutionary extension of our science “Thrust Area” focus to mesh with a “River-Basin” focus for coordination and integration of SAHRA science activities. While SAHRA scientists will continue to organize many activities around the Thrust Area themes, the overall project coordination and budgetary decisions will, from the fourth year on, be coordinated around the selected river-basins (currently the Rio Grande and San Pedro/Gila) in order to achieve stronger science integration.
Progress toward Meeting Third-Year Objectives

During the past 10 months, considerable progress in achieving the third year objectives (see “Plans” above) has been made:

a) Science: Major field sites have been established and many science projects are now into their third year and beginning to mature. A number of interesting results have begun to emerge; selected science findings are listed at the end of this executive summary (detailed reports appear in Section II). A major activity during this reporting period was our comprehensive review and evaluation of the organization of SAHRA science. This has led to an ongoing discussion (at a series of science workshops) of the role of basin-related “relevant scenarios” and “major issues” as driving mechanisms for guiding SAHRA science. Based on this we have moved toward a river basin focus for integration and coordination of science activities. So far, this appears to be a productive direction to pursue. We continue to actively involve stakeholders in the review and discussion of the major thrusts of our research activities.

b) Education: A significant amount of our educational effort has been placed on course development and internal education activities, based on a careful assessment of needs. These include a graduate seminar, an undergraduate water issues course, a seminar series, a professional degree program in Water Resources Engineering, a spring snow field camp, graduate assistantships for community service, research experiences for science and non-science undergraduates, a high school intern program, an undergraduate environmental hydrology course, and science education research. External education activities include teacher workshops on integrating inquiry and water issues, development of a high school curriculum on semi-arid hydrology, the joint SAHRA/Project WET collaboration, the joint SAHRA/GLOBE collaboration, an informal education water sustainability module, and environmental education outreach for Native American K-12 teachers. Professional development activities included a tribal watershed analysis and management workshop and a workshop for watershed collaborations. Details appear in Section III. The success of these programs will be judged by their persistence, growth in numbers served, and quality of product.

c) Knowledge Transfer: Our objectives have not changed, but our emphasis continues to evolve and broaden. We continue to enhance internal knowledge transfer (KT), but have focused on improving KT with water resources professionals, and developing KT initiatives with stakeholders and the general public. Examples of the latter include our Web-based News Watch Service and Residential Conservation information, Rural Water Resource Centers and Sabino Canyon Visitor Center display. We continue to seek areas where potentially useful information is not currently available from other sources, and to integrate content components so as to create synergies. Our international activities also are broadening, as we move beyond a focus on northern Mexico.

d) Recruitment: Postdoctoral researcher, student, and staff recruitment has continued. Postdoctoral research associate (PDRA) Elizabeth Hancock (TA6/Education) was brought on board, bringing the total complement of junior scientists to six. SAHRA is currently supporting 65 graduate and 28 undergraduate students, of which approximately two-thirds are located at the UA and one-third at the various partner institutions. Also, six high school student interns were recruited to work on SAHRA projects during the summer. Five new staff positions were also filled including one technician (Tom Vega), a computer support systems analyst (Dean Jones), an editor (Mary Black), a graphic designer (Brad James), and a support systems analyst (Steven Schroeder). During the year an unsuccessful attempt was made to recruit a mesoscale modeler at a research scientist level position; this position remains unfilled and recruitment efforts are continuing. A search continues also for the TA5 (Social Science) PDRA, with two candidates scheduled for interviews during August 2002. NSF provided SAHRA with an REU supplement of $54,000 for the period 6/01-5/02 and followed this with a second REU supplement of $57,500 for the period 6/02-5/03. A total of 12 REU positions were filled in the last 10 months and we expect to fill 15 REU positions this year on four SAHRA campuses.

e) Communication: Communication is carried out via in-person group meetings, phone conferencing, e-mail, website and workshops. Activities and reports are coordinated by e-mail and phone. “Blue
rooms” (phone conference facilities augmented with data sharing technology) are being set up at three additional partner locations; the one at UNM is operational, and the two at NMT and ASU are under construction. A multi-point test of the conferencing facilities is scheduled for August 2002. The public web site (www.sahra.arizona.edu) is now quite mature and is updated regularly. The web site has a private side where information specific to SAHRA researchers (including documents, reports, presentations, database, and meeting minutes) can be accessed. A series of SAHRA sponsored seminars by prominent scientists is ongoing; during the past reporting period, SAHRA researchers Prof. Chris Duffy (PSU), Dr. Regan Murray (LANL), and Dr. Stan Leake (USGS) and guest scientists Dr. Eric Webb (SNL), Dr. Matt Parker (CSU), and Dr. Dag Lohmann (NCEP) gave seminars in Tucson, and Prof. David Brookshire gave a seminar in Socorro.

f) Organizational Meetings: The Executive Committee meets monthly, typically on the last Tuesday of each month. The pattern is two successive meetings by phone conference followed every third month by an in-person two-day meeting at the University of Arizona. Administrative staff meetings are held weekly on Thursday mornings. The five staff directors meet approximately monthly to coordinate and discuss strategy. The Associate Director makes periodic visits to some of the partner institutions (primarily those in New Mexico) to coordinate and discuss science integration and other issues. The NSF site visit will be held in Tucson on August 28-29, 2002. The External Advisory Board (EAB) meets annually; this year’s meeting is tentatively scheduled to be held in Tucson on October 4, 2002.

g) Annual Meeting: The second annual meeting of SAHRA scientists and stakeholders was held in Tucson, Arizona on February 25-28, 2002. The 4½ days of activities included oral and poster science presentations, with an emphasis on student participation, a “public” day to which numerous guests were invited, thrust area planning break-out sessions, and various student activities including a field trip to the San Pedro basin experimental sites. Members of the EAB and the NSF oversight team attended, along with Dr. Nathaniel Pitt (Director, NSF Office of Integrative Activities), who was present as an observer. There were 226 attendees at this year’s meeting (compared with 155 attendees at the First Annual Meeting in 2001). The meeting produced important feedback from the EAB and NSF teams, which significantly influenced activities during the remainder of the year.

h) Science Workshops & Coordination Meetings: As a follow-up to the “SAHRA workshop on recharge” held in Socorro, NM, on March 22-23, 2001, an AGU Special Session on “Recharge and Vadose Zone Processes in Semiarid and Arid Regions” (organized by SAHRA researchers Phillips, Duffy and Hogan) was held at the Fall 2001 meeting of the American Geophysical Union in San Francisco, December 12, 2001. Related to this, an AGU monograph on recharge is under preparation for publication by the AGU press, with anticipated publication in Spring 2003 (see Section VIII). A Committee on Integration was formed and a series of science integration discussion meetings were held in Tucson resulting in a proposal for restructuring of SAHRA science activities based on a river-basin focus. This led to several important planning meetings in both Tucson and Albuquerque, with the focus on basin-scale integrated modeling. These include three workshops; a SAHRA wide “modelers” meeting in Albuquerque, September 20-21, 2001, a “Rio-Grande river-basin” science workshop held in Taos, NM on June 6-7, 2002 attended by 38 researchers and a “San-Pedro/Gila river-basin” phone-conference workshop on July 11, 2002, attended by 24 researchers. A follow-up “Rio-Grande river-basin” science workshop will be held in Albuquerque, NM on September 26-27, 2002. In addition to helping focus and coordinate the science, these meetings have resulted in the identification of a number of new and exciting cross-disciplinary and multi-investigator science initiatives that are now being actively developed. Another outcome is the formation of a Core Integrated Modeling Team, which had its first meeting in Tucson on July 17, 2002; the charter of the group is to coordinate and push the development of the basin-scale models that will serve to incorporate and integrate the model components under development by other SAHRA researchers, with particular emphasis on the marriage of social and natural science model components. In addition, SAHRA hosted a Model Parameter Estimation Experiment (MOPEX) workshop (Tucson, AZ, April 8-10, 2001), and was a co-sponsor of the AGU Chapman Conference on Eco-hydrology of Semiarid Landscapes, Interactions, and Processes, (Taos, NM, September 9-13, 2002) and the Water Advisory Council Meeting (Mayer, AZ, July 18, 2002).
i) **Facilities:** Architectural plans for the new SAHRA facilities, to be located on the entire fifth floor of the new Marshall Foundation building, have been refined, completed and approved by the University. However, construction of the building has been delayed and is now scheduled for completion around August 2003.

j) **Funding:** Given the broad scope of SAHRA’s mission and the wide-ranging nature of its activities, the need for additional financial resources continues to grow. SAHRA has been successful in acquiring additional funding to help support those needs listed in Section VII. In particular, NSF was very helpful in providing us with a considerable amount of supplemental student support (REU funds) and in matching us with California State University, Los Angeles in a collaborative research initiative (CEA-CREST).

**Overview of Significant Accomplishments**

a) **Research:**
- A fully equipped 30m eddy correlation tower was installed on Mt Bigelow.
- Improvements to the spatial and temporal continuity of SWE estimates were achieved, which indicates that the snow-covered area (SCA) beneath clouds can be determined with some success.
- The optimal set of electrical resistance tomography (ERT) arrays to be used in conducting an ERT survey has been identified. This is a critical first step to adapting ERT to monitoring transient hydrologic processes. One surprising result is that the most sensitive (and therefore preferred) array type is neither of the commonly applied arrays. That is, we have demonstrated that the current practice of ERT measurement is not optimal and we have developed guidelines to improve ERT measurements.
- Rainfall intensity-infiltration relationships have been developed for four ecological sites (soil vegetation complexes) within the San Pedro Basin.
- A rainfall estimation algorithm based on a cloud classification scheme was developed. We have distinguished snowfall from rainfall and estimated snowfall depth from Snow Water Equivalent (SWE) where temperature was less than 2°C for daily snowfall estimates at 0.25 x 0.25 lat/long resolution over the southwest U.S. Daily snow estimates using PERSIANN precipitation and surface temperature from Eta model were produced.
- The semi-empirical, distributed MMS/PRMS hydrologic model was used to produce stream discharge forecasts in the 21 headwaters basins in the upper Rio Grande.
- Regional-scale ET and soil moisture calculated using SEBAL (Surface Energy Balance Algorithm for Land) compares favorably with eddy covariance measurements, making this a promising technique for stakeholders such as the Middle Rio Grande Conservation District and in the modeling effort (for both input and validation).
- Preliminary results, from 21 experimental drought plots at the shrubland – grassland transition in the Sevilleta LTER, indicate that shallow soil moisture content is the dominant control on ET. Vegetation type does not significantly affect ET rates, however it does affect how ET is partitioned, with grasslands having greater transpiration rates.
- The combined use of several isotopic systems (O, H, S, C, $^{3}$H, $^{14}$C,) clearly indicates the importance of large arroyos (e.g., Rillito, Santa Cruz, Rincon Creek) for groundwater recharge in the Tucson Basin, with the exception of the center of the basin which may represent upwelling of mountain block recharge from deep flowpaths.
- Research on the Hueco Bolson (undertaken with our partner NSF center, CEA-CREST at California State University, Los Angeles), underway for ~6 months, has already succeeded in developing the cooperative agreements and collaborations on both sides of the US-Mexico border that will be necessary to complete this project.
- Cottonwood and willow abundance were found to increase across longitudinal river gradients in the San Pedro at sites with shallow groundwater and higher flow frequencies, whereas saltcedar abundance decreases.
- Streambed temperature sensors were used to classify stream reaches as perennial, intermittent, or ephemeral.
Two transects of novel scour pans have been established to measure real-time sediment scour and fill in a point bar during episodic flow events on the San Pedro River.

Chemical analyses of organic matter sources throughout the year confirm that the increases in DOC and DON during the monsoon are the result of terrestrial organic matter being transported to surface water.

Disaggregated consumer demand experimental and survey responses were used to investigate demand for water. The experiments simulate water consumption from a potentially exhaustible source, revealing heterogeneous demand for water. Econometric estimates of water demand were estimated for differing consumer groups.

Existing research on the demand for water is based upon prices that do not reflect the full cost. Thus, the predictive ability of these models is limited. A set of experiments using Albuquerque water users as subjects simulated water use in a variety of historical price, income and rainfall conditions. Preliminary results indicate that a context-specific experiment can elicit responses that correlate to actual water use. This sets the stage for experiments that are conducted over price regimes that reflect the full cost of water.

Alternative procedures, both parametric and non-parametric, were defined for the bivariate characterization of drought severity, intensity and duration.

b) Education:

Internal workshops were held on integrated modeling and research emphases related to the Rio Grande.

Successful external education projects included GLOBE workshops for teachers in New Mexico and Arizona, a teacher workshop on content and practice in teaching for hydrologic literacy, and student and researcher presentations at the AGU fall meeting.

Development of the Student-centric Program for Learning About Semi-arid Hydrology (SPLASH), a water curriculum, continued throughout the year and will be piloted in the fall of 2002. This program involves intensive collaboration among middle and high school science and social studies teachers, scientists, and science educators.

c) Knowledge Transfer:

The SAHRA web site has been expanded into an international resource and clearinghouse for several types of water information. Water News Watch debuted in Fall 2001, and currently contains nearly 3,000 summaries of Web-based news reports and scientific reports. We now cover material posted in seven languages (English, French, Italian, Spanish, Portuguese, Farsi, and Greek), with 375 of our summaries covering non-English sources. We have added a survey function, and graphics to illustrate selected stories. Other enhancements include “Residential Water Conservation” and “Isotopes in Hydrology” areas.

SAHRA is developing new ways to inform stakeholders and the general public. Rural Water Resource Centers are nearing completion for two Arizona counties (Cochise and Yavapai), and will eventually be established in Cooperative Extension offices in all rural counties. Each center includes a county-specific collection of printed materials and an Internet-connected computer system with county-specific searchable databases and other materials. Users can get information in printed form, on CDs, or by e-mailing it to themselves. In cooperation with the US Forest Service and the US Geological Survey, SAHRA has developed static displays, a touch-screen kiosk, and an animated Web site on Sky Island climatology and desert stream hydrology for the Sabino Canyon Visitors Center (Tucson, AZ). Both projects will be complete in Summer 2002.

Efforts in the area of Professional Development are starting to bear fruit. Planning continues for the first SAHRA water professionals’ mini-course, on the subject of Indian Water Rights, scheduled for Spring 2003. SAHRA has worked with the US Army Corps of Engineers to develop a new version of the UA’s Masters of Engineering in Water Resources degree for working professionals. The Corps will be sending mid-career staff to the UA starting Fall 2002.
d) Leveraged Funding:

- SAHRA received an Eisenhower Grant, two CATTS fellowships, and State of Arizona Proposition 301 funds to support development and implementation of curriculum modules for the SPLASH high school science course in semi-arid water resources.
- SAHRA is receiving support from the Bureau of Reclamation, the Audubon Society, and Cochise County for research into disaggregating residential water demand using low-cost technology.
- SAHRA is sharing resources with the US Forest Service, Coronado National Forest, and the US Geological Survey’s Tucson office to develop displays, a kiosk and a Web site on the hydrology of desert mountain streams for the Sabino Canyon Visitors Center.
- SAHRA received significant and much needed grant supplements from NSF for Center-wide remote conferencing facilities ($32,000), REU’s ($57,500) CEA-CREST Glue Grant ($529,710 over 3 years), and supplemental graduate student support ($319,274).
- Several other sources of research funding have been obtained (see Section VII).
II. RESEARCH

1a. Overall Research Objectives

The mission of SAHRA is to “promote sustainable management of water resources in semi-arid regions.” Because SAHRA is a university-centered NSF Science and Technology Center, its activities are strongly focused around the physical and behavioral sciences. Therefore the mission statement can be expressed as the question “How can SAHRA use science to help communities manage their water resources in a sustainable manner?” This question highlights SAHRA’s concern both with advancing the understanding of fundamental principles in semi-arid hydrology (science research), and with developing strategies for implementing scientific understanding on a practical level (knowledge transfer and education).

Clearly, the ability of SAHRA to achieve its mission depends on a number of factors. On the one hand, SAHRA must advance the science. On the other, we must ensure that the principles and models in practical usage are kept current. The former involves coordination and integration of existing understanding and methods from a number of diverse physical and behavioral disciplines. In addition, it requires that we continue to target and support novel and cutting-edge research activities that advance our understanding of the fundamental principles in semi-arid hydrology.

To ensure that sound, up-to-date scientific understanding is properly integrated into the water allocation and management process (from operational practice through policy making), the activities of SAHRA are organized towards establishing a smooth connection between science processes and decision-making processes at both the operational and policy levels. We recognize that the needs of decision makers at these two levels should influence the selection of SAHRA science activities by identifying areas where science can provide improved understanding of the physical and behavioral components of the system. At the same time, SAHRA aims to foster more effective application of existing and emerging scientific understanding. To achieve the former, SAHRA continues to develop strong interactive relationships with a broad spectrum of resource-manager stakeholders. With regard to the latter, the science activities currently supported by SAHRA have been selected to emphasize important semi-arid regional water-related science issues that are either not well understood, or are not currently receiving sufficient attention. The key research objectives of SAHRA are listed below:

- To estimate and model the spatial and temporal components of the environmental water balance in semi-arid regions by intensive and continuous field observations, coupled with modeling, in subalpine areas and a variety of ecological locations on the desert floor.
- To understand surface and subsurface water and solute balances in semi-arid regions at large spatial and temporal scales (i.e., up to the scale of a river basin and up to decadal and longer time scales).
- To understand how riparian systems affect and are affected by changes in water quantity (e.g., due to ground-water pumping or conjunctive stream-water management) or water quality (e.g., nitrogen inputs from precipitation or agricultural runoff).
- To integrate emerging scientific understanding into comprehensive river basin models that can be used in the analysis of water resources management issues.
- To examine and analyze issues related to water-resources policy, including behavioral, sociological, and economic factors of demand in semi-arid regions of the Southwestern U.S., and integrate current SAHRA modeling and physical sciences efforts with community water planning and management.

To achieve these five objectives, the science activities of SAHRA are organized into five Thrust Areas (TAs) with the activities of each TA focused around the major topics listed below. The list indicates which TA has the lead role for a topic; there is considerable interaction between TAs on most topics. Note that Thrust Areas 1-3 represent the natural sciences, Thrust Area 4 represents the integrated modeling sciences, and Thrust Area 5 represents the social and behavioral sciences. The individual TA descriptions in Section II provide details regarding the objectives and accomplishments of each thrust area.
### TA1: Spatial and Temporal Components of the Water Balance
- Environmental water balance above the mountain front
- Runoff and infiltration in semi-arid regions
- Remote sensing and modeling of precipitation
- Hydrologic modeling of headwater basins

### TA2: Basin-Scale Water and Solute Balances
- Vegetation and vadose zone processes of the basin floor
- Basin-scale hydrologic systems

### TA3: Functioning of Riparian Systems
- Water and carbon exchange in riparian systems
- Nutrient cycling in riparian systems

### TA4: Multi-Resolution Integrated Modeling of Basin-Scale Processes
- Fine resolution integrated modeling
- Medium resolution integrated modeling
- Basin-scale systems modeling

### TA5: Water as a Resource: Competition, Conflict, Planning, and Policy
- Institutional analyses and social assessments
- Behavioral aspects of water markets and water banking
- Non-market valuation
- Water resources and management operations

#### 1b. Performance and Management Indicators Developed to Assess Progress
SAHRA research addresses the many facets of hydrology and water resources in semi-arid regions. The Center program involves a number of researchers from many institutions, working together through long-term, coordinated and interdisciplinary research. Scientists in the Center conduct basic, often high-risk research in partnership with stakeholder groups, leading to the rapid dissemination and application of cutting-edge scientific knowledge. To evaluate the performance of SAHRA research we must consider both the ability to conduct research in a “center mode,” as well as the dissemination and impact of research results. Below we list some indicators by which our success can be gauged. Throughout the research narrative that follows, many of these points are highlighted.

**Indicators of “Center Mode” Research**
- List / Number of disciplines represented within SAHRA
- Number of multi-disciplinary presentations and publications
- Number of multi-institution presentations and publications
- List of integrated field sites / sampling campaigns
- Number of students with multi-disciplinary or multi-institutional thesis committees
- Dollar amount of resources being leveraged
- List / Number of workshops / meetings held at partner institutions
- List / Number of stakeholder partnerships
- List / Number of stakeholders participating in SAHRA workshops / meetings
- List / Description of SAHRA participation in stakeholder group meetings

Indicators of Research Results and Impacts
- List / Number of publications and presentations subcategorized as “multi-disciplinary authorship,” “multi-institution authorship,” etc.
- List / Number of invited talks (professional meetings, peer institutions, public forums etc.) subcategorized as “multi-disciplinary authorship,” “multi-institution authorship,” etc.
- List of nominations, honors and awards (for individuals and the Center)
- List of research sessions organized/chaired at professional meetings
- List of student theses, highlighting those having “multi-disciplinary” and/or “multi-institution” advisors/committee members
- List / Number of edited research monographs
- List / Description of participation in relevant local, regional, national and international committees, panels, and boards
- List / Description of press coverage of SAHRA research
- List / Description of water resources policy/management decisions and operational procedures impacted by SAHRA research

1c. Problems (past and anticipated)

Problems that have hindered progress towards achieving our research objectives can be categorized as a) Delays in recruiting, b) Delays in implementation of communication systems, c) Issues in science coordination, d) Financial limitations, e) Delays in field sites becoming operational, and f) Need for development of a coordinated knowledge-base. These problems and how we are dealing with them are described below with further detail of some of the issues provided in Section VII.

A) Delays in Recruiting:

As described in Section VII, we have experienced delays in recruitment of certain personnel, thereby slowing the process of setting up the infrastructure that supports the research. During the past reporting period PDRA Elizabeth Hancock (TA6/Education) was brought on board, bringing the total complement of junior scientists to six. Five additional staff positions were also filled including one technician (Tom Vega), a computer support systems analyst (Dean Jones), an editor (Mary Black), a graphic designer (Brad James), and a support systems analyst (Steven Schroeder). However, finding suitable candidates for the TA5 (Social Science) PDRA has proven difficult; two candidates have recently been scheduled for interviews during August 2002. It has also proven difficult to recruit a suitable candidate for the TA4 Mesoscale Modeler Research Scientist position; one promising candidate was offered the position but decided to accept a faculty position elsewhere. A new candidate is scheduled to be interviewed at the end of July 2002.

B) Delays in Implementation of Communication Systems:

Regular phone conferencing has been routinely used. The video and data sharing facilities in SAHRA’s conferencing room have been used far less often due to the lack of comparable facilities at partner institutions. The teleconferencing supplement from NSF has enabled us to set up three identical remote conferencing (phone and data) rooms at the University of New Mexico (complete and working), the New
Mexico Institute of Mining and Technology (under construction), and Arizona State University (under construction). A multi-point test of these facilities is scheduled for August 2002.

C) Issues in Science Coordination:

During this reporting period, the SAHRA administration and executive committee gave considerable attention to coordination of the science activities. While there were minor issues across the board, it became apparent that major strategic changes might bring about greater and more meaningful integration of the various science activities. Based on the Conceptual Integration model proposed by the Committee for Integration, the first strategic change was to adopt a multi-resolution approach to basin scale modeling at the September 2001, TA4 workshop in Albuquerque (see TA4 report). The second strategic change was to adopt a “river-basin” focus. The management team has worked steadily during this past year to implement both of these changes. The first move was to organize presentations at the SAHRA Annual Meeting into sessions devoted to the Rio Grande river basin and the San Pedro river basin. Next, a series of basin-focused workshops were held: a “Rio Grande river-basin” science workshop held in Taos, NM on June 6-7, 2002 and a “San Pedro/Gila river-basin” phone-conference workshop on July 11, 2002. A follow-up “Rio Grande river-basin” science workshop is scheduled for Albuquerque, NM on September 26-27, 2002. Finally, a Core Integrated Modeling Team, was formed, which had its first coordination meeting in Tucson on July 17, 2002; the charter of the group is to coordinate and push the development of the basin-scale models that will serve to incorporate and integrate the model components under development by other SAHRA researchers, with particular emphasis on the marriage of social and natural science model components. A primary objective of the next reporting period will be to review all science projects with a view to strengthening the river-basin focus and to making considerable progress toward developing conceptual and numerical models of the Rio Grande basin.

D) Financial Limitations:

Our original proposal for the SAHRA Science and Technology Center requested and was awarded approximately $16M of the maximum possible $20M. The proposed budget included insufficient funds to cover inflation in salaries and other costs, and for certain critical activities such as developing teleconferencing facilities and the knowledge base. The SAHRA STC includes many more partner institutions than most other STCs, and the travel and communication overhead is therefore significantly greater. Further, the science ambitions of SAHRA researchers have expanded considerably as the Center has become established, and as the magnitude of the sustainability problem in semi-arid regions has become better understood. In response, SAHRA has sought out and obtained additional funding to help support these needs as listed in Section VII. Other leveraging possibilities are being actively explored. These additional funding sources will facilitate a more comprehensive implementation of the mission of SAHRA, while spawning offshoots to the primary research initiatives.

E) Delays in (and threats to) field sites becoming operational:

A major unanticipated problem has caused delays to some of our planned fieldwork. In May-June 2002, after several construction delays, the hydro-meteorological instrumentation towers at Mt. Bigelow (near Tucson) were almost completely installed when a major wildfire swept across the Santa Catalina Mountains. Access to the site was cut off, and for nearly two weeks the site was under imminent threat of being destroyed. Fortunately, national forest fire crews halted the fire about 100 meters from the tower site and the entire installation (an expenditure of approximately $250,000) escaped damage. Unfortunately, none of the instrumentation was operational and SAHRA missed a major opportunity to collect fire event data. The site is now operational and remote access data acquisition mechanisms are currently being tested and refined. We anticipate being able to collect full monsoon and snow season data from now through Winter. In a separate incident, two of SAHRAs field sites in the San Pedro River basin for studying rainfall-runoff processes were burned. We expect to obtain valuable information about the changes in infiltration/runoff rates caused by rangeland fires. Fire hazards for San Pedro field sites remain high.
Another major problem is that SAHRA has not yet acquired a vehicle for accessing field sites. SAHRA researchers continue to use personal or rented vehicles. Travel to these sites, and maintenance of them, has resulted in higher-than-expected operational expenditures, which draw funds away from other budgeted categories. These expenses are likely to increase, making it difficult to maintain the sites in top condition so that data gaps are minimized.

F) Need for Development of a Coordinated Knowledge base:

We mentioned in the second annual report the urgent need to develop an easily accessible web-based “knowledge-base” repository of information to enable sharing and communication of research plans and results, and to support science, education and knowledge transfer activities. Although we have begun development of this coordinated knowledge base (Section VII), progress has been slow and is lagging behind (and hampering development of) the science. Partly, this is because the “knowledge-base” effort has proved to be a more complex task than previously imagined, but a primary reason is that SAHRA personnel have been heavily burdened by other (administrative) tasks such as conducting meetings and workshops, planning for the project review, and responding to NSF’s requests for early preparation of the Annual Report and the Renewal Proposal. We have engaged the assistance of HyDIS researcher Eve Halper in the initial phase of this effort, but have not yet found the time to recruit a dedicated database specialist. This continues to be a priority, and now that the Core Integrated Modeling Team is operational, rapid progress during the next reporting period is expected.
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<th>Spatial and Temporal Components of the Water Balance</th>
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Thrust Area 1 - Spatial and Temporal Components of the Water Balance

The major goal of Thrust Area 1 is to measure, estimate and model the spatial and temporal components of the basin-scale water balance (snow accumulation, distribution, and melt, rainfall, evapotranspiration/sublimation, runoff, and infiltration) by intensive and continuous field observations, coupled with modeling, in areas above the mountain front and a variety of ecological locations on the desert floor.

There are four focus areas within TA1. The first focus is on the subalpine process and modeling studies aimed at partitioning precipitation and snowmelt into evapotranspiration/sublimation, soil moisture, runoff and groundwater recharge. The second focus is on runoff infiltration in semi-arid regions. The third focus is on estimating and modeling the regional distribution of precipitation using remote sensing. The fourth focus is on hydrologic modeling of headwater basins. All four research areas are linked by the common goal of trying to understand the components of the water balance across a catchment area and are differentiated by location and scale. Within the first two research areas, there are multiple projects.

1. Environmental Water Balance above the Mountain Front

The major goal of this focus area is to measure and model the components of the water balance above the mountain front. Determination of water yield from mountain precipitation and snowmelt is vital for estimating the annual water balance in large semi-arid watersheds. Currently there is very limited information about the distribution of hydrologic variables above the mountain front at the spatial and temporal resolutions needed for regional scale hydrologic modeling. Uncertainty in spatially distributed estimates of hydrologic variables introduced by the up-scaling of point measurements and down-scaling of course resolution space-borne remote sensing data motivates research on improving our understanding of the distribution of hydrologic variables at intermediate (0.1km -10 km) resolutions. Three research areas are being pursued in which improved understanding of water, energy and carbon cycling processes (sub-task 1.1.1) are used to improve parameter estimates for spatially distributing hydrologic variables (sub-task 1.1.2). Hydrologic modeling, incorporating the improved inputs and information about input uncertainty, is then used to assess the dependency of output accuracy on parameter and input uncertainty (sub-task 1.1.3).

The three individual research efforts share common primary data acquired in the field as well as common modeling efforts related to snow distribution, melt, runoff and evapotranspiration/sublimation. Similar energy balance, evapotranspiration/sublimation, soil moisture and carbon flux data sets are being collected by TA1 above the mountain front, by TA2 on the desert floor and by TA3 in the riparian zone. An additional data set from a high elevation alpine area has also been leveraged. These data sets are necessary for model development, calibration, and validation, both within these thrust areas and for integration in TA4. The point and basin scale snowmelt models developed and refined by this group are to be integrated into TA4 modeling efforts.

Water, Energy and Carbon Cycling in Southwestern Subalpine Forests

Shuttleworth, Brown, Bales, Harlow (UA-HWR)

Among the ecosystems present in the semi-arid environment of the southwestern US, the sky island forest is unique has a unique relationship to the sparse surface-water resources available in the region. This ecosystem exists only at the top of mountains because only there does long-term average precipitation input exceed evapotranspiration to the extent that forest vegetation can survive. Sky island forests, therefore, command potentially significant source areas for the water (some originally falling as snow) that ultimately leaves topographically high ground to recharge aquifers in the plains below via mountain-front recharge. Quantifying and understanding water, energy, and related carbon cycling and budgets of this sustainable source of water is of direct relevance to the mission of SAHRA.

The Mount Bigelow project aims to provide an empirically based understanding of the hydro-micrometeorological dynamics of a sky island sub-alpine forest in the southwestern U.S. The fundamental
science issues are: characteristics of the surface-atmosphere exchanges of water, energy and carbon; storage of moisture and energy in plants and soil; and partitioning of winter snow and rain between evapotranspiration/sublimation, deep drainage, and the near-surface environmental water resource that sustains the forest. In order to achieve our objective, a network of four below-canopy hydro-micrometeorological stations 3 m tall, and one above-canopy 30 m tall high-resolution eddy correlation tower were deployed within a predominantly Douglas fir/pine second growth forest. This network will operate for a minimum of two years and ideally for the next seven years, in order to capture strong interannual climate variability, as well as to leverage on the GEWEX-CEOP related activities as their semi-arid sky island reference site for the larger basin modeling activities. The Mount Bigelow project is the first study to document, analyze, and model the water, energy, and (related) carbon exchanges of the sky island forest ecosystem. The observations have year-round value. Data gathered in winter aids understanding of how water resources are replenished by winter snow and rain. Data collected in spring aids understanding of the partitioning of water between deep drainage and the near-surface environmental water resource that sustains the forest; while data gathered in summer and fall aids understanding of the evolution of the environmental water resource as it is depleted by evapotranspiration but replenished by monsoon storms. Because the sky island forest environment is unique and because the Mount Bigelow study is unique, every measurement made is novel, and every result obtained is potentially publishable.

Activities and Results:

During the period of September 2001 to June 2002 our research activities were primarily centered around the logistics of getting the eddy correlation tower installed and operational (permission for the tower was granted by the Forest Service in August 2001), and adjusting and refining the hydro-micrometeorological network that was installed in the summer of 2001. The observational system for the eddy correlation tower was successfully field tested and recently installed and operational. These systems are capable of routinely documenting, at the plot scale, the surface-atmosphere exchanges of water, energy, and carbon, the storage of moisture and energy in plants and soil, and the above- and below-canopy micrometeorological variables that control these exchanges and storages in a representative sky island forest ecosystem growing in the semi-arid southwestern U.S. The data from the micrometeorological network show distinct spatial variabilities in terms of below-canopy net radiation, soil and surface temperature, as well as in seasonal differences in the interrelationships of these variables as a function of location and canopy characteristics. The soil core equipment and subsequent analysis of the soil core samples taken at the sites were provided by SAHRA researchers at the US Salinity Lab, who will in turn use the results to enhance their database for semi-arid pedo-transfer functions. Our research is relevant to mountain block recharge studies and to high elevation snowmelt studies, and enables more detailed/accurate representation of the southwestern sky island in the various SAHRA modeling activities. The major activities over this period were:

- Installation of an abbreviated version of the scaffolding tower structure at a site in Tucson. Several sections of the scaffolding tower were installed at an easily accessible site in Tucson. Mounting designs and instrument layout were then tested. The observational system and power systems were also tested at this site. The data acquisition system was customized and installed at the local test site.
- Installation of the 30 m tower on Mt Bigelow. The 30 m tower on was completed in April 2002.
- Redeploying and installing the entire eddy correlation observational system on the 30 m tower on Mt Bigelow, which includes: 1 sonic anemometer, 1 open path Licor H₂O/CO₂ infrared gas analyzer, 1 4-way radiometer, 2 net radiometers, 3 profile levels with wind, temperature and relative humidity, 2 infrared thermometers (1 canopy and 1 surface), 3 sets of soil temp arrays (7 levels), 6 water content reflectometers, a total of 24 thermocouples installed for bole and xylem temperatures of 6 trees, and 1 rain gauge. The eddy correlation data is logged at 10 Hz and the profile, soil, vegetation data at 15-minute averages.
- Designed, customized and tested data processing routines for flux calculations.
- Acquired and examined eddy correlation data from several forested tall tower sites.
- A hydrometeorological seminar course was designed around the activities of the project and offered during the winter semester. Nine graduate students were engaged in both field and
theoretical aspects directly related to this project, and made valuable contributions to our progress.

- In collaboration with the Knowledge Transfer section, a group of 15 high school students completed a vegetation survey of the main eddy correlation site.
- Maintained and regularly download hydro-micrometeorological data from the four micrometeorological stations.
- Installed soil moisture probes and rain gauges at all sites. Multiple water content reflectometers and rain gauges were installed at all sites. Soil cores were taken from these locations and sent to the US Salinity Lab for analysis by SAHRA researchers at that facility.
- Analyzed and prepared data for publication from the micrometeorological network that was installed in the summer 2001.
- Researched innovative processing and delineation of high resolution DEM and vegetation images.
- Tested alpine spatial snowmelt model on a small watershed.
- Collection, quality control and post-processing of the eddy correlation data. The acquisition of 10 Hz eddy correlation data started in June 2002.
- The Mt. Bigelow eddy correlation tower has been incorporated as a reference site for GEWEX-CEOP, and has been participating in the associated planning activities for this endeavor.

**Plans for the Next Reporting Period:**

Sustained observations are ongoing at the Mt. Bigelow site and will be maintained using the current observational system (and any additional monitoring systems installed) at the main tower site and three subsidiary sites for at least two full annual cycles. This will allow us to sample the response of the sky island forest ecosystem to inter-annual variability of climate in the southwestern U.S., and as the high altitude, semi-arid observation site for GEWEX-CEOP. Over the next two years we plan to accomplish the following:

- Monitor, analyze, and model the partitioning of winter snow and rain between deep drainage and the near-surface, environmental water resource that sustains the forest. This will involve 1) during the spring months of 2003 and 2004, maintaining the routine observations needed to document the amount and vertical movement of water in the soil at the main tower and three subsidiary sites and the water balance of the Mountain Island Forest ecosystem as a whole, and adding any additional measurements required better to meet this objective; 2) implementing one-dimensional soil-vegetation-atmosphere transfer models with realistic, multi-layer simulation of soil water and energy movement at the main tower and three subsidiary sites, calibrating these models against the available data, and using them to calculate the proportion of water leaving as deep drainage and that retained for use by the forest; and 3) reporting results in presentations and journal articles.

- When there is winter snowfall, document, analyze, and model the evolution in snow and ice cover at four sample locations in the sky island forest ecosystem. This will involve 1) during the winters of 2002/2003 and 2003/2004, maintaining routine automatic observations relevant to snow and ice cover studies and undertaking additional snow surveys, as required, during periods when there is snow present at the main tower and/or three subsidiary sites; 2) implementing one-dimensional snow accumulation/melt models with different complexity at the main ec tower and three subsidiary sites, evaluating their comparative performance and, if required, modifying these models to improve their performance; and 3) reporting results.

- Monitor, analyze, and model the seasonal evolution in the near-surface, environmental water resource that sustains the sky island forest ecosystem, its depletion by evapotranspiration and sublimation and replenishment by snowfall and monsoon storms, and its relationship to plant physiological processes and to the exchange of carbon between the forest and the atmosphere. This will be achieved by: 1) processing and promptly controlling the routine observations from the Mount Bigelow sites to ensure provision of high quality data, 2) analyzing the fast-response data to investigate and define the nature of the turbulent regime at the mount Bigelow site; 3) analyzing the fast response data to provide routine documentation.
of the surface energy, water, and carbon dioxide fluxes for a typical Mountain Island Forest ecosystem; 4) analyzing the relationship between the surface energy, water, and carbon dioxide fluxes and meteorological, plant physiological, and soil water availability controls on these fluxes; 5) implementing and testing a plot-scale soil-vegetation-atmosphere transfer scheme (selected to be consistent with the preference of the SAHRA modeling group) for a typical Mountain Island ecosystem, and calibrating the parameters therein using the data from the Mt. Bigelow site; and 6) reporting results.

- As the selected high altitude, semi-arid observation site for the GEWEX Coordinated Enhanced Observing Period (CEOP), participate in CEOP by maintaining the collection of observations at the Mt. Bigelow site and providing these in timely manner as quality-controlled data to the CEOP data base. This will involve: 1) controlling the quality of routine observations made at the Mt. Bigelow in a timely manner and publishing these through the CEOP data system; 2) initiating collaborative research at CEOP semi-arid sites; and 3) reporting results.

- To the extent feasible, document over at least two years the difference in the surface exchanges of energy, water, and carbon for fully-grown sky island forest and forest that has recently been burnt. This will involve: 1) vectoring the high-resolution ec data according to wind direction and footprint, and analyzing the respective energy and carbon fluxes; and 2) reporting results.

- The activities listed above will provide SAHRA researchers with high-quality, high-resolution datasets for model validation, and functional relationships and understanding of the interrelationships between the subalpine hydro-micrometeorological variables and the physiological/physiographical characteristics.

**Spatial Distribution of Energy Balance, Snow Water Equivalence and Snowmelt in Seasonally Snow Covered Watersheds**

*Bales, Davis, Fassnacht, Molotch (UA-HWR)*

**Activities and Results**

The scientific questions that have been addressed during the current reporting period have been aimed at improving the spatial and temporal continuity of remotely sensed snow water equivalence (SWE) estimates, which are limited due to cloud cover, and improving our understanding of the uncertainty associated with the up-scaling of point measurements of snow water equivalence. These efforts apply directly to the overall goal of the project, which is to develop an advanced set of tools for accurately estimating spatially distributed energy balance variables, snow accumulation and melt in seasonally snow covered catchments. Spatial and temporal continuity improvements were achieved by using spatially distributed temperature estimates to define the snow cover extent under clouds in the Salt-Verde basin, Arizona. The spatial continuity of the SWE estimates was improved with a mean error of 21%, indicating that the snow-covered area (SCA) beneath clouds can be determined with some success. Improved understanding of the uncertainty associated with the up-scaling of point SWE measurements was obtained by using intensive field observations to validate spatially distributed SWE estimates derived from the interpolation of the Natural Resource Conservation Service’s (NRCS) Snow Telemetry station (SNOTEL) network. Field observations were collected at 7 sites during the 2001 and 2002 snowmelt seasons in the headwaters of the Rio Grande. Results showed that, at maximum SWE accumulation, SNOTEL stations overestimated the SWE across the study area domain. The overestimation of the SNOTEL stations resulted in an overestimation of spatially distributed SWE across the Rio Grande headwaters, with greater overestimation at peak SWE accumulation and increased accuracy as the melt season progresses. The data set collected during the field campaigns of 2001 and 2002, as well as the improved spatially distributed SWE estimates will provide a comprehensive ground truth estimate of SWE for modeling efforts in other thrust areas and sub-tasks, that can be used to validate/evaluate model-derived SWE.
Plans for the Next Reporting Period

Given the gaps in the hydrologic data acquisition needed for the goals of sub-task 1.02, the next logical step is to acquire and spatially distribute the remaining required hydrometeorological variables for the snowmelt modeling in the Rio Grande headwaters and Tokopah basin. The next step involves running a pair of snowmelt models.

- A physically based energy balance snowmelt model based on the equations of SNThERM.89 (Jordan, 1991).
- A parameterized snow melt model based on the equations of the modified SRM (Brubaker et al., 1996) in which snowmelt is computed based on the radiation and temperature fluxes between the atmosphere and the snowpack.

The two models are being used in the two different basins so that model output uncertainty can be compared for the following 4 cases:

- High-resolution physically based modeling with low-input uncertainty
- Low-resolution physically based modeling with high-input uncertainty
- High-resolution parameter based modeling with low-input uncertainty
- Low-resolution parameter based modeling with high-input uncertainty

Outputs of spatially distributed snowmelt and SWE from both modeling efforts will be validated/evaluated based on the SWE data already collected during the 2001 and 2002 snowmelt seasons for the Rio Grande and during the 1997 and 1998 snowmelt seasons for the Tokopah Basin. This effort will afford an estimate of the change in uncertainty when the techniques are applied at different scales and with different input data accuracies (i.e., the change in uncertainty when the model is applied at the research basin scale versus the operational basin scale).

Hydrologic Modeling of Alpine Snow and Runoff

Bales (UA-HWR), Fassnacht (UA-HWR), Miller (LBL), Nijssen (UA-HWR), Dressler (UA-HWR)

Activities and Results

Two research questions are being addressed under this research: 1) What is the impact of incorporating spatial maps of snow properties (from sub-task 1.1.2) into energy balance and mass balance models on runoff potential from alpine snowmelt; and 2) Which model parameter(s) are most crucial for accurate streamflow estimates when used at different spatial scales, and parameter grouping schemes (e.g. Hydrologic Response Unit vs. Grid Response Unit). Both questions have been addressed using the Precipitation Runoff Modeling System (PRMS) and will continue to be addressed using the NOAH Land Surface Model (LSM), forming a link with TA4 in the integrated modeling framework. Key results include a decision on which interpolation method is optimal for assimilation of SWE data at the scale of the Colorado River Basin and the conclusion that vegetation representation from differing sources is significant in accurate prediction of cumulative streamflow in the Salt River Basin using the PRMS model. Snowmelt modeling, basin scale hydrologic modeling and model parameter improvement efforts will be directly integrated with the modeling efforts of TA4 to address the various established scenarios.

Plans for the Next Reporting Period

Over the next two years we plan to:

- Assimilate the currently available snow data products into hydrological models and evaluate the impact of this assimilation on the runoff potential and streamflow prediction. The hypothesis is that assimilation of these data products will lead to better snowmelt forecasts and will enable improved management of water resources in the Southwestern U.S. Emphasis will be placed on the Salt-Verde River system in the Colorado Basin and the Upper Rio Grande River Basin. To
facilitate up-scaling of results to the SAHRA region at large, current modeling studies will implement the NOAH LSM as part of SAHRA’s integrated modeling framework.

- Improve snow process parameterizations, in the context of NOAH LSM, based on the results of detailed snow process studies. In this way, the research will provide a link between the high resolution, location-specific process studies and the basin-wide, medium resolution modeling efforts undertaken by TA4.

Information learned using PRMS will be transferred to the modeling with the NOAH LSM, as vegetation parameterization studies using PRMS are completed for publication. The overall focus of NOAH LSM studies will be point versus basin scale modeling in each of two study basins (i.e. Upper Rio Grande and Salt River Basins).

2. Runoff and Infiltration in Semi-Arid Regions

In semi-arid regions, the partitioning of precipitation into surface runoff, infiltration and potential recharge is highly variable in space and time. Understanding the spatial and temporal variability of these processes at a range of scales improves our ability to quantify and manage the available water resources. This research group is interested in understanding and quantifying the relationships among soils, their hydraulic properties, and hydrologic processes (rainfall, infiltration, and runoff) on upland areas and within ephemeral channels. Developing relationships between easily measured soil properties and vegetation characteristics and hydrologic processes is essential for up-scaling from point, plot, and sub-watershed to basin scale. Individual research efforts include: Quantification of recharge within ephemeral channels using ERT; Characterization of soil hydraulic properties; Estimating infiltration and runoff response of semi-arid rangelands.

Soil cores and measured associated hydrological parameters from the various research sites are sent to the USDA Agricultural Research Service’s Soil Salinity Laboratory (USSL). The USSL uses traditional laboratory techniques to derive soil hydraulic conductivity properties. These hydraulic and hydrological properties will be used as inputs for their neural network models for developing pedo-transfer function across a range of semi-arid environments. The hydraulic conductivity properties derived by the USSL from soil cores taken at the TA3 San Pedro sites will be compared (and used to evaluate) with those derived from in situ measurements using the electrical resistance tomography (ERT) method, a promising new geophysical method for characterizing the subsurface distribution of soil water. ERT relies on the dependence of the bulk electrical conductivity of a medium on its volumetric water content. The research of upland rainfall, infiltration, runoff and recharge in ephemeral channels will integrate with TA3 (riparian hydrology) for San Pedro basin scale modeling. Hydraulic properties and hydrological processes will also be provided to TA2 for a range of soil and vegetation complexes. The primary goals and objectives for this research focus area are to: 1) develop and test the ERT method of measuring soil moisture fluxes in ephemeral stream channels; 2) develop hierarchical pedo-topo-vegetation transfer functions (PTVTFs) to estimate soil hydraulic properties at different spatial scales (point, plot, patch, sub-basin, basin, region), and 3) determine the relationships among ecological site characteristics, rainfall intensity and the hydrologic response of an area.

Quantification of recharge within ephemeral channels using ERT
Ferré (UA-HWR), Furman (UA-HWR), Hinnell (UA-HWR), Simunek (UCR)

The electrical resistance tomography (ERT) method is currently used to qualitatively assess the two- or three-dimensional distribution of water and solutes in the subsurface. Our efforts have been aimed at 1) improving the practice of ERT to allow for monitoring transient hydrologic processes; 2) improving the inversion of ERT measurements to allow for quantitative subsurface imaging; and 3) providing guidelines for subsurface hydrologists to determine whether ERT is appropriate for their specific investigations.
Activities and Results

The focus of efforts during the past 10 months has been application of the analytical element method to ERT. Typically, several tens of ERT arrays are measured to construct a single subsurface image. While this is acceptable for defining static properties such as geologic structure, it limits the application of ERT to the monitoring of transient hydrologic processes. As a critical first step to adapting ERT to monitoring transient hydrologic processes, this research group has used the analytic element analysis approach to identify the optimal set of ERT arrays for use in conducting an ERT survey. The remainder of the summer 2002 will be focused on the continued development of coupled hydrologic and geophysical numerical models in conjunction with Simunek at the USSL.

The analytic element method is well suited to modeling the flow of electricity through a heterogeneous subsurface. Our initial approach has been to conduct a perturbation analysis to determine the spatial distribution of sensitivity of an ERT array throughout the subsurface. This method allows one to define the change in electrical potential throughout the subsurface due to the addition of a body that has an electrical conductivity that is different from the background. Based on these results, the response of any four-electrode ERT array can be predicted. Because the analytic element is so rapid, all possible arrays for each subsurface location can be investigated. Then, the sample area of each array can be described and the array can be uniquely identified with the greatest sensitivity to each point in the subsurface. A surprising result is that the most sensitive (and therefore preferred) array type is neither of the commonly applied arrays. That is, we have demonstrated that the current practice of ERT measurement is not optimal and we have developed guidelines to improve ERT measurements. Further efforts will focus on the optimization of ERT arrays for specific hydrologic applications. The goal of the research is to optimize the use of ERT to monitor transient subsurface hydrologic processes.

Plans for the Next Reporting Period

We have just begun to see the benefits of our fundamental research into the ERT method. Over the next two years, analysis will be advanced through the development of coupled hydrologic and geophysical models. In parallel, the improved ERT method will be applied to monitor infiltration and recharge beneath ephemeral streams and, in conjunction with other SAHRA researchers (Conklin and Grimm: TA2) and to monitor solute transport through streambed sediments.

Characterization of soil hydraulic properties

van Genuchten (USDA-ARS), Mohanty (TA&M), Leij (UCR), Schaap (UCR), Shouse (USDA-ARS), Simunek(UCR), Zhu (TA&M)

Soil hydraulic properties are the key constitutive relationships for water flow in the vadose zone. These properties quantify how porous media retain and transmit water while they also greatly affect the relative amounts of subsurface and surface flow. Measurement of unsaturated hydraulic properties is notoriously cumbersome and impractical for the simulation of subsurface flow and transport at the catchment scale. The main objective of our work in Riverside is to develop a pragmatic approach to estimate hydraulic properties for the San Pedro basin and to quantify the uncertainty of our estimates. To meet this objective, we have been measuring soil hydraulic and other basic soil properties, developing neural network models to predict hydraulic properties from soil and topographical attributes with pedotransfer functions (PTFs), and investigating the up-scaling of hydraulic properties from the sample scale. Our research will be applicable to several other SAHRA activities. Among them are the spatial distribution of hydraulic properties to elucidate patterns of runoff flow and erosion and the simulation of hill-slope hydrology in the San Pedro Basin. Furthermore we are involved in the inverse modeling and calibration of ERT surveys to conveniently estimate water content and solute concentration in the vadose zone.

Activities and Results

Approximately 120 soil samples are being analyzed for their unsaturated soil hydraulic properties at the Salinity Laboratory. Samples were taken from several sites in Arizona, especially from the San Pedro
basin. Water retention was measured using Tempe cells, and hydraulic conductivity was estimated using numerical inversion of the multi-step outflow data. Twenty-two soil cores are measured in each experimental run, which may last up to three months. Additional retention data are obtained at suctions of 1000, 3000, 8000, 15000 cm using pressure plate extractors. Soil texture and related soil physical properties have also been measured. Some 50 samples have been analyzed thus far.

Topography affects soil formation and some correlation has been found between topographical attributes and infiltration, surface water content and retention points. The effect of topography on hydraulic properties may be particularly pronounced for hillslopes. In collaboration with the investigators from the University of Naples in Italy, we therefore studied how well PTFs perform that use both basic soil properties and topographical attributes for a hillslope in Basilicata, Italy.

We continued the work on averaged hydraulic properties and water fluxes for a heterogeneous soil with an emphasis towards implementation and application. Pixels in meso- and regional-scale Soil-Vegetation-Atmosphere Transfer (SVAT) schemes of hydro-climatic models for semi-arid regions may represent an area between several hundred m² to km². Guidelines were developed how to best average hydraulic parameters for different textures and correlations.

Plans for the Next Reporting Period

Hydraulic properties will be required to model subsurface flow and transport for the Rio Grande and San Pedro basins and such properties may also be useful indicators for soil quality. In year 4 we will finish the measurement of soil and hydraulic data on the core samples and we also hope to garner some results from our involvement with ERT. We will then implement our findings in the SAHRA context using the general framework of predicting hydraulic properties over different scales that we developed in the first three years. Specifically, we will:

- Retool the Rosetta and UNSODA software for the San Pedro basin and, possibly, other areas
- Cooperate with other SAHRA researchers to utilize the data and to develop meaningful conclusions and guidelines for a range of scales and applications.

It is conceivable that the predictions with the newly calibrated PTFs will lead to systematic differences between estimated and observed hydraulic properties. PTFs for soils from the Southwestern U.S. will undoubtedly differ from those developed on more general databases that contain many soils from regions with humid climates and moderate temperatures. Several strategies may be pursued to improve estimates, including the use of Bayesian statistics. A central theme of our predictive methods is that we want to quantify the uncertainty associated with the estimation, including the distribution of predicted hydraulic parameters. Up-scaling can be achieved by running the Bayesian models on NRCS texture maps, developed from soil surveys, of the Rio Grande and San Pedro basins.

Estimating infiltration and runoff response of semi-arid rangelands

Goodrich (USDA-ARS/UA), Warrick (UA-SWES), Paige (USDA-ARS), Stone (USDA-ARS)

This research objective is to understand and quantify the relationships among soils, their hydraulic properties, and hydrologic processes (rainfall, infiltration, and runoff) in semi-arid upland areas. Developing relationships between easily measured soil properties, vegetation characteristics, and hydrologic processes is essential for up-scaling from point, plot and sub-watershed to the basin scale. Field research is being conducted on key ecological sites (soil – vegetation complexes) within the upper San Pedro Basin to quantify the relationships among rainfall intensity, ecological site characteristics and the resulting hydrologic processes, infiltration and runoff. Rainfall simulator experiments are being conducted to quantify these relationships at the plot and hillslope scales.
Activities and Results

The full range of infiltration rates for four ecological sites has been determined. These rates are related to easily measured soil and vegetation characteristics. The relationship has been developed and appears to be robust; however, it is still being validated. The field experiments and analysis will continue through the summer on a range of ecological sites. The results from the rainfall simulator experiments are being compared with results from soil hydraulic property research being conducted under subtask 1.2.2. Soil cores were taken within the ecological sites where the rainfall simulator experiments are being conducted. The results from the simulator experiments will be compared with the results from the soil cores and the pedotransfer functions. These will be used to improve our ability to scale up from point (soil cores) to plot and hillslope (rainfall simulator) and eventually to the watershed scale. This research is being conducted on uplands within the upper San Pedro River Basin. The results from this research will be important for linking the hydrologic processes on the uplands with the riparian areas in the basin-scale modeling efforts of SAHRA.

Over the past 10 months the research has had two distinct focal points:

- Infiltration theory and scaling
- Improving methods and methodologies for measuring infiltration and runoff on rangelands

Significant improvements have been made to the rainfall simulator. Both the mechanics for the simulator in general and the programming of the timing for the lower rainfall intensities (25 – 40 mm/h) have been significantly improved. The improved timing for the lower rainfall intensities has made it possible to measure infiltration and runoff processes right at the threshold intensity where runoff begins on most of the ecological sites within the San Pedro Basin.

Rainfall intensity-infiltration relationships for the four sites are being refined and validated using measurement results from the rainfall simulator experiments on ecological sites and hydrologic simulation models. In addition, extensive work has been conducted in collaboration with scientists at the USSL to develop pedo-transfer functions for the ecological sites on which we are conducting rainfall simulator experiments.

The results from the rainfall simulator experiments show distinct relationships between rainfall intensity and infiltration and runoff processes for the specific ecological sites on which we have conducted our research. These relationships are defined by the vegetation and cover characteristics of the site as well as the soil. The results indicate that the relationships are unique for a given ecological site and that they can be quantified. The implications of the results to date are that a range of infiltration parameters can be defined for a given ecological site. These results, in conjunction with the research being conducted in TA1.2.2 should significantly improve our ability to model rainfall, infiltration, and runoff processes on uplands within the upper San Pedro Basin.

Plans for the Next Reporting Period

Field experiments are planned at five more ecological sites this summer. The validation of the intensity-infiltration relationships will be extended to the watershed scale on sites located within the Walnut Gulch Experimental Watershed. A preliminary analysis of the hydrologic properties of the soils from the ecological sites was conducted by USSL from soil texture data. These will be validated with the 50+ soil cores that we collected from 9 ecological sites this spring. USSL scientists are currently conducting the analysis of the soil cores. These results will be compared with the plot scale results from the rainfall simulator experiments being conducted this summer. The resulting relationship(s) will be used to develop methods to scale up from point scale measurements and properties to plot and site scale rainfall runoff processes.
3. Remote Sensing and Modeling of Precipitation

There is one active project within this sub-area:

**Estimating Precipitation Over the Southwestern U.S. at 6hr/12km Resolution From Remotely Sensed Data**

*Gao, Gupta, Hong, Hsu, Mahani, Sorooshian (UA-HWR)*

Obtaining reliable quality of precipitation observations is important to the hydrologic simulation and weather forecasting. Many areas in the mountains of the southwest U.S. lack sufficient and effective means of measuring precipitation, and traditional observations from gauges provide limited and unreliable data. This research attempts to provide and improve precipitation observations over various seasons and scales using multiple sources of observations, including gauges, radar, and multiple-satellites. Our research goals are: 1) to develop techniques that will enable our estimation of rainfall at high spatial-temporal resolutions (6-hourly, 12 km x 12 km), and 2) to improve precipitation estimates and rain/snow classification during the winter seasons.

Providing high quality regional precipitation observations at 6-hour 12 km x 12 km is highly relevant to many SAHRA research activities. This project is in support of water balance study and the model simulation and validation of the SAHRA modeling group studies at both regional and basin scales. The results from this research will provide precipitation input for Thrust Areas 1, 2, and 3 and connect in close coordination with climate modeling in TA4.

**Activities and Results**

Three research activities are highlighted in this reporting period, and are listed below:

- **Cloud classification and rainfall estimation** - A rainfall estimation algorithm based on a cloud classification scheme was developed. Other than using local pixel-based approaches, this cloud classification algorithm identifies various cloud types according to the cloud features extracted from cloud textures at several temperature threshold levels. Rainfall distributions of various cloud types are trained and assigned from the radar rainfall measurements. This procedure separated rainfall estimation from satellite infrared imagery into three stages including cloud segmentation, cloud classification from selected features, and rainfall estimation. The variable threshold approach was applied to separate infrared cloud images into various cloud patches. The fixed threshold used in the constant threshold approach was not able to separate cloud patches in detail. The variable threshold approach, however, gives significant improvement over the constant threshold approach in the segmentation of individual cloud patches. Features consist of threshold temperatures in various cloud heights, cloud texture, and shapes. Initial experimental results show that the rainfall estimates from the cloud classification algorithm provide a tool for fine scale rainfall estimation at a 4 km resolution. The current plan is to implement, test, and include this rain algorithm during the monsoon season rainfall period in the coming reporting year.

- **Winter season snow estimation** - Ground/air temperature (every 3 hours from Eta model) and surface elevation (DEM) were used for distinguishing snowfall from rainfall and estimating snowfall depth from Snow Water Equivalent (SWE) where the temperature was less than 2°C. The investigation was applied to the daily snowfall estimates at 0.25 x 0.25 lat/long resolution over the southwest U.S. The model was trained by TRMM satellite-TMI and estimated PERSIANN-SWE was validated using daily SNOTEL-SWE from Natural Resources Conservation Service (NRCS) data source. Daily snow estimates using PERSIANN precipitation and surface temperature from Eta model were produced. Investigation of SWE in one test period, December 2001, showed high correlations between SNOTEL observation and PERSIANN SWE estimates.

- **PERSIANN product evaluation** - The PERSIANN global-product was compared with TRMM-satellite (3B43) and GPCP global products at a 1°x1° resolution on a monthly and daily basis.
The comparison was applied globally from 40°S to 40°N for a 22-month period from March 2000 to December 2001. Over landmass, PERSIANN estimates are observed to be higher estimates than those estimates of GPCP and TRMM 3B43, during the high rainfall period; however, all three estimates are similar over the oceans. Further evaluation of rain estimates over the southwest is continuing and will be reported in the next reporting period. Evaluation of PERSIANN estimates in higher spatial-temporal scale using local gauge and radar measurements are ongoing and will be reported in the next period.

Plans for the Next Reporting Period

Many regions over the southwest US are not well covered by rain gauges and radar. Observation of precipitation is very difficult and limited. This research will be intensified. Our observations and understanding of precipitation distribution in various seasons and scales from multiple sources of information are providing reliable rainfall/snow estimates over the southwest U.S. In the past three years, we have developed techniques integrating satellites and ground-based measurements to improve our ability of estimating precipitation. In years 4 and 5 we plan to conduct research and data service as follows:

- **Develop an algorithm providing high-resolution rainfall estimation at 6-hour, 12 km resolution**
  Develop/improve rainfall algorithm (cloud classification approach) and select effective satellite cloud features in the classification of cloud type and rain distribution estimation. Currently, a limited selection of satellite cloud features was selected in the cloud type classification and rainfall estimation. We plan to evaluate additional static and dynamic features of the rain cloud image to quantify rain cloud types and rainfall intensity.

- **Generate rainfall estimates at 6-hour, 12 km x 12 km resolution**
  Current PERSIANN estimates provide 6-hour, 25 km rainfall. Down scaling of PERSIANN rainfall to the 12 km resolution will be useful to hydrologic applications at the basin scale. Rainfall generated from the cloud classification map is at an hourly 4 km satellite infrared pixel resolution. However, at a 4 km level, the rainfall estimates from satellite imagery do not provide good pixel-to-pixel correspondence, resulting in pixel displacement errors and necessitating geo-location adjustment. Two adjustments are considered: 1) the up-scaling of hourly 4 km to 6-hour 12 km rainfall, which will reduce the pixel miss-location error, and 2) applying adjustment displacement error of images at the pixel level. Six-hour 12 km x 12 km rain product will be available for areas covering the regional (southwest U.S.) to basin (Colorado river, San Pedro, and Rio Grande basins) scales. This precipitation data set is useful to those SAHRA research activities that use precipitation forcing to drive hydrological models.

- **Validate rainfall products at basin scale level using gauge and radar measurement**
  A validation program will be carried out with the selection of experimental sites over the Colorado and Rio Grande river basins. Several sites at a 12 km x 12 km scale with a large density of gauge networks and radar coverage will be selected. Rainfall products covering various spatial-temporal scales at 4 km, 12 km, 24 km and 3-hour, 6-hour, 12-hour and daily accumulation will be evaluated. Bias of rain estimates from the satellite-based algorithms will be quantified. Bias removal of satellite and radar estimates at designed spatial and temporal will be quantified and applied to those regions in which gauge and radar coverage is limited.

- **Integrate multiple sources of information in rainfall estimation**
  Possible observation errors from gauges, radar, and satellite measurements will be quantified. A merged product consisting of satellite, gauge, and radar rainfall measurements will be generated. This product will consider bias of satellite estimates and uncertainty of gauge measurement with respect to the density of gauges, and radar bias corrections from gauge measurement.

- **Estimate snow water equivalent in the wintertime**
  Daily PERSIANN-SWE will be compared to daily-observed SNOTEL-SWE in a different approach from the method that was applied in the 3rd year. Specifically, hourly-based surface/air
temperature from the RUC data source will be used for partitioning snowfall from rainfall by applying a 2°C temperature threshold (snow level). Different Indices will be estimated for snow, rain, or a mixture consisting of snow and rain in relation to the ratio of the precipitation event length and time of the event that temperature is less than the threshold for a day. These indices will be used to select a day as a snow, rain, or mixed day. Daily SWE estimates will be validated using SNOTEL-SWE. A time series investigation will be carried out for all storms occurring in 2.5 months (from February 05, 2002) over different 1° x 1° regions in the southwest U.S.

4. Hydrologic Modeling of Headwater Basins

There is one active project within this sub-area:

**Using multi-objective parameter optimization and snow survey data to improve operational forecasting in the Upper Rio Grande**

*Boyle (DRI/UNR), Fassnacht (UA-HWR), McConnell (DRI/UNR), Bardsley (DRI/UNR), Gorham (DRI/UNR), Hobson (DRI/UNR), Kirick (DRI/UNR)*

Physically based, spatially distributed, dynamic models of stream discharge offer the potential to significantly improve stream forecasts and so lead to improved reservoir management. A primary goal of SAHRA is to foster and facilitate the use of state-of-the-art hydrologic models and improve understanding of them in water resource management. However, acceptance of new management approaches by water resource managers and implementation of new technologies is often not easily accomplished. Calibrated, physically based, distributed basin-scale models to evaluate and integrate process level studies and related computer modules are required, together with mechanisms to transfer this understanding and modeling capability directly to the stakeholders. Our research approach is multi-faceted. First, in close collaboration with the USGS and other agencies and with significant leveraging of SAHRA funds, we are developing, implementing, and calibrating a semi-physically based, spatially distributed hydrologic model in twenty-one headwater basins in the Rio Grande. The model output will replace the empirical predictions currently used as input to the Upper Rio Grande Water Operations Model (URGWOM). Second, we have undertaken field snow surveys in the Colorado portion of the Rio Grande and in Sagehen basin (a local test basin in the Sierra Nevada) that are designed to evaluate the performance and accuracy of both the spatially distributed hydrologic model and the SNOTEL data traditionally used to drive such models, with particular emphasis on the distribution of snow and snow water equivalence, evolution of the snow pack, and water balance. Third, with a fully calibrated and operational hydrologic model in place and with a clearly established link with water resource managers in the Rio Grande, it is now possible to efficiently implement and evaluate new computer modules developed from SAHRA-funded process level studies.

**Activities and Results**

In anticipation of a week-long snow measurement field campaign in spring 2002, we purchased two snowmobiles and other field sampling equipment using funds leveraged from DRI and the State of Nevada. However, because the snowpack in the Rio Grande in 2002 was much lower than normal, the field campaign was scaled back to include: 1) a 3-day, focused field campaign and modeling effort in the South Fork of the Rio Grande, and 2) graduate student Tim Bardsley’s ongoing 1-km² snow distribution measurements around the SNOTEL sites in the area. USGS researcher S. Markstrom and incoming DRI graduate student A. Hobson joined DRI faculty J. McConnell and D. Boyle and DRI graduate students T. Gorham and T. Bardsley in the field. Monthly 1-km² snow distribution measurements around the Independence Lake SNOTEL site in the Sagehen test basin were also made throughout the year.

MMS/PRMS modeling was implemented and calibrated for headwaters basins in the Rio Grande using SAHRA, USGS, DRI and State of Nevada funds with the objective of improving stream discharge forecast capability at 21 input nodes of the URGWOM operations model. Evaluation of the results and historical comparisons with the NRCS-based forecasts used previously by URGWOM are underway.
High spatial resolution MMS/PRMS modeling in the headwaters of the Rio Grande above the Del Norte gage was undertaken. This included high resolution modeling in the South Fork of the Rio Grande designed in conjunction with DRI's field measurement campaign in April 2002. A second objective of the high spatial resolution modeling is to allow optimization of the MMS/PRMS model using the Del Norte gage and model validation using internal gauged nodes within the headwater basin. Initial results are promising. We have also initiated comparisons between MMS/PRMS modeled snow water equivalence/snow distribution and similar remotely sensed products from colleagues at Arizona. We are currently evaluating various ways of assimilating the remotely sensed products into the model. With the development of a MOCOM module for MMS/PRMS in year 2 and MOGSA more recently, we have begun to look at the use of multi-objective criteria optimization in our hydrologic modeling above the Del Norte gage on the Rio Grande and on the Sagehen test basin.

Results from the reporting period are as follows:

- Use of the semi-empirical, distributed MMS/PRMS hydrologic model to produce stream discharge forecasts in the twenty-one headwater basins in the upper Rio Grande showed significant improvement over the purely empirical NRCS based forecasts used previously by water resource managers.
- Field measurements of SWE around SNOTEL sites in the upper Rio Grande headwaters and in the Sagehen test basin showed that the SNOTEL point measurements significantly overestimate SWE at 1-km² scales. Furthermore, the degree of overestimation changes in time with overestimation increasing sharply as the snow season progresses.
- Comparisons of field measured SWE and snow depth with MMS/PRMS modeled estimates showed generally good agreement in the South Fork of the Rio Grande basin. Similar comparisons between time series of MMS/PRMS modeled SWE and estimates derived from remotely sensed products also showed general agreement. More extensive and detailed comparisons and development of methods to incorporate remotely sensed products into the model are underway.
- Validation of MMS/PRMS modeling above the Del Norte stream gage using internal stream gage nodes suggested that the model reasonably predicts flows within most of the basin, although the model consistently underestimates discharge from the South Fork of the Rio Grande. We are investigating the reasons for this underestimation and testing possible solutions.
- Initial tests of multi-objective criteria optimization in the MMS/PRMS modeling suggested that significant improvements in stream discharge modeling in the Rio Grande headwater basins, and hence flow forecasts, are possible.

Plans for The Next Reporting Period

We propose to continue our current efforts aimed at improving the implementation, optimization, and validation of the MMS/PRMS and other models in the headwaters of the Rio Grande through coordinated field, modeling and remote sensing studies. We will evaluate different methods for distributing precipitation around the headwaters above the Del Norte gage by trying different parameterizations of the current XYZ method used elsewhere by USGS researchers in conjunction with MMS/PRMS. Continued use of internal gage nodes within the basin for evaluation and comparisons with remotely sensed SWE and SCA are crucial to these efforts.

We will continue and extend field snow surveys and coordination with related Arizona studies of snow distribution and soil moisture. Complete evaluation of current MMS/PRMS modeled flow forecasts and historical comparisons with NRCS-based discharge forecasts at the twenty-one headwaters basin nodes used to drive the URGWOM operations model. Complete current initial evaluation of MOCOM and MOGSA multi-objective criteria optimization of MMS/PRMS in the headwaters basin above the Del Norte gage.
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**Participants**

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<tr>
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**Affiliates (under 160 hours)**

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<td>4. Thomas Kretzschmar</td>
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<td>8. Jirka Simunek</td>
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**Funding (reporting year)**

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Thrust Area 2 - Basin-Scale Water and Solute Balances

The major goal of Thrust Area 2 is to understand the dynamics of water and solute balances of semi-arid regions at large spatial and temporal scales (i.e. the river basin scale and decadal and longer time scales). The majority of the research in TA2 is focused on the Rio Grande Basin above Fort Quitman (~150 km below El Paso). Those research projects working outside the Rio Grande Basin are either nearly completed or are taking advantage of significant leveraging opportunities in other semi-arid regions. Research in TA2 is divided into two groups: I) Vegetation and vadose zone processes of the basin floor; and II) Basin-scale hydrologic systems.

1. Vegetation and Vadose Zone Processes of the Basin Floor

Sustainable use of groundwater in arid and semi-arid regions requires that all components of the water and solute balances within a basin be well quantified, especially recharge. Basin floor environments, which represent ~50% of the Rio Grande drainage in CO and NM, have been given scant attention until recently. Basin floor vadose zones are significant sites of salt storage and - over decadal to century time scales - perhaps water flux. Researchers in this group seek to understand the processes that control water and solute balances of basin floor, especially the role of vegetation and soil structure. In addition researchers are also working to develop new methods to study these processes. Perturbations to water and solute balances caused by vegetation change (resulting from human land use practices or climate change) are of critical importance. Individual research efforts include:

- Response of rangeland vegetation to multiyear drought: integrating water, plant, and soil processes and their role in vegetation change
- Vegetative control on the hydrodynamics of semi-arid vadose zones
- Regional distribution of soil moisture, evapotranspiration, and soil hydraulic properties
- Quantifying long-term groundwater recharge using $^{32}$Si

Response of rangeland vegetation to multiyear drought: integrating water, plant, and soil processes and their role in vegetation change

Small, Elliott (NMT)

Semi-arid shrubland and grassland ecosystems should respond differently to precipitation variability due to contrasting plant traits, nutrient cycling, and surface hydrology. During drought, shrublands may respond more slowly than grasslands because soil resources are concentrated in “islands of fertility” and the vegetation is more deeply rooted and drought-tolerant. If this is the case, then drought may be an important force behind the transition from grassland to shrubland that has been observed in semi-arid ecosystems worldwide. Using rainfall manipulation at twenty-one extensively instrumented plots (grassland, shrubland, and mixed grass-shrub) we are addressing three questions: 1) How do grasslands and shrublands respond to multiyear drought? 2) On what timescales do different ecosystem components respond? 3) Is the plant response simply a direct result of changes in rainfall amount or do changes in surface/vadose zone water cycling lead to feedbacks?

Activities and Results

Our activities during the past year fall into two main categories:

1) Establishment of additional rainfall manipulation plots: At the request of the NSF ecosystems panel, we expanded our experimental design to include 6 pure grassland and 6 pure shrubland plots in addition to the 9 mixed grass-shrub plots already in place. (See web site http://www.ees.nmt.edu/Hydro/faculty/Small/research_2000/drought_folder/drought_main.html for photos and details). To ensure that all plots were subjected to the same conditions, we delayed the onset of water limitation/addition treatment until July 2002. Drought plots receive 50% less rainfall than control plots, yielding a drought similar to that observed in the 1950’s. Our monitoring includes
the primary components of surface/vadose zone water cycling, nutrient and carbon cycling, and plant productivity and physiology.

2) Monitoring and analysis of components of water cycling and plant-water interactions: We continued our intensive monitoring of soil moisture, ET, and others aspects of the surface water and energy budgets. In addition, we completed 9 ‘reference storms’ at the ecotone plots to assess the coupled plant-water response to summertime rainfall. A 15 mm artificial rainfall event was added to each plot, followed by \(~10\) days of intensive measurements. Finally, we began a detailed spatial analysis of the patterns of canopy and interspace in grassland and shrubland environments.

We have measured and analyzed two summers of data from grassland and shrubland. Key results include:

a. ET dynamics are nearly identical in grassland and shrubland, controlled primarily by near-surface soil moisture. However, this does not mean that evaporation and transpiration are identical. Instead, evaporation is expected to be much higher in shrubland due to extensive bare soil (~70%).

b. There is intense temporal variability of ET and evaporative fraction (EF) following rainfall events. Drydown is faster in shrubland, however both locations return to low values (ET \(~0.5\) mm/day; EF \(~0.1\)) within only a few days.

c. We observed a linear relationship between EF and surface soil moisture (Figure 1), however EF increases more rapidly with soil moisture at the shrubland site.

![Figure 1](image)

**Figure 1** Midday average summer evaporative fraction versus volumetric water content (0-5 cm) for both grass and shrub locations. We note that the slope shrub = 4.9 and grass = 3.5, and the \(r^2\) values are \(~0.8\) at both locations.

d. Following rain events, the soil tends to be wetter beneath grass than shrub canopies. Compared to both canopies, interspaces are relatively dry. In general however, infiltration is shallow; soil at depths greater than 45 cm is usually dry.

e. Grass response to a 15 mm rainfall event is more dramatic than for shrubs. Grass plant water potential increased substantially following a rainfall event whereas shrub plant water potential increased only slightly. The transpiration responses, normalized to pre-storm values, were similar: grass transpiration increased by a factor of five whereas shrub transpiration did not even double. This results in greater carbon assimilation by grass.

The implications are as follows: First, shallow soil moisture (0-5 cm) is the key control of ET in these environments, suggesting a large bare soil evaporation component. Second, temporal variability of ET is substantial and must be represented by models of land-atmosphere interactions (e.g., NOAH). Third, vegetation type does not noticeably influence the total flux of water back to the atmosphere, although it influences the partitioning between evaporation and transpiration. Fourth, the primary control on the amount of carbon fixed during the observed storm was the pattern of infiltration: the soil beneath grass was wetter, so this plant type fixed more carbon and lost more water.

**Plans for next reporting period**

During years 4 and 5, we will continue rainfall manipulation treatment and monitoring at the drought plots at the Sevilleta. This will yield drought and control experiments \(~>2.5\) years in duration, including three
consecutive summer monsoon seasons (2002-2004). At that point, it will be sensible to reevaluate whether to continue drought treatment or to end the treatment and observe the subsequent recovery. Our measurements and analysis will encompass three main areas of ecosystem function: 1) water cycling: spatial and temporal patterns of soil moisture and soil water potential, surface water redistribution and infiltration, runoff, and evapotranspiration; 2) nitrogen and carbon cycling: mineralized N in soil, soil organic carbon, and carbon assimilation; and 3) plant physiology and productivity: above- and below-ground production, percent cover of canopy and interspace, leaf gas exchange, and water relations. The plant and soil components of this work are greatly enhanced via leveraged support from the Sevilleta LTER.

Our results thus far and those we plan to get from monitoring will better constrain surface and vadose zone water cycling in the extensive valley floor environments of semi-arid regions, in particular with respect to the role of vegetation. Results and data from this process study will be integrated into SAHRA-wide efforts in two ways. First, we will derive effective parameters (e.g., K_s) for LANL model grid cells at the hillslope scale. Second, the changes in these effective parameters caused by our drought experiments will be used as landscape boundary conditions in drought scenarios. This information is critical to understand water balance at the basin scale, and to predict how it changes in response to drought and human-induced land surface change.

**Vegetative control on the hydrodynamics of semi-arid vadose zones**

*Phillips, Walvoord (NMT)*

The groundwater recharge rate is a critical component of the water balance from the viewpoint of sustainability of water resources. Recharge rates in arid regions are known to be much higher at high elevations than at low elevations, but the magnitude of recharge rates at low elevation has long been a matter of controversy. Even very low recharge over desert floor areas could be quite significant for water use. For example, an average recharge of 1 mm yr\(^{-1}\) over the desert floor area of the Rio Grande basin could supply the domestic needs of a population twice the current one of New Mexico. This project aims to understand vegetation control on the hydrodynamics of desert vadose zones and ultimately groundwater recharge rates.

**Activities and Results**

Activities during the current year centered primarily on finalizing simulations and writing up results for publication. Considerable effort was invested in modifying the FEHM code to properly simulate the transport of stable isotope tracers. There was also a major effort to perform extensive sensitivity analyses. Michelle Walvoord wrote and defended her Ph.D. dissertation, with much of this work in press or in revision.

We have relied on vadose-zone profiles of chloride concentration and water potential as our main lines of evidence, and have interpreted these using the multi-phase (liquid and vapor), variable temperature model FEHM. Our results have shown a remarkably uniform pattern of water movement in vadose zones of desert floor areas. These are characterized by upward water potentials in the upper ~50 m and inventories of chloride equivalent to >10 kyr of atmospheric deposition. The pervasive occurrence of such profiles in desert lowlands implies that these areas have not been sources of diffuse groundwater recharge since the end of the last glacial period, 10 to 15 kyr ago. Based on

![Chloride profiles beneath different vegetation types and the implication for groundwater recharge.](image)

**Figure 2** Chloride profiles beneath different vegetation types and the implication for groundwater recharge.
intercomparison of vadose-zone profiles under differing vegetation communities (Figure 2) we have concluded that the main control on vadose-zone hydrodynamics (and thus recharge) is type of vegetation. Desert shrub (and to a lesser extent desert grassland) creates root-zone water potentials so low that no water can move below the root zone and, in fact, water is extracted from the deep vadose zone.

Our results have three major implications. The first is that where we observe characteristic vadose-zone profiles consisting of very negative water potentials (~<-4 MPa), combined with large soil chloride inventories, we can infer that the vadose zone is locked into a long-term drying transient that precludes any diffuse groundwater recharge. This inference is of significance for both water-balance studies in the SAHRA project and for water resources investigations in arid regions in general. A second implication is that when these conditions are met, total hydraulic gradients in the top ~50 m of the vadose zone are upward, and thus contaminants cannot be transported downward to the water table. This implication is of considerable significance for nuclear waste disposal programs, and other types of waste disposal as well. Finally, preliminary data from our Trans-Pecos investigations suggest that the key controlling factor on vadose-zone hydrodynamics is vegetation, and that areas in which hydraulic gradients are at least episodically downward can be identified by mapping vegetation type. If confirmed, this finding has important implications for both quantifying the distribution and amount of groundwater recharge, and for ecohydrological controls on the positions of ecotones.

Plans for next reporting period

Our investigations so far have resulted in two major findings: 1) a conceptual model that indicates that during the last 10,000 years desert floor environments have been areas of upward hydraulic gradients, dominated by vapor transport, and thus are not sites of active recharge; and 2) water fluxes below the root zone are mainly controlled by vegetation, and measurements across certain ecotones indicate that recharge is happening beneath vegetation communities other than desert scrub and desert grassland. The critical aspect of this second finding is that it implies a vegetational, rather than direct climatic control on recharge. The first finding is certainly relevant for assessment of water balances in arid drainage basins, but further exploration has implications for paleohydrology and waste disposal issues. In contrast, the second finding can be pursued to develop a tool that will permit soil/groundwater balances to be estimated on the basin scale, based largely on remote sensing data.

At present, the ecohydrological linkage between vegetation and fluxes below the root zone is based on a very limited data set. Our first priority will be to test and quantify the ecohydrological hypothesis by the collection of more data. We will drill shallow soil augerings and measure matric potential and chloride concentration along climatic transects that cross ecotones. These will avoid areas of steep topography, so climatic gradients will be gradual. In contrast, ecotones are abrupt. Abrupt changes in the pattern of matric potential and chloride across the ecotones will support the ecohydrological control hypothesis, whereas gradual transitions will support hydroclimatic control. In either case, the results can be directly applied to quantification of water balance and soil-water partitioning that are on-going projects within TA2. Ultimately, our results should enable the basin-scale model that will integrate SAHRA's efforts to be parameterized for the interconnection of shallow and deep vadose zone processes.

Regional distribution of soil moisture, evapotranspiration, and soil hydraulic properties

Hendrickx (NMT)

Information on regional distributions of soil moisture and evapotranspiration in river basins is critical for the prediction of plant water availability, land surface evaporation and transpiration, runoff generation, contaminant movement through soils, ground water recharge, and irrigation scheduling. In this project we are implementing and further developing the Surface Energy Balance Algorithm for Land (SEBAL) for the Rio Grande Basin. This algorithm uses remotely sensed optical imagery for the determination of the regional distribution of the energy balance components and soil moisture. We have verified that SEBAL yields reasonable estimates for daily evapotranspiration (ET) in irrigated fields, riparian areas, and on arid ranch lands in the Middle Rio Grande Basin. Results for mountain slopes facing west and basalt flows are questionable and need improvement. Our regional distributions of ET and soil moisture are essential as input and validation data for the Los Alamos Rio Grande Basin hydrological model. In addition, our ET
images will be available for other SAHRA researchers and stakeholders (such as the MRGCD – Middle Rio Grande Conservancy District) who have an interest in ET.

Activities and Results

In year one, we monitored soil water content in the top 5 cm of the soil at fourteen sites in the Sevilleta NSF - LTER site. We found a significant linear relationship between soil water content and the reflectance of selected wavelengths of the electromagnetic spectrum measured by LandSat. Thus, this highly empirical method may have potential for calibration of LandSat images to regional soil water content distributions. In year two, we validated SEBAL for conditions in the Rio Grande Basin. We analyzed three LandSat images using two versions of the SEBAL code: 1) surface roughness lengths derived from an empirical relationship with the Normalized Difference Vegetation Index (NDVI) (WaterWatch); and 2) surface roughness lengths derived from the more or less known height of vegetation and a land use classification from the LandSat image (NMT). SEBAL results were compared with eddy covariance measurements at sites run by Dr. James Cleverly (UNM) and Dr. Eric Small (NMT). During the past year we have focused all our efforts on the implementation of SEBAL on our computers at New Mexico Tech. We decided to not continue with the soil water content measurements in the top 5 cm of the soil in the Sevilleta. The data from the fourteen different sites were quite similar from dry day to dry day and from dry site to dry site. Once, we have a number of SEBAL generated soil moisture maps at different dates during the year we will use these data for determination of optimal locations for soil moisture monitoring and resume field measurements.

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<th>SEBAL ET (mm/day)</th>
<th>SEBAL ET (mm/day)</th>
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<td>WaterWatch</td>
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*Measurements in riparian areas by Dr. James Cleverly, University of New Mexico.
1Measurements in desert areas by Dr. Eric Small, New Mexico Tech.

A comparison between the evapotranspiration rates measured in the field on September 14, 2000, in the Middle Rio Grande Basin and those derived with SEBAL is presented in Table 1. Overall, both versions of SEBAL seem to represent very well relative ET differences and compare well with measured values. The ET values in the riparian areas for cottonwood and saltcedar fall within the noise of the eddy covariance measurements and SEBAL. For desert environments the SEBAL/WaterWatch yields lower values than the field measurements while the SEBAL/NMT yields higher. The ET image (Figure 3) is quite instructive for understanding the regional ET distribution. For example, it clearly shows the high ET rates in the irrigated fields and riparian areas in the Rio Grande Valley versus the low ET rates in the surrounding deserts. The city of Albuquerque has much higher ET rates than the surrounding desert. In the Estancia basin, the round center pivot systems have a much higher ET than the
surrounding dry lands. The basalt flow in the southeastern corner of the image has a high ET. Although part of this is due to a misrepresentation of the soil heat flux (in this SEBAL analysis the soil heat flux has been calculated in the same way for the entire image), it may inform us about a relatively higher ET on basalt flows after a precipitation event.

**Plans for next reporting period**

We now know how to implement SEBAL under the conditions of the Middle Rio Grande Basin and obtain reasonable ET estimates for irrigated fields and riparian areas. However, a much more rigorous test of SEBAL is needed to assess its results for ranchland, mountain areas, and basalt flows. We plan three research activities to better understand the potential and limitation of SEBAL for the basin wide determination of evapotranspiration.

1) **Sensitivity Analysis of SEBAL.** We need to conduct a sensitivity analysis of SEBAL’s empirical relationships to find out which are critical for the Rio Grande Basin. Examples are: a) the relation between the thermal infrared surface emissivity and the Normalized Difference Vegetation Index (NDVI); b) the relation between emissivity of atmosphere and air temperature; c) the relation between soil heat flux and soil temperature, albedo, and NDVI; d) the relation between crop height and Leaf Area Index (LAI); and e) the relationship between crop height and surface roughness for momentum transport among others.

2) **Comparison of field measurements with SEBAL values.** How can we compare an ET measurement from eddy correlation stations with a footprint of up to several hundred meters with a SEBAL derived ET rate? To do so with more confidence we plan to install at least one scintillometer for direct measurement of the sensible heat flux over distances of up to 2.5 km. We expect to learn much from adding an independent measurement of the sensible heat flux to the current field measurements and SEBAL-derived components of the energy balance.

3) **Increase temporal resolution.** Our current implementation of SEBAL is based on LandSat, which has a good spatial resolution of 30×30 m but the temporal resolution is, at best, once every 16 days. MODIS images have a spatial resolution of 1000×1000 m (in the thermal infrared band) but a temporal resolution of 1 to 2 days. The ideal situation for water managers would be to have information available with a spatial resolution of 30×30 (which would cover most individual fields) at a temporal resolution of 1 to 2 days. Therefore, we will explore how we can combine the information from LandSat images and MODIS images. This is necessary to up-scale the use of SEBAL to entire river basins.

**Quantifying long-term groundwater recharge using \(^{32}\text{Si}\)**

*Ekwurzel, Einloth (UA-HWR)*

This project is the first application of \(^{32}\text{Si}\) to determine long-term recharge rates and the first rigorous study of \(^{32}\text{Si}\) activities in soil. \(^{32}\text{Si}\) has a 140-year half-life and theoretically can be a useful tracer for processes on the 100 to 1000 year time-scale, a time length for which there are few other available tracers. Studies have found that \(^{32}\text{Si}\) is not an ideal groundwater tracer because most of the tracer is lost during transit through the vadose zone before reaching the groundwater table. It is this “loss” in the vadose zone that is exploited for recharge research in semi-arid regions. The research plan for this work includes three phases: development of analysis capabilities and determination of feasibility; application to well-defined systems; and extension to other regions of interest for recharge purposes. The major advancements made this year were the development of laboratory facilities with the capability to quantitatively separate silica from soil and to analyze for \(^{32}\text{Si}\) by liquid scintillation counting of the daughter product \(^{32}\text{P}\), and the collection of precipitation and soil samples from key SAHRA field locations. We have collected samples from the three southwestern deserts (Sonoran, Mojave, and Chihuahuan), and from three different segments of semi-arid regions: valley floor, stream and wash channels, and the mountain-front. The understanding gained about the basic recharge processes in these types of environments can potentially be generalized and applied basin-wide and between basins. This can be achieved by a categorization of desert areas and through correlation with other geochemical and geophysical properties measured.
Activities and Results

The past reporting period encompassed the laboratory development and heavy field sampling stages of the research. The net result is that water sample lab procedures have been completed and will be published in the next reporting year. Soil sample handling procedures are still being refined, but we expected them to be finalized by September 2002. The majority of the samples that will be analyzed and interpreted were collected in this report year.

Precipitation: To understand the $^{32}\text{Si}$ input to semi-arid systems we need to collect sufficient precipitation and surface water samples. Several large-volume rain gauges have been collecting precipitation at the two locations: the San Pedro River Basin and the Mojave Desert. In addition we have been collecting event-based precipitation samples within the Tucson Basin to test for any trends in $^{32}\text{Si}$ deposition. The Tucson Basin was chosen for the logistical needs necessary for capturing large volume event-based precipitation samples.

Soil Sample Collection: A second major component is to understand the influences of recharge location, vegetation impact, and soil properties on long-term recharge in semi-arid regions. Below is a brief synopsis of field activities:

- **San Pedro River Basin** – Eleven vadose zone boreholes were drilled over a total of 170 m and 615 $^{32}\text{Si}$ samples were collected. Concurrently the USGS and SAHRA TA1 researchers collected geophysical, sedimentary, and geochemical ($^3\text{H}$, $^{18}\text{O}$, D, Cl) data.
- **Mojave Desert** – Mojave vadose zone borehole cores are archived and the USGS has agreed to share core samples (J. Izbicki, USGS, pers. comm.). This field sampling campaign is similar to the one described above for the San Pedro River Basin.
- **Socorro, NM Cooperative Trench Study** – Soil samples were collected from four vertical sections. Two profiles were beneath established vegetation and two profiles lacking surface vegetation. Again, $^{32}\text{Si}$ interpretations will benefit from the extensive data (e.g. total Cl, root density, soil properties) collected by New Mexico Tech TA2 researchers.

Lab Development: Three separate facilities were established: the Soil-Leaching Laboratory, the Scintillation Preparation Laboratory, and the Scintillation Counting Facility. Due to the nature of the laboratory-building phase of the research, the achievements were predominantly in the area of process improvements leading to a published method. We have established two notable improvements to the methods:

1) The focus of the current project is on the vadose zone, which required rigorous study of soil leaching parameters and development of procedures to generate reproducible results.
2) For water analysis ~ 50-500 L of sample are required, therefore a small filter device was designed to extract the silica from the water source onto a polypropylene filter impregnated with iron hydroxide.

Plans for next reporting period

The next steps for this research include analyzing the soil and precipitation samples; evaluating the data along the vertical transects and comparing the data with geochemical and geophysical properties in order to assess infiltration depths and recharge rates; and, if necessary based on the field results, conducting column studies. The most immediate task is sample analysis. The first set of samples analyzed will be the precipitation (snow and rain) and the soil cuttings from the San Pedro region. The precipitation and the first set of San Pedro soil samples (half of the wells) have a projected completion date of December 2002. The transect evaluation and modeling of the first results will occur between approximately November 2002 and April 2003. A manuscript on the new analysis process is to be written by December 2002.
2. Basin-Scale Hydrologic Systems

Groundwater stored in alluvial aquifers is by far the largest reservoir of water in semi-arid basins. In addition to providing a ready source of water, groundwater also sustains the baseflow of many rivers for most of the year. Understanding the dynamics of this system is of critical importance for balancing sustainable water use and maintaining the remaining riparian areas. The objective of the Basin-Scale Hydrologic System group is to develop tools for determining recharge areas, flowpaths of groundwater, and residence times along those flowpaths at the scale of a basin aquifer, using a combination of emerging and routine environmental tracers. Individual research efforts include:

- Understanding the mechanisms of mountain block recharge
- Isotopic tracers of the sources, flowpath and ages of groundwater at the basin scale
- Solute balance of the Rio Grande
- Mountain-Front Recharge: Hydroclimatic Variability and Low-Dimensional Recharge-Runoff Models
- Groundwater and surface water salinization in the El Paso / Juarez Region

Understanding the mechanisms of mountain block recharge
Wilson, Gu (NMT)

Mountainous regions play a critical role in the hydrology of semi-arid drainage basins. Due to orographic forcing of precipitation, especially snow, they receive much more water than surrounding areas and they provide most of the runoff. They also provide most of the groundwater recharge. We hypothesize that a significant proportion of groundwater recharge for the entire Rio Grande basin, and other semi-arid basins, originates as infiltration through fractured bedrock high in the mountains and, depending on the geology, much of it reaches the alluvial aquifer systems by permeating range-bounding faults. This leads us to four general questions. What is the spatial pattern of mountain front recharge: is it diffuse or focused, surface or subsurface, and shallow or deep? What is the temporal pattern: can at least part of it be regarded as quasi-steady instead of intermittent? How non-linear is it? What are the roles of climate, landscape, vegetation and geology? We are using existing information, remote sensing, field visits with isotope and water chemistry sampling, and groundwater modeling to address these and related fundamental questions and to improve our conceptual understanding. Our efforts to understand hillslope processes will be integrated with similar SAHRA-wide efforts for other, below the mountain front, environments of the Rio Grande Basin, and used to help develop effective property models for the basin wide model. Our efforts at the hillslope and mountain block scales will be integrated with the LANL basin-wide modeling effort, to ensure that it properly represents hydrologic processes in mountain blocks. Efforts at both scales will also be integrated with TA1 studies of snow accumulation, distribution, melt and runoff.

Activities and Results

Our main activities fall into two categories: 1) mathematical modeling and 2) field studies. To date both efforts have been at best cursory, but we expect to dramatically expand them in the future through collaborations within and outside SAHRA.

Modeling: We obtained a two-dimensional saturated-unsaturated (variably saturated) flow code, HYDRUS 2D, that we have been using in profile (cross-section) to model processes at both the hillslope (~100 m) and mountain block (10-50 km) scales. The code did not include dual permeability, or any other ability to readily model fractures. With the cooperation of SAHRA collaborator Jirka Simunek, a composite property capability was added to HYDRUS to allow a first cut simulation of fractured rock. The code is currently being upgraded to dual permeability capability. We also began preliminary simulations with the dual permeability model Tough 2 and are considering other codes (e.g. HMS-Modflow and FEHM) for future simulations. There are other SAHRA researchers interested in the hillslope scale studies, and we will make our code selection in cooperation with them. HYDRUS includes a rudimentary model of ET and the
effects of vegetation, an important consideration in our studies and in most of these other SAHRA studies. Properties for different soils and rocks in our work were taken from a literature search, while various mountain blocks in the Rio Grande basin served as models for various aspects of the models. New Mexico Tech structural geologist Laurel Goodwin assisted us with geological models for the basin and range province, focusing on the Rio Grande rift. Precipitation in the complex terrain of mountain blocks was estimated from gauge records using co-kriging and other geostatistical tools.

Field Studies: Our field efforts have focused on the Sandia Mountains, bordering the Albuquerque Basin, and the Magdelenas Mountains just west of Socorro. These sites were picked because of their geographic convenience, availability of data, and the presence of relevant processes. The Sandia's are fractured and faulted granites, capped with carbonates on the eastern slope, while the Magdelenas include substantial volcanic rocks. In both mountain blocks we have sampled springs and streams at various times of the year, while we've also sampled mine water inflow to a deep mine in the Magdelenas.

Figure 4 illustrates the conceptual models used in this study. The entire mountain block, on the order of 10 km in horizontal scale, and hundreds of meters to a couple of kms in vertical scale, constitutes the domain we are studying to understand the net processes leading to mountain front recharge. The hillslope scale, a few tens of meters both vertically and in horizontal extent, is used to understand how rainfall and snowmelt is partitioned into soil moisture and runoff, and how soil moisture is partitioned in the shallow subsurface into recharge into the mountain block, downslope interflow in the soil layer (and then to runoff), and ET. Our current modeling treats this partitioning crudely and focuses mostly on the partitioning between interflow and recharge.

Key but preliminary results for the first year of this project consider a range of space and time scales.

At the hillslope scale we have the following preliminary results:
- If the bedrock (a combination of fractures and matrix) is insufficiently conductive, there is effectively no recharge. All soil moisture recycles to the atmosphere via ET or moves downslope in the shallow soil cover. This would be more common in crystalline rocks.
- If the bedrock conductivity is high then there is no barrier to deep recharge into the mountain block, and the soil cover only serves to store water for this recharge and ET. There is little downslope interflow in the soil cover. This would be more common in volcanic rocks.
- Intermediate to these conditions the amount of recharge depends on conditions, with apparently neglected properties, like the topography at the bedrock surface, playing a larger role than expected. Where only a small percentage of soil moisture will recharge with a uniformly sloped bedrock surface, a majority may recharge on a rough slope, presumably because of increased storage.
- While we have seen evidence in these simulations for the effects of percent soil cover, vegetation, slope, aspect, and other features, our preliminary findings are incomplete. We propose to emphasize these additional features in future years.

At the mountain block scale we have the following preliminary findings concerning groundwater flow and mountain front recharge:
Geology is a dominant control on mountain block hydrology.

- Highly permeable carbonates and volcanics can carry virtually all the recharge nature can provide, and conduct it to discharge into adjacent valleys. Fractured and faulted crystalline rocks, on the other hand, cannot carry as much water.
- Bounding faults play a significant role in redistributing the water along the mountain front, due to the enhanced conductivity of damage zones located around the fault.
- Range bounding fault zones, due to reduced permeability, can reduce the capacity of a mountain block to deliver water to adjacent valley aquifers by redirecting water to the surface springs and streams.
- It is important to note that the geology that allows significant deep movement of groundwater is the same geology that maximizes recharge at the surface.

The other significant control is topography.

- Although cross-sections do not allow us to properly examine the effect of topography in mountain blocks, it is clear that topography drives the flow, from snowmelt in the mountain highs to discharge along the mountain front.
- Topographic variation within the mountain block leads to smaller-scale circulation systems and discharges to local streams and springs.

It is not surprising that geology and topography play the dominant roles once water percolates deep below the soil cover. They are recognized as important controls in almost every hydrogeological study. Nor is it surprising that the some rocks yield more water than others. This has long been observed in basic scale hydrogeologic studies around the southwest (e.g., the Alamosa Basin portion of the Rio Grande, with crystalline rocks in the mountains on the east and volcanics on the west). However, we hope to move this from subjective understanding to more quantitative understanding and prediction.

Plans for next reporting period

We intend to continue our preliminary mountain block scale research by conducting extensive 2D cross-sectional simulations of various mountain block architectures, then expanding that to 3D, taking into account complex terrain and surface drainage patterns, and finally synthesizing these simulations with spring and stream samples of isotopes and chemistry to build a more complete picture of processes at this scale.

- Cross-sectional simulations of vadose zone and groundwater hydrology across a range of geological mountain block architectures.
- Three dimensional simulations of vadose zone and groundwater hydrology, and related “base flow” for a variety of mountain terrains, geomorphologic drainage patterns and underlying geology, for mountain blocks typical of the basin and range (and rift) mountains of the Rio Grande and Colorado River basins.
- Synthesis of modeling studies with isotopic and chemical samples from springs and streams.

Isotopic tracers of the sources, flowpath and ages of groundwater at the basin scale

*Long, Eastoe (UA-GEO)*

We are investigating recharge processes in semi-arid basins, with emphasis on questions concerning the age and origin of groundwater, mapping groundwater flow paths, and the location of zones where recharge is rapid. We approach this research problem by applying a variety of isotope measurement techniques (stable O, H, S, C; ³H, ¹⁴C) available in our laboratory to ground and surface water samples. Our principal focus has been on the Tucson Basin, where our study has demonstrated the advantage of concurrent application of different isotope systems. We expect that a similar approach in other basins, e.g. the Hueco Bolson (2.9), will produce equally valuable results. We believe that detailed knowledge of recharge zones and flow paths is essential to basin modeling studies.
Activities and Results

In the current reporting period our primary emphasis has been on processing our data for the central part of Tucson Basin and have begun a manuscript on that area. We have also mapped $\delta^{18}$O(sulfate) in groundwaters and evaporites of the basin, finding that this parameter distinguishes sulfate originating by oxidation of sulfide in crystalline rock from dust and evaporite sulfate in the basin sediments. And finally we have extended sampling to fill a small number of gaps in our data set.

We obtained $\delta^{18}$O(sulfate) values for about 60 water and gypsum specimens from Tucson Basin. Dissolved sulfate and gypsum from sediment in the central basin have higher $\delta^{18}$O(sulfate) values (>5‰), in contrast with near-zero values for sulfate in water drawn from fractures in crystalline rock near the Rincon Mountains. Comparing with acid mine drainage in the Patagonia area, we interpret the low $\delta^{18}$O values to indicate oxidation of sulfide. We will apply this information as we attempt to identify recharge from the mountain block to shallow sediment cover in Rincon Valley in future studies.

Figure 5 illustrates the groundwater domains in Tucson basin overlaid on a satellite photo of Tucson and vicinity. Principal washes are blue, urban areas are outlined in red and the study area is within the green rectangle. Few or no data exist for areas without color. The domains can be related to major washes by location and by values of $\delta^{18}$O and $\delta^{34}$S, except for that shown in light brown, in which may represent water of mountain origin upwelling through gypsum with $\delta^{34}$S = 12‰ in the SE corner of the basin.

Plans for next reporting period

The isotope study of the central part of the basin is complete. What remains is writing journal articles, information dissemination through public speaking engagements, and the resolution of some problems regarding the peripheral parts of the basin. Our results to date illustrate the importance of recharge through alluvial channels. What remains unclear is the nature of the connection between the mountain block and basin sediments. We plan to obtain more samples near the edge of the basin to explore this connection:

- **Rincon Valley.** The local well-owners’ association has offered to cooperate in a thorough study of the area. Rincon Valley differs from the central part of Tucson basin in having only a thin sedimentary cover over crystalline rock of the upper detachment plate. Data in hand suggest that much of the groundwater in the area is supplied through fractures in the crystalline rock beneath the sediments. Rincon Valley is thus the only extensive area of the Tucson basin where we can study recharge from the mountain block into basin sediment, a process that is almost certainly also happening beneath the very deep sediment in the basin center.

- **Tucson Mountains.** We currently have relatively few samples from the area, including the foothills on the eastern side. Available data suggest that hot water with $\delta^{18}$O lower than expected from low-elevation rain is emerging from bedrock at several locations; we do not yet have an explanation for the origin of these waters, or an adequate knowledge of their extent.
c. **Catalina Foothills.** We have little data between Rillito Creek and the Santa Catalina Mountains. We are aware of only a few wells in the area, but we will seek extra samples (probably 5) and obtain a full suite of measurements.

d. **Oracle Junction to Oracle.** No isotope study has been attempted in this area, in which large suburban developments have been proposed. Water will most likely be obtained locally for new subdivisions (as in Catalina and Oro Valley to the south where pre-1950’s water is being pumped in certain wellfields). Local government should be aware of the potential limitations of water supply before issuing permits. We envision sampling existing wells from Oracle to Oracle Junction (20 to 30 sites) to determine water origins and ages using our full suite of isotopic measurements.

**Solute balance of the Rio Grande**  
*Phillips (NMT), Hendrickx (NMT), Hogan (UA-HWR)*

The water quality of the Rio Grande, like many arid region rivers, degrades with distance downstream. In particular, salinity levels limit the municipal and industrial use of the Rio Grande in the El Paso region. The causes of salinization are often complex, with multiple natural (saline groundwater, hydrothermal springs, and dissolution of evaporite deposits) and anthropogenic (agricultural return flow and wastewater from sewage treatment plants) sources, in addition to the concentrating effect of evapotranspiration. A comprehensive understanding of the sources of salinity and the processes affecting its increase are necessary for basin-scale salinity management. For the past three years we have conducted twice-annual synoptic sampling of the Rio Grande. We have employed a variety of environmental tracers to separate different salinity sources as well as the effects of evapotranspiration. Our research is focused around the following questions: What are the major sources of solutes and how are they partitioned between natural and anthropogenic origins? What are the relative roles of solute input and evapotranspirative concentration in producing the observed salinity in the lower basin? What is the solute-burden history of the river basin and why has it varied in time? Are significant transients in solute burden likely in the future? What management alternatives are available for reducing salinity? The immediate goal of this research project is to identify and quantify the sources of salinity to the Rio Grande. The long-term goal of this research is to develop a water/solute mass balance model for the Rio Grande that is capable of modeling past temporal variation and can investigate future-use scenarios.

**Activities and Results**

We have conducted five synoptic samplings of the Rio Grande. During these sampling campaigns roughly 100 sites were sampled along the river. Samples were analyzed in the field for TDS, EC, pH and in the laboratory for Cl and Br concentrations. Salinity increases in a stepwise fashion, with roughly five localized sections of the river where there are significant increases, that is remarkably consistent with minimal seasonal or interannual variability (Figure 6A and 6B). Some of these increases are correlated with known sources (agricultural drains, hydrothermal areas). Others

![Figure 6](image-url)

Figure 6. Results from synoptic sampling of the Rio Grande. (A) Rio Grande from headwaters to Elephant Butte Reservoir, note the stepwise increase in chloride concentration. (B) Rio Grande from Elephant Butte to Fort Quitman, note the seasonal changes caused by reservoir releases. (C) Results of isotopic analysis, note the large increases caused by evaporation from Elephant Butte Reservoir.
are not correlated with known discharges but occur at the lower end of sedimentary basins leading to the speculation that they are the result of discharge of deep, saline, groundwaters. Of particular interest is the Albuquerque basin where, in two distinct steps, the TDS of the river doubles from ~150 mg/L to ~300 mg/L and Cl increases from ~10 mg/L to 30-40 mg/L (Figure 6A). With little change in river discharge for this reach, this represents a significant increase in the solute burden of the river. We have used several solute ratios (e.g. Cl/Br, Ca/Sr, Cl/SO4) in conjunction with a two component mixing – evaporation model to study the solute balance of the Rio Grande. Results indicate the importance of solute inputs, especially from Albuquerque to Elephant Butte Reservoir where ~60% of the solutes enter the system.

During the past 10 months much of our focus has been on applying isotopic tracers to “fingerprint” and quantify the sources of solutes at these locations. We are currently employing four solute isotopic: (1) $^{87}$Sr/$^{86}$Sr in collaboration with J. Ruiz at University of Arizona; (2) $^{36}$Cl/Cl at the PRIME Lab facility; (3) $\delta^{34}$S in collaboration with C. Eastoe; and (4) $\delta^{11}$B in collaboration with C.P. Chamberlain at Stanford University. In addition, samples have been analyzed for oxygen and hydrogen isotopes (with C. Eastoe) (Figure 6C). Oxygen and hydrogen isotopes reveal the importance of evaporation, especially from reservoirs. Preliminary results from solute isotope systems do “fingerprint” saline groundwaters as the solute source (e.g. low $^{36}$Cl/Cl and high $^{87}$Sr/$^{86}$Sr ratios). In order to quantify saline groundwater inputs, one must understand the chemical composition of the groundwater system. In order to do this we have developed partnerships with the USGS (Albuquerque basin), New Mexico Interstate Stream Commission (Socorro basin), and through SAHRA’s partnership with CEA-CREST (Project 2.9: Hueco Bolson - El Paso area). We are currently in the process of analyzing end member groundwater samples obtained through these partnerships.

Finally, during the past reporting period we have begun our efforts on dynamic simulation modeling. We started with modeling the Elephant Butte Reservoir system where we have observed increase in Cl concentration from ~40 to ~60 mg/L during our three years of sampling. The increase is clearly correlated with the decrease in storage volume during this same period. The situation allowed for a critical test of both water and solute mass balance modeling. We developed a model covering the period from 1997-2002 with a monthly time-step. Results of this initial model were successful. The water balance was easily modeled using USGS gauge data from surface water input and output in addition to simple precipitation and evaporation input. In order to successfully model the chloride mass balance we needed additional saline groundwater input into the reservoir.

Plans for next reporting period

Activities in the coming year will be focused on three goals:
1) Continue river sampling but with a reduced number of samples; the next sampling trip is planned for August 2002. We will continue to collect filtered samples for organic/nutrient analysis (3.9).
2) Wrap up the isotopic analysis. Determine the geochemical composition of saline groundwaters. Quantity saline groundwater fluxes using isotopic mass balance.

Mountain-front recharge: hydroclimatic variability and low-dimensional recharge-runoff models

Duffy (PSU)

The hypothesis of this research is that historical hydroclimatic observations, signal processing tools, and multi-scale dynamical models collectively provide a systematic strategy for scientific discovery for advancing our understanding of mechanisms, rates, and time scales of recharge and discharge fluxes within the Rio Grande. The modeling approach is based on a low-dimensional representation of local hillslope hydrologic processes, which is then upscaled to more complex terrain. The modeling is driven by multi-resolution GIS coverages for model input and a basin hydrogeologic conceptual model (HCM). This blueprint for modeling embraces data assimilation, optimization, and water resources forecasting. Our data analysis show that low-frequency oscillations in seasonal to interannual and decadal climatic forcing may 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 basin. Evidence suggests that low-frequency components in mountain front runoff are consistent with the El Nino-Southern Oscillation, quasi-biennial, and quasi-decadal signature. However, the physical role that the basin hydrogeology, topography and vegetation play is unresolved. Discussions with J. Wilson regarding his basin cross-section models currently under development at NMT, and the LANL Virtual Modeling Laboratory, will provide additional means of dynamical model comparison with high-resolution results. C. Duffy has had substantial interaction with the USGS (Stan Leake) regarding their regional investigation of recharge across the southwest. In the area of information management, our group is working with the University of Arizona and LANL scientists (H. Gupta, E. Springer) in developing a strategy for a multi-scale Geographical Information System (GIS) for the Rio Grande. Preliminary coverages (DEM, stream networks, geology, etc.) are found on the http://cataractis.cee.psu.edu/riogrande/ web site.

Activities and Results

During the last 10 months the emphasis has shifted from hydroclimatic data analysis to the dynamical modeling, parameter identification, and recharge estimation. Validation of the approach is being done using data sets generated by LANL for the Parajito plateau in cooperation E. Springer and B. Newman, the Rio Puerco watershed, and ephemeral mountain-front streams of the Sangre de Christo mountains at the Great Sand Dunes National Park, as well as numerical experiments using integrated surface-subsurface models (HMS-MOD). The genetic algorithm (GA) technique has been implemented to identify the model parameters with the observed daily precipitation (rain and snow), temperature and runoff. The GA method is shown to be useful where parameter ranges of the dynamical system can be specified a-priori. The model allows us to uncover nonlinear processes, feedbacks and resonance-like effects from observed hydroclimatic, groundwater and runoff data in the basin. We have developed a visualization procedure using 3-D block diagrams for hydrogeologic-conceptual model. A new version of the Rio Grande Web Site and digital field trip is nearing completion (July 22). This includes a GIS layers (geology, soils, topo, basin/watershed boundaries), historical hydroclimate data.

As part of our attempt to evaluate the space-time scales of mountain-front recharge and determine the prospect for storage-type dynamical models, we have used numerical experiments with Richards’ Equation to guide our understanding of the recharge process in the field. For example, results for the Upland Recharge-Runoff Regime (Figure 7) where atmospheric input to the model is: forcing = noise + periodic terms. Singular spectrum analysis is then used.
to evaluate the signatures of infiltration, recharge, runoff, and deep recharge (leakage) for the numerical experiment. The results show a power-law spectra over a fairly broad range of frequency. The power-law structure compares favorably with the long-term soil moisture experiments at Los Alamos National Laboratory (Nyhan and Duffy, 1998). Our conclusion is that the local recharge-runoff process is low dimensional and relatively simple but nonlinear models may indeed describe such systems. The implications of the power-law behavior in the soil moisture is the prospect for scaling relations which we hope to discover and lead to a new dynamical theory for recharge estimation.

**Plans for next reporting period**

During the next two years we intend to finish our numerical experiments on surface water/groundwater-coupled modeling and complete the intercomparisons with field data, including the effects of macropore flow. We are currently carrying out numerical experiments on recharge at an intermediate scale within alluvial fans and deep valley aquifers. Field sites have been selected at Los Alamos, the Sand Dunnes National Monument in Colorado, and the Rio Puerco below Albuquerque. The goal of the next 2 years is to find a clear linkage between recharge and long-term climate oscillations across multiple space and time scales. Extension of the low-dimensional model to large regions is the long-term goal of the research. Instead of a regular grid such as in a Finite Difference method or the Triangulated Irregular Network (TIN) as in Finite Element method, our strategy is to decompose the river basin into sub-basin using GIS tools. This not only makes our model fully GIS-driven, but also makes it highly scalable. For example, a large watershed is decomposed into twenty elements and every element can be considered as a sub-watershed with low-dimensional representation (Figure 8). The multi-scale concept means that the model is a function of the “support” used to delineate the basin from the GIS. The hydrogeologic conceptual model will be an essential element of the GIS, since this provides the hydraulic geometry and parameters for large-scale surfacewater-groundwater model development.

**Groundwater and surface water salinization in the El Paso / Juarez Region**

Hibbs (CalState LA), Hogan (UA-HWR), Eastoe (UA-GEO)

NSF, through a “Glue Grant”, has recently funded a joint research program between SAHRA and CEA-CREST. CEA-CREST (The Center for Environmental Analysis at Cal State-LA) promotes the development and testing of theories predicting natural and anthropogenic changes in ecosystems, with a particular emphasis on Southern California and the southwestern U.S. (Additional information on the CEA-CREST Glue Grant is in Appendix F). One effort of the Glue Grant is focused on understanding the causes of groundwater and surface water salinization in the region around City of El Paso/Ciudad Juarez international metroplex. The questions we are addressing are as follows: What are the spatial and temporal dynamics of hydrologic flowpaths within the basin aquifer systems of the El Paso region? How do these flowpaths control the salinization of groundwater and surface water resources? How does climate change affect groundwater recharge, basin flowpaths and residence times?

Water supply and water quality problems facing the City of El Paso and Ciudad Juárez are complex and interrelated. Over-pumping of shared water resources from the Hueco Bolson has resulted in excessive drawdown of the water table, encroachment of brackish groundwater,
and the early retirement of wells because chloride now exceeds the maximum recommended limit of 250 mg/L (Figure 7). Chloride data in time series tend to correlate to drawdown in wells. Water quality decline threatens existing freshwater resources in these aquifers, which are being extracted at a rate 15 to 20 times the rate of natural recharge.

Most of the previous studies of salinization were based on anecdotal analysis. To determine the causes of salinization more accurately, the CEA-CREST – SAHRA research team is age-dating groundwaters with radioisotopes (carbon-14 and tritium), tracking stream/aquifer interactions with stable isotopes (oxygen, hydrogen, carbon, and sulfur), and assessing mixing of saline and fresh waters with halides (chloride, iodide, and bromide). Other institutions collaborating in this study include New Mexico State University, Universidad Autónoma de Ciudad Juárez, and United Nations University. Governmental agencies are also participating in the project by providing existing data, access to water wells, and other support services. Participating agencies include El Paso Water Utilities, US Environmental Protection Agency, US Army Fort Bliss, International Boundary and Water Commission, Comisión Internacional de Limites y Aguas, Comisión Nacional del Agua, and Junta Municipal de Agua y Saneamiento de Ciudad Juárez.

Activities and Results

Formal agreements for collecting groundwater samples on the U.S. side of the international border were established with El Paso Water Utilities and US Army Fort Bliss. Both entities operate a large number of water wells. Formal agreements were also established with Universidad Autónoma de Ciudad Juárez (UACJ) for collaborating on the study. UACJ, in turn, was given permission to sample water wells operated by Mexican governmental entities. Water supply companies for Horizon City, Fabens, and Tornillo (Lower Valley cities) were contacted about sampling their deeper water supply wells. Discussions have been positive, and Memoranda of Understanding (MOUs) are being prepared to sample these wells.

To date, forty-three groundwater samples have been collected from the Hueco Bolson aquifer and flanking highlands. Twenty of these wells are located in the Mexican portion of the aquifer. Three deeper wells were sampled in the Lower Valley, four wells were sampled in the Franklin and Hueco Mountains, and two wells were sampled in the New Mexico part of the Hueco Bolson. Stable isotope, radioisotope, and general minerals analysis have been performed on these samples. The data show promising variations in all parameters. Additional sampling is currently underway.

Plans for next reporting period

This project began in Fall 2001. We have subsequently recruited the graduate students for this project, established many agreements for collecting groundwater samples on both sides of the border, and begun initial sampling and analysis. We will continue collection and analysis throughout the coming year. We plan to perform an initial analysis of the isotopic results in order to refine our sampling strategy. We hope to evaluate the role of saline groundwater in the solute balance of the Rio Grande in this region. Additional details about this project can be found at:
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Thrust Area 3: Functioning of Riparian Systems

The major goal of Thrust Area 3 (TA3) is to understand how riparian systems affect and are affected by changes in water quantity (e.g., due to ground-water pumping or conjunctive stream-water management) or water quality (e.g., nitrogen inputs from precipitation or agricultural runoff).

Research in TA3 is generally separated into two foci: 1) Water and carbon exchange in riparian systems and 2) Nutrient cycling in riparian systems. These two groups are linked through the common need to understand the dynamics of the water balance and movement within the riparian zone, as well as within the basin. This need for common knowledge also necessitates the collaboration of TA3 members with researchers from TA1, TA2 and TA4 for understanding the possible long-term effects of climate-change and anthropogenic stressors on the health of the riparian system. Much of the research being performed is a continuation of the SALSA (Semi-Arid Land Surface Atmosphere) project, and is heavily leveraged with many entities in the Upper San Pedro River Valley.

1. Water and Carbon Exchange in Riparian Systems

The major goal of this group is to develop a holistic approach for assessing the effects of ground-water development and conjunctive surface-water management on riparian ecosystems. Most of the historic riparian areas in the southwest have disappeared over the last century. This is believed to be a direct consequence of groundwater pumping for agriculture, mining, and municipal needs. These riparian corridors harbor a large majority of the regional biodiversity, and provide an aesthetic value for many humans, and presently, they are facing great stress. Researchers in this group seek to understand the effects of changing hydrologic dynamics (ground, vadose, surface, and plant water movements) on riparian ecology on the time scales of hours to years.

Individual research efforts include:

1) Determination of the interplay of the riparian plants and the movement and availability of water, and how the water usage is related to nutrient storage and fluxes
2) Response of riparian vegetation water uptake under stress due to groundwater pumping
3) Relationship between hydrologic and geomorphologic conditions and survival rate of exotic versus native riparian tree seedlings
4) What are the hydrologic, ecological, and anthropogenic controls on spatial and temporal distribution of flowing and non-flowing reaches of desert streams?

These projects are closely related as they are focused directly on the interplay of the riparian plants with the movement and availability of water. The sum of these projects will be new tools to predict ecological succession with changing hydrologic stress. Since this work is interested in long-term effects of hydrologic changes on the riparian ecology, there are connections with the infiltration/runoff studies in TA1 and the basin-scale, water-balance studies in TA2. In addition, the micrometeorological flux measurements will tie into similar measurements in TA1 and TA2. This data will also be used to calibrate land-surface models in TA4. Furthermore, the understanding of what sources of water are used by which plant communities will be critical information for basin management, and therefore will tie into TA5.
Activities and plans for next reporting period

The major activities of the various task areas for the last 10 months are listed below:

**Determination of the interplay of the riparian plants and the movement and availability of water, and how the water usage is related to nutrient storage and fluxes**

*Williams (UA-RNR), Goodrich (USDA-ARS/UA), Scott (USDA-ARS), Lin (Biosphere 2)*

The goal of this work is to quantify many of the water, nutrient, and energy exchanges of a mature, riparian forest ecosystem and identify the eco-physiological mechanisms that are responsible for these exchanges. An exceptional strength to this project is that many different aspects of the ecosystem cycling are being looked at simultaneously via an interdisciplinary approach.

**Science goals**

We seek to identify how hydrological conditions (e.g., depth to groundwater, surface soil moisture status, hydrometeorology, etc.) determine the water and nutrient exchanges from riparian ecosystems. For this study, we are focusing on the functioning of a mesquite forest as this is the dominant ecosystem type along the San Pedro River. The efforts of this subgroup are connected with the efforts of: a) the riparian nutrient groups (Conklin/Grimm/Brooks/Villinski) by trying to understand soil nutrient cycling in riparian uplands and possible nutrient sources to the San Pedro; b) Ground Penetrating Radar (GPR) monitoring (Ferré) by using GPR at the site to determine vadose zone water storage changes; c) neural network soil pedotransfer functions (USSL) by training and using neural networks for soil hydraulic properties determination; and d) evapotranspiration above the mountain front (Brown) by sharing technical expertise in eddy covariance measurements.

**Approach**

The main activities for the reporting period were to complete the first full year (2001) and begin the second year (2002) of monitoring mesquite biohydrology. Continuous monitoring includes distributed meteorological stations, above-canopy water, carbon and energy exchanges, stem- and branch-level sapflow, soil water and energy stores, groundwater depth, and stream stage. Additionally, a series of intensive monitoring campaigns were conducted 19 – 23 September 2001, 12 – 19 June 2002. These dates were chosen to capture the effects of variable climatic forcing on ecosystem functioning. During these campaigns, additional measurements were made of leaf gas exchange, leaf area index, leaf water potential, plant water isotopes, atmospheric profiles of carbon and water isotopes, understory water/carbon/energy exchanges, and soil respiration.
Results

First, we have gathered considerable evidence to suggest that there are two principal water sources for the riparian terrace ecosystem. The deep-rooted mesquite trees are accessing groundwater and appear mainly to rely on this relatively stable source. The understory vegetation, however, is highly dependent on recent precipitation and is active mainly during the summer monsoon. Evidence for this conclusion is based on the nearly constant overstory water use (i.e., mainly tree transpiration) from the pre-monsoon to monsoon period and the nearly constant relationship between tree water use and water table fluctuations (Figure 3-1) during 2001. Thus, changes to total ecosystem water use were due principally to changes in the understory evapotranspiration. These results, determined by micrometeorological techniques, indicate that the maximum tree water use seems to be nearly constant at an estimated rate of 2.5 - 3.0 mm/day throughout the growing season (i.e., after the leaves were fully mature around 1 June). These results emphasize the importance of separating out understory versus overstory water use in mesquite forests. The growing season for the mesquite was bounded by the last spring freeze and the first fall freeze. Since the nighttime temperatures within the riparian corridor of the San Pedro are typically 5 – 10 °C less than the surrounding valley floor, the growing season is only about 5 months.

Secondly, the ability of the trees to access a stable water source and the dependence of the understory on precipitation leads to interesting results in regards to ecosystem nutrient (C and N) fluxes. Net ecosystem uptake of carbon dioxide actually decreased during the rainy season even though the understory vegetation (and thus a greater total vegetation water use and carbon uptake) was active during the monsoon. This decreased uptake was due to the greater increase in soil respiration. Mesquite is a C₃, N-fixing legume that produces very high-quality litter compared to the C₄ grasses. When mesquite roots reach stable groundwater supplies, relatively large quantities of this litter can be added to the soil because photosynthesis and growth will no longer be limited by plant water availability. Large quantities of C and N are accumulating in the mature mesquite community especially in the surface litter. The presence of large amounts of carbohydrates and amino acids in the soils is of interest as these compounds are generally short-lived in soil due to the preferential metabolism by soil microorganisms. The large quantity of available C that can be readily degraded in the mesquite soil was confirmed with soil cores collected from the mesquite community that were incubated in the laboratory under moist field conditions for 80 d. The large amounts of litter that persist in the mesquite community are due to soil-water limitations that restrict the activities of soil microorganisms. Thus, shifts in precipitation patterns to greater/lesser summer events will speed/decrease the mineralization of the litter layer present in the mesquite communities.

Our assembled research team constitutes a highly integrated, multi-disciplinary team. The benefits of this multi-disciplinary approach and longer-term funding cycle of SAHRA have enabled us to look at the how component fluxes of the riparian vegetation water and nutrient cycling are related and interact (e.g., how the eddy fluxes of carbon dioxide relate to the cycling of carbon and nitrogen in the soil). One of the broader implications of this work will be a novel understanding of riparian vegetation functioning.

Future Plans

- Continuous eddy flux measurements will be collected through 2003 in order to determine the effects of wintertime precipitation on ecosystem fluctuations.
- Additional intensive measurement campaigns are planned for August 12-19, 2002 along with an attempt to monitor understory/overstory flux partitioning using stable isotopes immediately after and during the drydown of a large rain pulse.
- We are expanding this work to additional sites along a grassland to forest mesquite invasion gradient to look at the consequences of mesquite invasion on nutrient and water fluxes. An additional collaborator, Dr. Travis Huxman (Ecology and Evolutionary Biology faculty, UA) has been brought on to help in this effort.
- We will also be developing a GIS-based, riparian ET tool to assist land managers in helping to identify and predict total riparian ecosystem water use.
Response of riparian vegetation water uptake under stress due to groundwater pumping
Ferré, Maddock, (UA-HWR)

Riparian plant communities can exist only where and when their roots have access to plentiful supplies of surface water or groundwater. Due to the population increases in the semi-arid Southwest, groundwater pumping exceeds the rate of recharge in many basins. Therefore, sustainable development of this area requires an improved understanding of the response of these systems to increased water extraction through improved hydrologic models.

Science question and approach

In coordination with an EPA/NSF project managed by Tom Maddock and Kate Baird (UA) studying the effect of lowering the water table on cottonwood ET, drainage in the unsaturated zone due to pumping was monitored by Gerd von Glinski in late May/early June 2001, when cottonwood growth was strong, and in September 2001, when growth had subsided using borehole ground-penetrating radar (BGPR). Monitoring soil moisture drainage as well as re-saturation after recovery of the water table provided a picture over time (one week) as well as over distance.

Results

The focus of efforts during the past 10 months has been analysis of the field measurements. The BGPR-measured change in water content provides detail that cannot be achieved with any other existing water content measurement method. Figure 3-2 shows the evolution of a drained region above the water table (horizontal dashed line) during pumping and refilling during recovery (periods separated by a vertical dashed line). The results can be combined to determine an instantaneous specific yield as a function of time. This shows the time associated with delayed drainage (approximately 1 day) after which the specific yield assumes a reasonable value of 0.35. After pumping, the specific yield rises as high as 0.67. Numerical modeling shows that this is not due to hysteresis, but rather due to air entrapment during recovery. This monitoring method may allow for far more accurate analysis of unconfined aquifer pumping tests, improving the characterization of aquifer properties for water resource and subsurface hydrologic investigations. Variably saturated flow modeling is being conducted in coordination with researchers at the U.S. Salinity Lab (Simunek). These researchers have modified existing inverse numerical models to allow for improved interpretation of soil hydraulic properties from BGPR measurements.
Plans for the next reporting period

- Coupled with numerical modeling of drainage, this work will be the basis of von Glinski’s master’s thesis.
- The remainder of the summer will be spent finalizing a manuscript to submit for publication in the *Vadose Zone Journal*.
- The method will be used in monitoring root-soil water exchange and deep recharge, undertaken in the San Pedro Basin in cooperation with Goodrich and Scott.
- The method will be used to ground-truth ongoing efforts to map changes in subsurface water storage with Electrical Resistance Tomography (Warrick) and gravity methods (Pool).

Relationship between hydrologic and geomorphologic conditions and survival rate of exotic versus native riparian tree seedlings

*Stromberg (ASU)*

The goals of this task area are to understand the effects of human activities, such as groundwater pumping and global climate change, on the structure and functioning of riparian ecosystems.

**Science Questions**

- How do structure, composition and diversity of riparian vegetation vary across a) longitudinal river gradients of site elevation, hydrology, channel geomorphology, and fire disturbance and b) lateral floodplain gradients of flood frequency and resource availability?
- What are the hydrologic thresholds for establishment and maintenance of valued riparian plant species and associations?
- How might the San Pedro riparian vegetation change in response to human-caused changes in stream flow and groundwater regimes and climate?

**Approach**

We are addressing these questions by conducting an opportunistic (natural) experiment. Our network of 28 sites distributed in the Lower and Upper Basins of the San Pedro River span gradients of site hydrology (groundwater depth, surface flow frequency), elevation and climate (rainfall, temperature), channel geomorphology, and fire history. For each site, we have data on woody and herbaceous vegetation structure and a suite of physical variables.

**Key results**

- We described the range of hydrologic conditions, with respect to surface flow frequency and groundwater depth, over which Fremont cottonwood (*Populus fremontii*), Goodding willow (*Salix gooddingii*), and saltcedar (*Tamarix ramosissima*) grow along the San Pedro River in southeastern Arizona.
- We identified hydrologic thresholds above which the native cottonwood-willow trees are dominant over the more xerophytic, non-native saltcedar shrubs.
- We described changes in forest biomass structure across hydrologic gradients of stream flow frequency and depth to groundwater.
- We identified hydrologic thresholds for maintenance of riverine marshland associations.
- We described patterns of change in herbaceous species abundance, composition, and diversity across longitudinal gradients of elevation, floodplain width, and site hydrology.
- We began data analysis to describe effects of fire on riparian vegetation structure.
- We began development of a riparian vegetation change model.
One major research findings and its implication is:

Along many rivers of the southwestern United States, riparian pioneer tree communities have shifted from native Fremont cottonwood-Goodding willow (*Populus fremontii-Salix gooddingii*) forests to woodlands and shrublands of the exotic tree/shrub saltcedar (*Tamarix ramosissima*). Because saltcedar woodlands often have different ecological functions than cottonwood-willow forests, this vegetation change has generated management concern. A handful of environmental factors are believed to contribute to this shift in species composition. For example, changes in flood disturbance patterns can influence species establishment, with saltcedar often becoming abundant on dammed, flood-suppressed rivers. Our results from the free-flowing San Pedro River highlight the role of other hydrologic factors on species distribution patterns. Across longitudinal river gradients, cottonwood and willow abundance (measured as canopy cover, vegetation volume, basal area, and stem density) increased at sites with shallow groundwater and higher flow frequencies, whereas saltcedar abundance decreased. Fremont cottonwood and Goodding willow maintained dominance at sites with flow frequencies greater than 78-80% and groundwater depths less than 3.3-2.8 meters (Figure 3-3).

These research results relate directly to one of the major goals of TA3, which is to understand how riparian systems are affected by changes in water quantity due to groundwater pumping or conjunctive stream-water management. These results are significant in that they provide river managers with hydrologic threshold values that can serve as management goals, highlighting the importance of focusing on underlying site conditions and of restoring the hydrologic conditions under which native trees are more competitive. With this information river managers can set target goals and identify trigger points for management actions. Our efforts to disentangle effects of site hydrology from other key environmental factors that influence riparian vegetation structure also are of potential value to river managers. Our results have theoretical implications regarding the interplay of flood disturbance and water resource availability on riparian plant species diversity patterns.

**Plans for the next reporting period**

The next logical step is to test the robustness of the relationships we have described between riparian vegetation attributes and site hydrology, site elevation and floodplain geomorphology, by extending our analysis to other low gradient, alluvial rivers in the Sonoran Desert region. Our purpose is to determine whether the particular stressor-response relationships that characterize the San Pedro River riparian ecosystem are typical of riparian systems throughout the region. Alternatively, it is possible that 1) different quantitative relationships link the same suite of indicator attributes to the imposed hydrologic and climatic stressors, or 2) different biotic attributes serve as the key indicators of riparian ecosystem response to changes in water availability. We will evaluate these possibilities by developing quantitative stressor-response relationships for riparian ecosystems on two additional rivers (one dammed and one undammed).

This research will provide a foundation for expanding the applicability of our biohydrology models to the regional scale. Ultimately, our goal is to develop general riparian vegetation models that predict riparian vegetation structure and diversity from key environmental factors. Our project has potential to link with...
studies of economic valuation of rivers as flyways for birds, given that bird habitat is linked with vegetation structure, which is in turn dependent on river hydrology. Our studies also can integrate with those of ground and surface water modeling of rivers. As hydrology (MODFLOW) models predict hydrologic change, our linked biohydrology models can then predict vegetation change.

What are the hydrologic, ecological, and anthropogenic controls on spatial and temporal distribution of flowing and non-flowing reaches of desert streams?

Leake (USGS)

A current concern is whether or not the San Pedro River is drying out. To complement the data currently available from existing stream gauges, the goal of this task is to use new techniques to determine the spatial temporal variation of in-stream flow.

Approach

- Forty temperature sensors were installed along the San Pedro River and in tributary washes from the headwaters below Cananea, Sonora, Mexico, to the mouth near Winkleman, Arizona, U.S.A.
- Data have been collected for over a year at many locations and thermographs have been constructed. The spatial and temporal distribution of stream flow was determined by statistical analysis of the temperature data.
- Because of the relation between temperature fluctuations and stream condition, it is possible to detect the presence and absence of stream flow by monitoring streambed temperature.

Results

The research activities for the current reporting period include further data collection and analysis geared towards ending the project. All temperature probes placed in the field during the initial reporting period were removed. Results indicate that streambed temperature sensors can be used to classify stream reaches as perennial, intermittent, or ephemeral. The presence or absence of water in a stream channel will affect streambed temperature in the same way regardless of the stream channel's classification. However, due to the different flow patterns associated with each type of flow, the differences in flow patterns can be recognized on streambed thermographs.

This project has shown that low-cost temperature sensors can be used to classify flowing and non-flowing stream reaches in the desert southwest. The method can also be used to monitor how a stream channel responds to stress, such as an extended drought. By being able to delimit what reaches can potentially dry out, it is possible to recognize areas that can potentially be impacted by changes brought about by human activities.

Plans for the next reporting period

This work will result in a master’s thesis and a refereed publication.

2. Nutrient Cycling in Riparian Systems

The central objective of this group is to understand the role of biogeochemical cycling in the various zones of the riparian/stream corridor as a pathway for removal of natural and anthropogenic solutes, and as a tool for understanding the health and sustainability of the riparian ecosystem. Zones within the riparian/stream corridor can be highly variable, depending on channel type, perturbations, and local vegetation. The interaction of nutrients and biota affects redox conditions in shallow ground water, which influences the movement of anthropogenic inputs in the system. The efficiency of this biogeochemical cycling depends on availability of nutrients, characteristics of the riparian ecotone, and hydrogeologic characteristics of hyporheic/riparian zone flowpaths. In streams of the semi-arid Southwest, the common
limiting nutrient is nitrogen. Large nitrogen inputs from precipitation, fertilizer applications, and other human activities thus could potentially contribute to eutrophication of aquatic ecosystems. In addition, rainfall and nitrogen inputs from floods exhibit seasonal patterns.

Individual research efforts include:

1) The influence of episodic flow events on nutrient and sediment loads in semi-arid streams
2) Relating hydrologic flowpaths to nutrient speciation and retention
3) Contribution of terrestrially produced dissolved organic matter (DOM) to carbon and nitrogen cycling in semi-arid riparian ecosystems
4) Spatial and temporal variations in the sources, sinks, and speciation of nitrogen and carbon in semi-arid rivers

These projects are closely related as they all concerned with nutrient cycling in the riparian/stream system. Crucial to all these projects and those of the other focus of TA3 is the understanding of the flow of water in the various hydrologic units within the system. Therefore, these projects will not only share data within TA3, but will also share data with TA1 and TA2 regarding hydrologic inputs into the riparian system. The ultimate goal is to create a “nutrient” model that combined with the other modeling activities within the San Pedro River Basin can result in an integrated riparian ecosystem model.

Activities and plans for next reporting period

The major activities of the various task areas for the last 10 months are listed below:

The influence of episodic flow events on nutrient and sediment loads in semi-arid streams
Conklin, Villinski (UA-HWR)

Our overall goal is to understand the coupling between the hydrologic cycle and nutrient inputs into riparian systems. Our hypothesis is that during flood events different compartments of the riparian system are linked due to overland flow and subsurface water inputs.

Science Questions

Our overall question is: What role do flooding events play in contributing nutrients to semi-arid rivers, both temporally and spatially?
- What are the important hydrologic pathways for nutrient delivery to semi-arid rivers? In particular, what are the roles of tributaries, relic floodplains, and channels for nutrient delivery?
- What are the linkages between sediment scour and fill (due to flooding events) and nutrient uptake rates in the sediments?

Approach

- Two autosamplers have been placed at both ends of our Boquillas Ranch study reach. Samples are collected hourly during storm events, and analyzed for major anions, nitrate, and ammonium. Precipitation and soil water samples were also collected.
- Two transects of scour pans and chains have been established to measure sediment scour and fill in a point bar at the Boquillas Ranch site. Over the last six months, water quality sampling and monthly respiration measurements were taken along a flowpath. Tracer tests were performed to establish flowpaths on the point bar at Boquillas Ranch.

Results

Two storms flood events were sampled: a complete small flood event (July 17-18, 2001) and the receding limb of a larger flood (August 8-10, 2001).
• **Sampling Event of July 17-18, 2001.** Using the nitrate, chloride, oxygen isotope and dissolved organic carbon (DOC) data, two scenarios can be proposed: a) there is a continuous release of water from either post-flood bank drainage or another source after peak flow or b) in-stream metabolic processes are at work during the receding limb. The second scenario is less likely, due to the short duration of the event and the condition that most organisms are rapidly transported downstream during the flood. These results have also been analyzed using a mixing model to determine the extent to which a particular hydrologic component has contributed to stream flow (Figure 3-4). Oxygen isotope and Cl- concentrations in precipitation, stream water and soil water were used as endmembers. Our mixing model results yielded that old water contribution was greatest just before and during peak flow, indicating a significant contribution from either groundwater or soil water flushing.

• **Sampling Event of August 8-10, 2001.** August samples were taken during the receding limb of a larger flood (> 300 cfs). These data illustrate the tendency for the stream to return to its normal chemistry levels after a flood. However, all stream chemical signals exhibited a significant change ~15 hours before the smaller flood occurred. DOC data reflect this phenomenon, but not as dramatically. These results provide evidence that a) relic flood channels may be releasing water to the stream during the flood recession, b) flood flow is “pushing” water through these relic flood channels, or c) bank drainage is occurring.

Point bar work to date has established water quality and respiration conditions that occur before and after leafout:

• Tracer injections were performed in February (pre-leafout) and May (post-leafout) to establish the direction of subsurface flowpaths.
• Respiration rates are highest at the stream-parafufluvial interface due to higher dissolved oxygen and nutrient concentrations flowing into the parafufluvial zone from the stream.
• Respiration rates do not appear to be depth-dependent in the spring baseflow period.
• After leafout, aerobic microbial activity in parafufluvial sediments, which are anoxic before disturbed and extracted, is positively correlated with dissolved oxygen concentration. This finding implies that despite an extended period without aerobic conditions, the parafufluvial microorganisms are able to use oxygen as soon as it becomes available.

Other research and field activities include the collection and analysis of diurnal stream samples during March, May and June 2002. Interesting trends were noted: nitrate levels were high from late evening to early morning before leafout, and during the day after leafout.

Our work on nutrient inputs during flood events, and mixing model calculations, has indicated that relic flood channels, and not bank drainage, is an important contributor during flood recession. The post-flood flows in these relic stream channels may be a potential source of nutrients to post-flood stream flow. The real-time scour and fill measurements from our scour pans will be the first time measurements of this type have been made. Coupling these measurements with respiration measurements and nutrient incorporation into sediments will provide an understanding of the role of nutrient deposition during flood
events. These observations point to the importance in identifying the important processes that control nutrient flow in developing a model of the nutrient flows in semi-arid riparian systems.

Plans for the next reporting period

- Continue to monitor sediment and nutrient fluxes on a meander point bar. Complement these measurements with laboratory respiration measurements using groundwater from the site with and without nutrient additions.
- Repeat current water quality and sediment scour measurements in a reach that contains a tributary. Most river basins have key geomorphic characteristics. To scale up the nutrient work to a basin scale, we need to examine nutrient movement associated with geomorphic characteristics. Tributaries should provide an inflow of both nutrients and sediments during flood events.
- Focus on the role of flowpaths in floodplains and relic channels for nutrient contributions during and after flood events. As we are trying to identify the important geomorphic characteristics that facilitate nutrient movement, characterizing the role of these units will help to provide a basin-wide description of nutrient movement and will facilitate the development of an ecosystem model.
- Develop real-time instrumentation for a cross-section of the San Pedro to quantify water quality and sediment movement on different temporal scales. A proposal by Villinski and Conklin will be submitted to leverage the infrastructure in place through SAHRA.

Relating hydrologic flowpaths to nutrient speciation and retention

Grimm, Schade, Lewis (ASU)

River-riparian ecosystems are characterized by dynamic interactions between terrestrial and aquatic subsystems, and between surface and subsurface waters. These dynamic interactions produce whole-ecosystem functions such as nitrogen retention, or net removal of N during transport. The central objective of this project is to understand how hydrology and biogeochemistry interact to influence nitrogen retention in arid-land riparian ecosystems.

The functioning of ecosystems may be contingent on the spatial arrangement and functioning of their constituent subsystems. Fluvial ecosystems can be conceptualized, using a framework of the Telescoping Ecosystem Model, as a series of concentric cylinders (Fisher et al. 1998). These cylinders, or zones, lie along a core-to-distal gradient. The surface channel runs through the core, and saturated hyporheic sediments envelop this core both vertically and laterally. The riparian zone constitutes the most distal element considered here. This zone exhibits vertical structure that includes the rooting zone of riparian vegetation underlain by a region of episodic saturation. We used this framework to understand the spatial and temporal dynamics of nutrient concentrations in the San Pedro River ecosystem.

![Figure 3-5. Seasonal variation of nitrate (NO3) and ammonium (NH4) concentrations in surface water, groundwater from gravel bars, and the riparian floodplain. Both forms of inorganic nitrogen exhibit a pattern of decreasing variability along the core-to-distal gradient. Seasonal fluctuations of nutrient concentrations are pronounced in the surface water, suppressed in the gravel bars, and relatively absent in of the riparian zone.](image-url)


Science goals

- Characterize the nutrient concentrations and speciation in different stream/riparian corridor zones.
- Determine how direction and strength of hydrologic linkage between stream and riparian zone influence nutrient concentrations and retention.
- Describe the patterns and uncovering the mechanisms of nutrient retention by the riparian zone, including location of hotspots for plant and microbial activity.

Results

Two sites along the Upper San Pedro River, Gray Hawk Ranch (gaining reach) and Boquillas Ranch (losing/intermittent reach) were instrumented in year 2 with 90 piezometers, installed on cross-river transects located every 50-100 m along the 400-500-m reaches. Subsurface water was sampled approximately bimonthly. Our findings from the year-long subsurface water sampling underscore the importance of hydrology for controlling variation in nutrient concentrations. Along the core-to-distal gradient, hydrologic flux decreases. That is, flow is fast in the surface channel, slower through gravel bar sediments, and slower yet through riparian soils. Along this gradient, consequently, temporal variation in nutrient concentrations declines, but spatial variation in nutrient concentrations increases (Figure 3-5).

We found flowpaths that moved in both directions across the riparian zone-stream interface. The interface was clearly an active site ("hot spot") of nutrient retention. However, the relative importance of these hot spots depends to a great extent of the total flux of water across the interface. At the locations where we have done these detailed studies, discharge is very low, so high rates of retention will not contribute much to overall ecosystem retention. Therefore, we intend to focus future efforts on locations where subsurface discharge is higher, such as the Gray Hawk Ranch toposequence site.

Plans for the next reporting period

- Results from the year-long subsurface water sampling campaign are being summarized in a manuscript by Lewis, et al. (in preparation).
- Seasonal changes in nutrients and major ions are being described in a manuscript by Schade, et al (in preparation).

Future Science Questions

- As to plant-soil-water-nutrient interaction along a relict channel toposequence, questions include: What is the hydrologic flux among the individual segments of this toposequence, and between the entirety of the series an its surroundings (i.e., the mesquite terrace uplands and the riparian floodplain). To what extent does the nutrient budget of a toposequence segment (defined here as a distinct ecosystem) derive from retention and internal recycling versus from exchange with other ecosystems? Does any exchange vary seasonally or in response to storms and the flux of water? What are the feedbacks between the processing of organic matter plus nutrients and the structure and diversity of the plant and detritivore communities?
- Solute injection experiments are needed to trace nutrients through hydrologic storage and biotic compartments.
- Beaver, microbes, and mammalian diversity: a project is being developed in collaboration with John Sabo (ASU), to address the following questions: What are the effects of localized beaver activity on forest biomass and species composition? What factors limit the spatial extent of beaver herbivory? How does large tree removal by beaver change resource and predator abundance for omnivorous mammals? Do strong negative feedbacks exist between beaver activities and subsequent reestablishment of preferred tree species?
Contribution of terrestrially produced dissolved organic matter (DOM) to carbon and nitrogen cycling in semi-arid riparian ecosystems

Brooks (UA-HWR)

The first 10 months (Year 3) of this research project has resulted in a refinement and reprioritization of research objectives. The qualitative and quantitative differences between mesic and arid ecosystems means that there are more baseline measurements that need to be performed before some of our original research questions can be answered. Consequently, we have taken two approaches to address these broader issues of hillslope, riparian, and stream connections in arid and semi-arid environments. First, we have coordinated our research with other SAHRA investigators within TA3 as well as across other thrust areas. Secondly, we have leveraged our SAHRA funding to obtain supplemental resources to make specific measurements and fund analyses.

Science Questions

- How are DOC, DON, and particulate C and N delivery to the aquatic systems related to changes in flow regime?
- What are the major controls on carbon and nitrogen concentrations in the Rio Grande drainage? Collaborative with Hogan (TA2) and Villinski (TA3 – see 3.8 for more information)
- How are the concentration, structure, and composition of inorganic and organic carbon and nitrogen related to flowpaths and hyporheic processes in the San Pedro? - Collaborative with Conklin (TA3)

Episodic flow events transport large amounts of terrestrial organic matter to the aquatic environments in semi-arid streams. Early during very large flow events, particulate organic matter (POM) exceeds dissolved organic matter (DOM) by a factor of two. During moderate flow events and between storms POM declines rapidly, presumably due to settling, while DOM remains elevated. The first few storms of the monsoon season result in a tripling of dissolved organic carbon (DOC) concentrations in the surface waters of the San Pedro River. Concentrations during subsequent storms are intermediary between baseflow values and the initial increase in concentrations. Baseflow concentrations exhibit very little variability during the remainder of the year. Dissolved organic nitrogen (DON) concentrations increase by a factor of 10 with the first few storms of the monsoon season, and then decline sharply to pre-monsoon values. Unlike DOC concentrations that remain relatively stable during the winter, DON concentrations increase again late in the year and remain elevated until spring. With the exception of the first flow events, the ratio of carbon to nitrogen (C:N) in DOM increases during the monsoon. Winter C:N ratios remain close to 10:1, similar to living biomass.

Chemical analyses of organic matter sources throughout the year confirm that the increases in DOC and DON during the monsoon are the result of terrestrial organic matter being transported to surface water (Figure 3-6). As the monsoon ends, dissolved organic matter gradually becomes dominated by aquatic sources, consistent with a late summer increase in in-stream primary production and absence of a transport vector for terrestrial organic matter. In-stream autochthonous production continues to dominate the available organic matter throughout the winter.

Current understanding of the connections between riparian and upland ecosystems is based on temperate, mesic ecosystems that are qualitatively and quantitatively different than semi-arid environments. This study has provided baseline information that can be used to develop external, integrative,
interdisciplinary proposals that address the key questions regarding the importance of hillslope land use change to the function and sustainability of these ecosystems. Specifically, this work has demonstrated the importance of episodic hydrologic transport events in the overall carbon and nitrogen balance of semi-arid river systems. These findings are analogous to findings from other seasonally flushed catchments, e.g. snowmelt dominated ecosystems. Because most arid and semi-arid streams ultimately originate in seasonally snow-covered high elevation environments, the emerging conceptual basis for understanding the structure and function of these systems invokes a pulsed ecosystem concept. The pulsed availability of water occurs on a variety of time scales from headwater reaches to main-stem rivers. These periods of increased water availability are associated with pulses of biological activity. Because they also transport the limiting nutrients and carbon required for biological processes, they appear necessary for the biogeochemical processes at the base of ecosystem function. Further quantification of the linkages between upland and aquatic environments is key to one of the goals of SAHRA: identifying the baseline sustainability of these riparian ecosystems.

**Plans for the next reporting period**

The majority of hydrochemical and biogeochemical research occurring on the San Pedro River is occurring at a few intensively studies locations. Results from this work are yielding important, mechanistic insights into the structure and function of riparian ecosystem in arid and semi-arid environments. Because many of the insights gained from this research are new, there are few (if any) data sets that can be used to expand the results from these areas to other reaches along the greater San Pedro. Results from this and other SAHRA projects suggest that future research directed toward understanding the structure, function, and sustainability of aquatic ecosystems in arid and semi-arid regions involves expanding the spatial and temporal insights gained over the last few years to larger spatial domains. To that end, we propose to focus our work on the following two general areas:

**Question A.** Do the intensively studied sites at Boquillas and Greyhawk on the San Pedro River represent water chemistry and stream riparian interactions throughout the larger San Pedro system?
   - A1. Will sites similar to the intensively studied reaches on the San Pedro exhibit similar patterns in water quality driven by hydrology?
   - A2. Are water quality and biogeochemical cycles along any specific reach more closely related to instream/upstream processes or to the terrestrial environment?

**Question B.** Are the results from the San Pedro applicable to other arid and semi-arid river systems?
   - B1. Are the sources of DOM in the Rio Grande similar to those identified for the San Pedro?
   - B2. How are riparian environments linked biogeochemically to adjacent hillslope and terrace environments?
   - B3. Do the large amounts of available nitrogen in semi-arid regions promote nitrate leaching to groundwater?

As discussed above, the majority of the biogeochemical research within SAHRA has occurred along the San Pedro River. There is general consensus that over the next two years this research needs to be expanded to include other semi-arid environments as well as integrated with other research projects within SAHRA. These three questions are designed to begin to address this need. Specifically, question B1 expands biogeochemical research out of the San Pedro and into the Rio Grande where there is significant research by other thrust areas. Question B2 is designed to link terrace research with riparian research building on the wealth of information in the San Pedro. Question B3 conceptually links biogeochemical research with questions of recharge.

**Spatial and temporal variability of the sources, sinks and speciation of nitrogen and carbon in semi-arid rivers**

*Villinski, Hogan, Brooks, Conklin (UA-HWR)*
Nitrogen is generally regarded as the limiting nutrient in semi-arid streams and rivers. Likewise, nitrogen is the element that has been most heavily impacted by anthropogenic means, mainly through the use of man-made fertilizers. Current understanding of nutrient dynamics, and anthropogenic impacts on these dynamics, are not well understood at the scale of the river in semi-arid and arid regions. In mesic, temperate regions, riparian corridors act as buffers, removing and transforming pollutants (i.e., nitrate). In semi-arid regions, compared to mesic systems, the movement of water is away from the stream during most of the year. We cannot, therefore, rely on mesic models to understand nutrient cycling in semi-arid riparian systems. To move from process-level studies of nutrient speciation and retention, we need to gather base-line data from semi-arid rivers under different management schemes.

Science questions

- What are the sources and sinks, and the mass loads of nitrogen and carbon species in the semi-arid rivers, both temporally and spatially?
- How do anthropogenic factors (agriculture, urban centers, groundwater extraction, reservoirs) affect the nitrogen and carbon loads and speciation?

Research approach

Our scientific approach is to perform synoptic sampling of two end-member rivers (the Rio Grande and the San Pedro River), collecting filtered samples from the length of the river at different times of the year (twice yearly on the Rio Grande and seasonally on the San Pedro River), and analyzing the samples for nitrogen species (nitrate, ammonium and dissolved organic nitrogen) and dissolved organic carbon in addition to the measurements being performed by James Hogan (TA2).

Results

This is the first year of this project. Synoptic sampling was performed twice along the Rio Grande, in August 2001 and January 2002, in conjunction with the salinity sampling performed by James Hogan, TA2. Samples were taken from ninety locations along the river from the near the headwaters in Colorado to south of Fort Quitman, Texas, as well as from tributaries, agricultural drains and the conveyance channel. Sampling on the San Pedro River will commence in fall 2002 in collaboration with research being done by the Upper San Pedro Partnership (James Leenhouts, USGS and Juliet Stromberg, ASU/SAHRA).

Results of the two synoptic sampling runs indicate that two major sources of nitrogen to the Rio Grande system are 1) municipal waste and 2) agricultural return flows (e.g., nitrate concentration, see Figure 3-7). Of interest is the fact that after a large increase in nitrate concentrations below the Albuquerque wastewater treatment plant, the nitrate levels do not decrease until the river reaches the Elephant Butte reservoir. This behavior may be due to a lack of primary production occurring in this region, and may be related to high sediment load decreasing light penetration. In contrast, as water moves through the sediments between the river and the conveyance channel, nitrate is removed, suggesting that microorganisms are utilizing nitrate as an electron donor.

![Figure 3-7. Nitrate concentration in the Rio Grande during August, 2001, including agricultural return drains, conveyance channel, and tributaries.](image-url)
Nitrogen levels, both nitrate and ammonium, were generally higher in the winter than in the summer, most likely due to the lack of agricultural production at that time. Mineralization of organic nitrogen results in ammonium, the lack of growing crops decreases the utilization of this nutrient, and the ammonium is then transported to the river. The increased nitrate levels maybe due to flushing of fertilizers. Concomitantly, the carbon to nitrogen levels in the dissolved organic matter in the river were generally lower in the winter than the summer, indicating that the river is not nitrogen-limited during this time.

The results of this project to date are providing a background level understanding of the overall levels, sources, and sinks of nitrogen species in the Rio Grande during two seasons. Most importantly, nitrogen increases occur in well-defined river segments, coinciding with agricultural return drains and the major urban centers of Albuquerque and El Paso/Juarez. Even though the nitrate-nitrogen levels are below the EPA-mandated MCL of 10 mg L⁻¹, recent research has linked bladder cancer to nitrate-nitrogen levels above 2.5 mg L⁻¹. This level of nitrate occurs in the winter months in the Mesilla Valley and El Paso/Juarez regions of the Rio Grande. In addition, the effects of these higher than background levels of nitrogen on the riparian ecosystem are not known at this time. Finally, during times of sustained droughts, with lower flows in the river, the nitrate levels in the river may increase to unhealthy levels (with a greater percent of the flow coming from agricultural drains and wastewater treatment plants).

**Plans for the next reporting period**

- Sampling will commence along the San Pedro River this fall after the monsoon season. This will allow us to assess the differences in nutrient levels and speciation due to different anthropogenic controls.
- Sampling will continue on the Rio Grande this summer and winter, with additional isotope measurements made to confirm nitrogen sources, distinguishing between animal-derived wastes (i.e., waste water treatment) and plant sources.
- Collaboration will commence with Julie Stromberg to study the linkages between riparian structure and diversity and nutrient levels.

This research is important to the goals of SAHRA because this is the first step to up-scale the nutrient work currently being performed under TA3 from the process/reach level to the length of the river. In addition, research will begin to address issues of transferability of results across basins. This work, in conjunction with Julie Stromberg’s work, should prove valuable in the creation of an integrated riparian ecosystem model.
Thrust Area 3: Functioning of Riparian Systems
Thrust Area 4: Multi-Resolution Integrated Modeling of Basin-Scale Processes

The major objective of Thrust Area 4 is to integrate emerging scientific understanding into comprehensive river-basin models that can be used in the analysis of water resource management issues.

After the SAHRA Annual Meeting in March 2001, a suggestion was made to reorganize the structure of TA4 to better coordinate with the efforts of other Thrust Areas. In that document a multi-resolution approach to integrated modeling was proposed; Thrust Area 4 has consequently been reorganized into three focus areas: 1) Fine Resolution (100 m) Integrated Modeling; 2) Medium Resolution (1-25 km) Integrated Modeling; 3) Basin-Scale (coarse resolution) Integrated Modeling. The rationale is based on the assumption that the computational burden of the fine resolution effort might not always be necessary to address a broad spectrum of basin scale issues, which range from the precise prediction of hydrologic behavior to the abstract consequences of policy decisions. Models with a coarser geographic resolution may facilitate incorporation of socio-economic responses within a watershed, where very precise spatio-temporal estimates of hydrologic behavior are not required.

During a Thrust Area 4 Workshop held in Albuquerque September 20-21, 2001, the Rio Grande basin was designated as the testbed for the integrated modeling efforts within SAHRA. Currently, ten projects are identified within the thrust area, but some are only at the beginning stages and therefore are not included in the present reporting period. A TA 4 workshop held in Taos June 6-7, 2002 helped to define the projects within the new basin context. Both workshops were instrumental in further developing this
integrated focus, with particular thought given to the use that SAHRA researchers working in socio-economic disciplines may have for the outputs from the physical models.

An important result of the Taos workshop has been the creation of a core integrated modeling team composed of representatives of the various physical modeling efforts and representatives of the economics and river operations teams. The goals of this team are to:

- Provide a conceptual model outline for the Rio Grande/Rio Bravo
- Coordinate between the three model scales being pursued
- Identify available data and data needs for the models
- Identify needed modules for integrated models
- Identify outputs from integrated models to answer the policy and science needs of SAHRA

1. **Fine Resolution Integrated Modeling**

There is one active project within this sub-area:

**Fine resolution integrated model of the Rio Grande Basin**  
*Winter, Springer, Costigan (LANL)*

This project provides a scientific computational foundation for water resource decisions by coupling detailed physical models of the atmosphere, land surface hydrology (including plant communities) and groundwater hydrology of the Rio Grande Basin. Policy makers and water resource managers must increasingly decide among complex alternative allocation and activities. Their decisions routinely affect multiple competing users of water (including human beings, endangered species, etc.) whose interactions are difficult to anticipate without detailed physical models of highly resolved, basin-scale water budgets. Furthermore, their decisions sometimes have unintended consequences because of non-linear interactions among system components. This project supports science-based decision making in three ways: 1) Increased physical understanding through experimentation. Physics-based models allow classical "hypothesize and test" science to be conducted on realistic virtual watersheds. 2) Scenario evaluation. Coupled physical models of the atmosphere, land surface hydrology and groundwater hydrology allow decision makers to evaluate the effects of alternatives on the entire Rio Grande system and their interactions. 3) Prediction. High performance computing supports Monte Carlo simulation of detailed basin-sized realizations. Development of deterministic equations for the moments of hydrologic variables (pressure head, runoff, etc.) yield efficient estimators and confidence intervals for system state variables.

Development of the Virtual Watershed Laboratory, a general computing environment for developing hydrologic models on parallel processors, has been postponed. The effort was too ambitious given the other tasks we are trying to accomplish.

Specifically during the last 10 months the following has been accomplished:

- A physics-based approach to coupling hydrologic regimes was developed for the stream aquifer interface. The scaling approach has application to other interfaces such as land surface and atmosphere.
- We completed our work on stochastic models of heterogeneous groundwater systems and published them in *Water Resources Research*.
- Parallel Application Workspace (PAWS) software was applied to the coupling problem. PAWS allows individual components to transmit data when required rather than being collected by a single processor and distributed through files.
The findings, results, and implications are:

- We produced soil moisture maps at 100 m for the Rio Grande Basin above Cochiti Reservoir for the early 1992/93 water year. Once these have been validated, they will provide an unprecedented level of detail about the distribution of a critical variable.
- We developed a method for closing moment differential equations that is robust against the large variances found in heterogeneous groundwater systems. This promises to significantly extend the range of applications of stochastic models because most groundwater systems are highly heterogeneous.
- We developed boundary conditions for stream-aquifer interactions that conserve mass and momentum on average and are faithful to the small-scale physics found near the interface. We characterized conditions under which boundary conditions reduce to a simple difference between pressures in the stream and aquifer, which is the ad hoc model assumed in most of hydrology. We give conditions in terms of Reynolds and Froude numbers under which the ad hoc model is acceptable.

This work has been supported by a $500K/year match from Los Alamos National Laboratory as part of its commitment to SAHRA.

**Plans for the Next Reporting Period**

During the next reporting period, we intend to accomplish the following:

1) Complete land surface-atmosphere coupling
   a) Examine alternatives to current statistical downscaling of atmosphere-land surface link
   b) Develop up-scaling for land surface-atmosphere link
2) Couple land surface-groundwater models
3) Couple stream-groundwater-land surface models
4) Computer Science
   a) Integrate 1-3 under PAWS
   b) Visualization
5) Develop requirements for additional modules
   a) Farm
   b) Riparian areas
   c) Socio-economic
   d) Water resources infrastructure
      i) Reservoirs
      ii) Irrigation Systems

The project will provide basic commodity inputs to UNM economic models. We will also collaborate with Eric Small to develop method for up-scaling experimental results to 100 m scale. We will validate the models using the remote sensing model (SEBAL) implemented by Jan Hendrickx. We will also provide water balance inputs to water quality models (salinity).

**2. Medium Resolution Integrated Modeling**

Current efforts in this sub-area include:
1) Medium resolution integrated land surface model of the Rio Grande Basin
2) MMS model of the San Pedro River Basin
3) A farm module for MODFLOW 2000: simulation of supplemental groundwater allocation in a surface water-based irrigation setting (Rio Grande from Caballo Dam to El Paso Narrows)
Medium resolution integrated land surface model of the Rio Grande Basin
Gupta, Bastidas, Nijssen (UA-HWR)

This effort is based on the assumption that simpler models may facilitate studies of the socio-economic responses within a watershed, where very precise spatio-temporal estimates of hydrologic behavior are not required. It constitutes an effort similar to the one being conducted at Los Alamos National Laboratory, i.e., it involves an atmospheric model, a land surface model, and a groundwater model, but with a coarser spatial scale and entire basin extent (from headwaters to the ocean and including the Mexican portion of the basin). The coupling of the systems faces similar issues to the ones faced by the fine resolution effort. During the reporting period, a grid system of 1/8 of a degree (~12 km) resolution was established for the Rio Grande Basin. In addition, a similar grid system was set up for the San Pedro River Basin as a pilot study. The San Pedro requires almost two orders of magnitude less computational effort (97 cells versus 5300), and is therefore ideal for testing the initial setup and model development. To drive the model, we are using a data set from the University of Washington in conjunction with the precipitation product provided by the PERSIANN system (TA1 project) and remote sensing estimates of radiation from the University of Maryland.

This project started as a separate entity in April 2001. A number of decisions were made, namely the use of MM5 as the mesoscale atmospheric model and of the NOAH model for the initial development of the land surface model, after conducting an extensive comparative evaluation of different Land Surface Models (LSMs) with different levels of complexity. The models compared were (in order of increasing complexity): Bucket, CHASM, BATS, NOAH, BATS2, and CLM. All the models were calibrated at six different sites, covering different climate and vegetation characteristics, in an offline fashion. The sites used were: ARM-CART SGP (in Oklahoma), BOREAS (Canada), Cabauw (Netherlands), Illinois, Ji-Parana (Brazil), and Tucson (Arizona). The results suggested that the performance of the models was consistent throughout the sites; the range of errors was similar at all sites for each model. The NOAH model (NCEP) was best at reproducing the results in the Tucson semi-arid environment.

We have gathered and quality-checked two years of meteorological tower data from the San Pedro basin (from the USDA-ARS Tucson office) at the Lucky Hills and Kendall locations. Using those data sets we carried out a new set of calibrations of the NOAH model in semi-arid environments. The calibrations used the point observations for driving the model. We also estimated the errors introduced by the use of remote sensing estimates of precipitation and radiation. At the same time (and using the same datasets) we conducted a pilot study of the influence that proper parameter estimation procedures can exert on the carbon simulations of the models. It was observed that the simulation capability of carbon fluxes in the models is very poor in the arid environments and that a new sort of formulation, appropriate for local environments, is required.

An initial scheme of the envisioned multi-resolution land surface model has been set up for both the San Pedro and the Rio Grande basins. The San Pedro basin is being used as a pilot study because of the almost 2 orders of magnitude difference in computational effort. The San Pedro model is being run using two years of data with a time step of 30 minutes and...
at resolutions of approximately 12 and 4 km. The driving inputs into the model are those of the University of Washington data set and a data set that includes the use of remote sensing information: the PERSIANN precipitation product and the University of Maryland radiation data. The Rio Grande Basin has been set up, up to the mouth, with a space resolution of 12 km and a time step of 3 hours.

The results obtained during the calibrations using the remote sensing values for driving the model at the tower sites suggests that the replacement of precipitation observations with the PERSIANN product induces a deterioration of 20-30% in terms of the root mean square error. The errors are double that obtained with observational forcing when replacement of the radiation forcing occurs. This implies that the PERSIANN precipitation product being developed in TA1 can be used for driving the model with a relatively small deterioration. That is not true for the use of the remotely sensed radiation forcing. Dr. Rachel Pinker from the University of Maryland has agreed to obtain values with a higher resolution both in time and in space. The results from this work constitute the basis for the intercomparison experiment in semi-arid lands proposed to the GLASS steering committee.

The first results from the San Pedro and Rio Grande medium resolution models will be ready at the end of the third year.

The project started 15 months ago and so far the advances are encouraging. The PERSIANN precipitation product from the precipitation estimation project (TA1) can be used as the precipitation forcing for the land surface model in off-line mode. The appropriateness of the parameter estimation procedures applied has also been shown. The results from the studies have attracted the attention of international projects and will give SAHRA recognition. The present project is part of the multi-resolution integrated modeling effort that will include the Mexican side of the Rio Grande Basin, therefore providing a strong international link.

Leveraging has come mainly from two projects. A project funded by the NOAA-GCIP allowed basic work to be completed in the parameter estimation for land surface models both in coupled and off-line modes, i.e., the development of methodologies and algorithms. In the past 10 months leveraging has also come from a NASA-funded project that seeks to monitor and predict water availability in the Lower Colorado River basin. This work has provided experience in the use of the MM5 atmospheric model.

**Plans for the Next Reporting Period**

We will develop a Multi-Resolution Model (MRM) for the Rio Grande that includes a land surface model, a river model, an agricultural and pumping model, an atmospheric model, a groundwater model, and an economic model. The MRM will cover the entire Rio Grande basin, from headwater to mouth, including the Mexican part of the watershed.

The model will be setup at 1/8° (~12 km) and 1/24° (~4 km) spatial resolutions so we can appraise the sensitivity to resolution. Two time scales will be considered. The first is 1 to 2 years, with a short time step (~30 min) to evaluate the hydrology. The farm module (see below) will be included in the groundwater representation. An evaluation of the precipitation product from the TA1 project on estimating precipitation over the southwestern U.S. will also be carried out. Other evaluations that will include comparisons with the fine resolution model being developed at LANL and the coupling strategies with the groundwater and the atmosphere will also be considered. The second time scale considered is 50 years; for purposes of scenario analysis and water resources we envision a simulation period of 50 years using the LSM forcing time series developed at the University of Washington.

We will link the engineering and control structures for agriculture, pumping, and return flows to the model. A demand and economics model will also be linked to the physical model.

The project will integrate with the other planned activities of SAHRA through the linkage with the scenario analysis and the demand and economics model. At the same time the goal of modeling the entire basin, down to the mouth and including the Mexican part, provides a strong international link for SAHRA activities.
MMS model of the San Pedro River Basin

Bastidas, Gupta (UA-HWR)

This project is complementary to the Rio Grande medium resolution model and is focused mainly on the development and parameterization of appropriate routing schemes for semi-arid environments that take into account the resolution dependency and channel transmission losses. The project is making use of the MMS environment and has provided a strong linkage between the USGS and the University of Arizona modeling groups. So far, this project is the sole user of the MMS capabilities of computing runoff using different time steps (storm mode) and has allowed for the improvement and correction of the corresponding computer codes.

We have gathered and quality-checked 10 years of records for different streamflow gauges in the San Pedro River Basin. At the same time the necessary precipitation information for driving the model has been gathered and processed to fulfill the code requirements. Because we are the sole users of the “storm mode” capability of the MMS framework, a number of bugs were found in the programs and we are interacting with the USGS team in charge of the model on an almost daily basis to fix the problems. A model has been set up, based on a hydrologic response unit distribution, and will constitute the benchmark against which the influence of the resolution (in a gridded mode) will have on the runoff simulation. Two other schemes, corresponding to grids of 12 and 4 km gridded resolution, have also been set up. The areal extent of the model corresponds to the setup used in project 4.4. We have helped the USGS team to correctly implement the MOCOM and SCE optimization procedures and the MOGSA algorithm for sensitivity analysis.

The results obtained with the hydrologic response units setup is encouraging, however some adjustments remain to be made. Specifically, the parameters that define underground storage and transmission coefficients need to be better specified.

The project started 5 months ago and so far the advances are encouraging. It has been shown that the PERSIANN precipitation product from the TA1 project can be used as the precipitation forcing for the land surface model in off-line mode. The parameter estimation procedures that were applied have also been shown to be appropriate. Results from the studies have attracted the attention of international projects and will help SAHRA gain recognition. The present project is part of the multi-resolution integrated modeling effort that will include the Mexican side of the Rio Grande Basin, providing a strong international link.

Leveraging during the last 10 months has come from a NASA-funded project that seeks to monitor and predict water availability in the Lower Colorado River basin. The mesoscale atmospheric model short-term forecasts (6 hours) will be used to predict areas under threat of flash floods.

Plans for the Next Reporting Period

We will develop a routing procedure that will parameterize the grid-scale dependence of the river network and channel transmission losses. Once the procedure is in place it will be linked to the LSM model of the San Pedro River for final testing. Finally the procedure will be included within the medium resolution model of the Rio Grande.

Farm module for MODFLOW 2000: simulation of supplemental groundwater allocation in a surface water-based irrigation setting (Rio Grande from Caballo Dam to El Paso Narrows)

Maddock (UA-HWR), Leake (USGS), Schmid (UA-HWR)

When a groundwater model such as MODFLOW-2000 is used to aid in the conjunctive management of surface-water dominated irrigation systems, it is necessary to have a Farm Module, which logically
integrates on a farm-by-farm basis the surface water delivery (DEL) with the farm delivery requirement (FDR) and with the supplemental well pumping required to sustain the growth of crops.

The central algorithm of the Farm Module Package (FMP) calculates an economic budget between FDR and DEL. The FDR will be modeled by the FMP based on the crops’ consumptive use, crop-effective precipitation, evapotranspiration losses from groundwater, and on-farm efficiency. The DEL is dependent on diversions from the river and conveyance losses and will be simulated by a modification of the stream flow routing package (SFR1).

The FMP will determine Supply (DEL) and Demand (FDR) per farm and irrigation season and distinguish between two major cases, where the economic budget (DEL – FDR) is

- negative, i.e., supplemental groundwater pumping or a reduction in acreage is required (if well capacity is insufficient, or if no wells exist at all)
- positive, i.e., excess streamflow is sent into the drain system (or back to the canal via waste-ways)

Apart from the completion of the conceptual development and the code algorithm, work has begun to implement the coding. In the future the FMP will be tested in the Rincon-Mesilla Groundwater Model developed for the New Mexico-Texas Settlement Commission for the Lower Rio Grande of New Mexico.

Based on work in years 1 and 2, a number of decisions were made regarding the approach to be taken and the processes to be used:

- The question of whether a soil water balance should be carried out in order to calculate the actual ET was discussed in detail especially with Dr. King and Dr. Slack. Since the scale and the water volume addressed by the Farm Module (as code) and by the district-wide model (test case EBID) are large enough, soil water storage may be inconsequential. In addition, a time lag between infiltration and recharge can be neglected for southwestern irrigation districts with considerably less shallow water levels. It was recommended we omit unsaturated flow to reduce the computation effort. The actual evapotranspiration (ETact) is the only variable needed, which generally could be evaluated by a soil water balance through stress imposed on plants by reduced soil water storage. However, instead of a soil water balance, ETact may also be determined by a stress factor available from the irrigator or the FAO.

- There was ongoing discussion during period 2 on whether the consumptive-use-portion (CU) of evapotranspiration losses from groundwater (ETgw) should be taken into account. In this case, this ETgw would have to be subtracted in the same way as crop-effective precipitation from the total consumptive use in order to calculate the Crop Irrigation Requirement (CIR). On one hand, phreatophytic crops/trees in their sum might ‘volumetrically’ only contribute a negligible amount towards the losses to consumptive use. On the other hand, if locally part of the CU is satisfied by ETgw, but not subtracted from the CU, then the CIR would be largely overestimated in places. The resulting Farm Delivery Requirement and the supplemental groundwater pumpage would both be too high accordingly. For example, the same farm might have phreatophytic conditions in reality, while the model may falsely start supplemental pumping of groundwater.

- Interviews of several partners revealed that the surface-water runoff could be neglected in the case of the EBID. However, in order to keep the module more general, the Farm Module will account for the surface-water runoff as a percentage of surface-water runoff related to the total unconsumed losses due to irrigation and precipitation.

- After interviews especially with Dr. King and Henry Magallanez from the EBID, three operational decisions turned out to be possible after budgeting the Farm Delivery Requirement (FDR) with the available delivery (DEL). If DEL is greater than FDR, the excess water remains in the canal/lateral or is sent as waste into drains, which are simulated by the SFR package. If the DEL is smaller, the FDR and wells exist with enough maximum capacity and the farm wells will pump the supplemental amount. If, however, the well capacity is not enough to cover the additional demand or no wells exist at all, the acreage is reduced accordingly until the Delivery Requirement is satisfied.
In order to integrate the FARM Module with its main program MODFLOW-2000, two steps had to be considered:

- Programming of different FMP-subroutines, and modifications or incorporations of source-or-sink term packages like the streamflow routing package and the well package (SFR1 and WEL)
- Integration of the FMP with its main program MODFLOW-2000

Coding of the Farm Module and other subroutines began in this reporting period and will be completed within the next period.

The code has been, and will continue to be, developed following a strategy that tries to address simpler 'core' codes first (e.g., considering an entirely groundwater-based irrigation system with lumped parameters) then subsequently expanding them to incorporate more complex settings of southwestern irrigation districts (surface-water based districts supplemented by groundwater; distributed parameters for instance of consumptive use, irrigation requirement and efficiency).

Apart from the completion of the conceptual development and the code algorithm, a first 'core' code has been completed, addressing the groundwater pumpage needed to sustain the farm delivery requirement in an entirely groundwater-based set of farms.

The Farm Module allows irrigators to estimate supply and demand per farm and irrigation season and to assist in operational decision making as to whether and how much supplemental groundwater pumping is required in case the demand exceeds the supply, or as to to what extend acreage needs to be reduced, if the total well capacity per farm is insufficient.

The quantification of surface water and groundwater use for irrigation districts will be especially useful for the Elephant Butte Irrigation District, which is required by the State of New Mexico adjudication of the lower Rio Grande to specify water quantities as a water user of the Rincon and Mesilla Valley.

Most finite difference and finite element codes simulating the groundwater flow domain rely in part on non-head-dependent source-term fluxes from point sources such as wells or areally distributed sources such as recharge.

With the Farm Module, MODFLOW 2000 will be able to establish well- and net-recharge-fluxes that are dependent on the demand (Farm Delivery Requirement) and the predominant supply (surface-water delivery). Since both the farm delivery requirement and the surface water delivery contain variables that are dependent on the aquifer-head (evapotranspiration from groundwater; stream/canal/lateral leakage), it becomes apparent that both the point source term for well pumpage and the areal source term for net recharge are first-time head-dependent source terms.

This work has been funded exclusively through SAHRA.

**Plans for the Next Reporting Period**

After the farm module is completed and integrated with MODFLOW, it will allow the simulation and mutual integration of surface water delivery, farm delivery requirement, and supplemental well pumping required to sustain the crops’ growth. At that point a hypothetical generic model will be run in order to test the consistency of the entire program "MODFLOW2000-with-FARM-module".

The Farm Module will be applied to the Rincon-Mesilla Groundwater Model developed for the New Mexico-Texas Settlement Commission for the Lower Rio Grande of New Mexico. The model area encompasses the Elephant Butte Irrigation District (EBID). Due to the abundance of farms in the District, GIS coverages will be essential to read in information like farm-location-ID, crop-distribution-ID, on-farm irrigation efficiencies, etc. Optimally, the application of the FARM module to the entire EBID is desirable.
The State of New Mexico adjudication of the lower Rio Grande requires the specification of water quantities to water users of the Rincon and Mesilla Valley. In addition to the FARM module model, which quantifies supplemental pumping, other alternative conjunctive management scenarios will be investigated that are constrained by the Rio Grande Compact.

3. Basin-Scale Systems Modeling

There is currently one active project in this sub-area:

**Regional scale simulation and prediction**
*Roads, Chen (UCSD)*

In the past, limited computer resources and lack of spatially distributed meteorological data at sufficient spatial and temporal scales have made it impossible to simulate coupled hydrologic systems at scales fine enough to be confident of the accuracy of underlying physical theories. Moreover, data about hydrologic systems have usually been limited to only a few samples, even though Earth systems exhibit considerable heterogeneity in both space and time. We have therefore developed a global to regional climate modeling system, the Global Spectral Model/Regional Spectral Model/Variable Infiltration Capacity macro-scale model (GSM/RSM/VIC) to simulate and predict short-term (synoptic) and long-term (climatological) characteristics of the Southwest. This modeling system not only is capable of potentially developing long-term simulations, but is also used to study coupled land-atmosphere processes.

As reported previously, Dr. Roads and Dr. Cui (2001) initially developed an off-line hydrologic simulation system using either observations or model variables to force a macro-scale hydrologic model focused on the U.S. Southwest. We have also developed a web site showing near-real-time daily to monthly forecasts for the U.S. Southwest, with a focus on hydrology components (see http://ecpc.ucsd.edu/projects/uastc/). Chen and Roads (2002) updated this hydrologic simulation and prediction system and augmented the web site with a description of the hydrologic models being developed for this project as well as links to sites describing the atmospheric models. We then began to validate the VIC streamflow in comparison to observed streamflow data from the Rio Grande.

During the reporting period, Chen and Roads compared observed streamflow data from the Rio Grande with the VIC output. Because of the heavy regulation of the Rio Grande, streamflow observations did not adequately assess the performance of the macro-scale hydrologic model. Moreover, little data was available to evaluate other model processes. We are therefore now beginning to use LDAS products as a benchmark to evaluate the RSM/VIC for this region. We also intend to use developing SAHRA snow products to evaluate the VIC snow water equivalent, since this variable provides some indication of the model’s verisimilitude.

We have now demonstrated real time simulation and prediction capability for the U.S. Southwest hydrology in general and the Rio Grande in particular. This real time system includes simulation and prediction of various land surface properties, such as soil moisture, snow, streamflow, evaporation, and other energy fluxes. This system has now run continuously since Sept. 27, 1997, and covers the entire period of the SAHRA project. All of this output data is archived and is being continuously re-analyzed as we better understand various model deficiencies for this region, and also how to improve these features.

We have developed a seasonal hydrologic simulation and forecast system using RSM/VIC over the Southwest and have begun to study and analyze the skill and limitations of the macro-scale hydrologic model simulations and forecasts. Our research will help to develop a regional-scale hydrologic simulation and prediction system that can be easily connected to current regional atmospheric models and eventually to higher resolution hydrologic and groundwater models.

We have not yet been able to fully validate this developing system, in part due to lack of adequate data, which is beginning to become available for this region. It should also be mentioned that streamflow
observations in heavily managed rivers and streamflow from physical models cannot be directly compared. We are therefore looking for other sources of data, including US LDAS products to help evaluate our simulation and prediction system for this region.

This work is being done in conjunction with the Scripps Experimental Climate Prediction Center, which is interested in first developing a hydrologic prediction system for the U.S. Southwest, in collaboration with SAHRA researchers, and then transferring the developed model to the rest of the U.S. and eventually to other global regions. The partial postdoctoral support from SAHRA is augmented with ECPC funds. The PI (Roads) devotes his time at no charge to the SAHRA project.

Plans for the Next Reporting Period

We are studying model-simulated runoff over the Rio-Grande at basin and regional scales and will eventually begin to study the Colorado River Basin. After validating and improving the VIC macro-scale land surface model, we are then going to integrate the model with the RSM, and study the hydrology forecast skill at higher resolution and for longer temporal horizons. Demonstrating a reliable hydrologic simulation and prediction system on a variety of scales is essential for decision makers. We therefore believe our proposed research is a key part of SAHRA.

Our proposed research could integrate well with other modeling activities that study local, micro-, and medium-scale hydrologic processes over the Rio Grande. In particular, our research provides an interface to a regional scale atmospheric model on a variety of spatial scales and a variety of temporal scales ranging from hours to decades. Also, field observations from TA1 can be used to evaluate our model performance and thereby improve the parameterizations of hydrologic processes in the VIC model. As confidence is gained in our model system, it could be used to extend the characteristics of scattered field measurements to the entire SAHRA region.
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<th>Thrust Area 5</th>
<th>Water as a Resource: Competition, Conflict, Planning, and Policy</th>
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Thrust Area 5 - Water as a Resource: Competition, Conflict, Planning, and Policy

The main goal of Thrust Area 5 is to examine and analyze issues related to water resources policy, including behavioral, sociological, and economic factors, in semi-arid regions of the Southwest and integrate current SAHRA modeling and physical sciences efforts with community water planning and management. Thrust Area 5 consists of four components: 1) Institutional analyses and social assessments; 2) Behavioral aspects of water markets and water banking; 3) Non-market valuation; and 4) Water resources management and operations.

1. Institutional analyses and social assessments

This focus area demonstrates how stakeholder surveys, background historic and socio-economic research can be used to assess the effectiveness of current water management organizations in addressing basin issues and to identify potential links between scientific research and stakeholder needs for more effective management tools. Similarly, the characterization and analysis of droughts are other means of addressing institutional, management, and policy issues of bi-national concern. Individual research efforts include:

- Extraordinary drought evaluation for the Rio Grande/Bravo basin
- Institutional analysis and social assessment of the Upper San Pedro river basin
- Institutional analysis and social assessment of the Salt Verde river basin
- Implementation of legal recognition of surface-groundwater links
- Assessment of institutional structures of demand-side management integrated modeling

Extraordinary drought evaluation for the Rio Grande/Bravo Basin
Dracup (UCB)

Activities and Results

Using unimpaired streamflow data and traditional forecasting methods (Frick, Bode, et al, 1990), the annual streamflows for the Rio Grande/Bravo Basin were simulated and synthetically generated for a period of 10,000 years. Droughts were determined for different tracer lengths utilizing the synthetically generated annual flows. Sets of 50, 100, 500 and 1,000 years were used to determine the severity, duration and intensity of all possible droughts. The droughts were later ranked based on each property value. Using return periods of 25, 50, 100 and 500 years the droughts were averaged and compared to historical values. In addition, an exploratory analysis of the effects of the El Niño – Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) on precipitation and streamflow in the river was conducted. Initial results show significant correlations between the ENSO and streamflows in the river, and in particular between the PDO and streamflows.

Plans for next reporting period

Additional analysis using paleoclimatological data for the Basin will be carried out, as well as additional analysis of the effects of ENSO and PDO. Development of an index to compare the severity of droughts within the Basin is expected, including a spatial analysis.

Institutional analysis and social assessment of the bi-national Upper San Pedro river basin
Varady, Browning-Aiken (Udall)

Given the difference in political and economic institutions and processes for managing water in Mexico and the United States, this project is studying whether watershed councils are effective institutions at a
binational level for articulating science research on hydrology and ecosystems with integrated watershed management. The hypothesis is that decision making about sustainable development in terms of water resources is based on a full assessment and analysis of complex ecological and socio-economic relationships within a watershed, and the availability of effective decision-making tools, such as Decision Support System models.

Our experiences in the Upper San Pedro Basin indicate that the potential for successful binational planning and management efforts increases with informal communication and cooperation among local borderlands agencies and NGOs. The research coordination, binational forums, and the evolution of the Partnership and ARASA working together all suggest a growing momentum toward coordinated water resources management. However, this process requires continued collaboration between policy and physical scientists to fully integrate science into decision making. SAHRA scientists face not only disparities in transboundary data collection, analysis, archiving, and dissemination, but also planning and decision-making processes sensitive to sovereignty and jurisdictional autonomy and water policies that fail to address stakeholder values other than market commitments. In general, the Binational Upper San Pedro Basin Project is essential for integrating science research with the needs of regional water resource management organizations and policy makers and for preparing policy makers and managers for more effective assessment and decision making about basin science questions.

Activities and Results

The research required for this assessment and analysis has included: 1) “Water Use and Needs” surveys in the U.S. and Mexican portion of the Upper San Pedro Basin; 2) interviews with water managers and policy makers in both portions of the basin; 3) capacity-building strategies for the development of the Mexican watershed council Asociación Regional Ambiental de Sonora-Arizona (ARASA)/The Sonora-Arizona Regional Environmental Association; 4) creation of a “San Pedro Dialogue on Water and Climate,” a binational forum for the U.S. and Mexican watershed councils to discuss and share hydrologic, ecological, and climate research needs; and 5) an exchange of information and research needs between SAHRA and non-SAHRA scientists and the basin watershed councils on both sides of the border.

During the past 10 months our activities fall into the categories of (i) collaboration and coalition building; and (ii) publications. In the category of collaboration and coalition building we have three major achievements. First, we built the capacity of the Mexican watershed coalition, ARASA, to address regional water problems by assisting in grant writing for operational expenses, management training, environmental conflict management and by promoting the collaboration of ARASA with other Mexican environmental non-governmental organizations (NGOs). We also have been facilitating the San Pedro Dialogue on Water and Climate with ARASA and the Upper San Pedro Partnership. Finally, we collaborated on the establishment of a binational environmental education program, called ECOSTART, focused on the Upper San Pedro River Basin.

Several papers were published and presented during the past 10 months or are currently in press (see Section VIII).

Our results have been: 1) an assessment of community water needs in Mexico and the U.S.; 2) the development of a Mexican watershed council, ARASA, with the capacity to attract funding for community water-related projects and management training for basin stakeholders, 3) the establishment of a binational steering committee to discuss additional hydrologic, ecological, and climate information needs within the binational basin (San Pedro Dialogue on Water and Climate), and 4) the successful establishment of a binational environmental education program, ECOSTART, with a primary focus on conservation of the San Pedro River. This work has been complemented by the development of a binational Upper San Pedro River Decision Support System (DSS) that merges knowledge from diverse disciplines and simulation tools in a practical, meaningful decision-making environment and assesses the reliability of management decisions of the Upper San Pedro Partnership and ARASA. The San Pedro hydrologic modeling efforts have been the result of working with SAHRA researchers Kevin Lansey, Tom
Maddock III, William Yeh, and James McPhee, and the binational education program has been established in part through collaboration with SAHRA researcher Jim Washburne’s UA GLOBE Program.

**Plans for next reporting period**

Based on earlier pioneering efforts in binational watershed management focused on riparian and growth issues, we have found that science that is relevant and that solves real problems is critical for decision makers in the Upper San Pedro Basin who are attempting to resolve water allocation challenges. Our research in watershed management issues and capacity building provides SAHRA physical scientists and economists the opportunity to tie their work to the needs of water managers and policy makers. Our research within the regional Southwest provides a model for other watersheds, as well as a context in which SAHRA scientists can collaborate with real stakeholders to produce socially and economically useful water management tools. With these goals in mind, we are proposing the following steps:

- Promote binational watershed management policies via continued capacity-building efforts for watershed councils and binational steering committees.
- Introduce concept of climate change and variability into discussions of water management on both sides of border via DWC and NOAA grants.
- Include aspects of water quality in integrated approach to management.
- Expand environmental education project (ECOSTART) into rural areas and include upper grades; extend collaboration with GLOBE for training teachers.
- Strengthen connections between SAHRA researchers, particularly modelers, and decision makers, especially watershed councils.
- Collaborate with UNM researchers (e.g., David Brookshire) on market economic valuation analysis.
- Work with stakeholders to develop, refine, adapt, and demonstrate use of models for integrated management.
- Seek additional funds to support above work.
- Continue to disseminate innovative results of work at national and international conferences and forums, and publish in journals, books, and other venues.

**Institutional analysis and social assessment of the Salt Verde river basin**

Varady, Browning-Aiken (Udall)

Given the variety of water interests in the Verde/Salt Basin, especially in regard to the number of watershed councils or associations, and the relatively recent Arizona Rural Watershed Initiative, our project seeks to determine if watershed councils are effective institutions for articulating science research on hydrology and ecosystems with integrated watershed management at the basin level. The hypothesis is that decision making about sustainable development in terms of water resources is based on a full assessment and analysis of complex ecological and socio-economic relationships within a watershed and the availability of effective decision-making tools such as Decision Support System models.

SAHRA social and physical scientists have selected the Yavapai County Water Advisory Committee as the strongest and most representative watershed organization in the basin and are focusing their efforts on the successful construction of the DSS model for the Prescott AMA and on building the capacity of the Yavapai County WAC to address basin water issues more effectively. However, this process requires continued collaboration between policy and physical scientists to fully integrate science into decision making. SAHRA scientists face not only complex scientific information about the geohydrology of the region, but also uncertainty in the planning and decision-making processes.

Our experiences in Verde River Basin indicate that the potential for successful planning and management efforts are challenged by the complexity of issues and the multiplicity of watershed organizations within the basin. The water export from Big Chino sub-basin, which is considered by many to be the source or origin of the Verde River, to Prescott, an Active Management Area (AMA) is the source of contention between the following groups: 1) upstream residents and developers; 2) downstream users, including
Phoenix; 3) environmental groups or agencies, including US Game and Fish, that are concerned with the habitat threat of a potential decrease in Verde River surface flow due to Big Chino groundwater export; 4) the Camp Verde Apache community, concerned with traditional uses, including gravel industry; 5) recreational or tourism supporters who fear the impacts of a potential decrease in surface flow; 6) communities such as Clarkdale, Jerome, Cottonwood, Paulden, and Camp Verde needing to consolidate water services to make them more economically efficient, but lacking the tax structure to develop community or regional water services.

Arizona’s lack of a regional or even state-wide water use and management plan has contributed to watershed conflicts because whatever one basin or even community does or does not do in regard to water management and planning affects everyone else in the region. Rapid population growth and the potential for development, particularly in the Big Chino and Prescott Valley, add to the need for this kind of planning in order to maintain sufficient water for the present as well as the future. Active Management Areas (AMAs) are the major focus of legislative attention to water management at this point because those areas are operating or are soon to operate with a groundwater deficit. Legislation, particularly in the form of the Arizona Rural Watershed Initiative, has supported research in the Verde Watershed in an effort to answer hydrologic questions about the relationships between the subbasins, the sources of the Verde, and the potential impacts of increased pumping in the Big Chino subbasin on the Verde River. However, legislative funding has not kept pace with the need of watershed initiatives for further research or organizational development.

Legal problems regarding water law also contribute to the conflicts in the Verde. First, Arizona water law is in the process of clarifying the hydrologic connection (subflow) between groundwater and surface water, particularly in wells located near streams. Second, other legal problems concern the incomplete settlement of Native American Indian claims (reserved rights to surface water) to the Verde, which could detract from the amount of water allotted to land owners in the Verde Watershed with prior appropriation rights (surface water). While the Yavapai in Prescott have achieved settlement of their water rights within Prescott and the Fort McDowell Indian Community as well, the Camp Verde Yavapai Apache settlement is still pending. Third, downstream water rights, particularly those of irrigation districts and the Salt River Project (SRP) near Phoenix (1/3 of Phoenix water comes from Verde River surface), are also at issue, as indicated above. Finally, the Endangered Species Act (minnow loach) and the Wild and Scenic River designation potentially could provide a legal basis for pumping mitigation or litigation. In a similar manner, in-stream flow rights in Arizona indicate that water levels in the Verde have to be kept sufficient for fish and wildlife.

Activities and Results of Year 3

The research required for the Verde Basin Conflict Assessment and Analysis has included: 1) historical and contemporary groundwater and surface water use in the Upper and Middle Verde Basins; 2) interviews with water managers and policy makers in the basin; 3) a history of the development of basin watershed organizations, their missions and objectives; 4) a survey of policy issues affecting water use in the Verde, specifically the designation of Prescott, AZ, as an Active Management Area (AMA), and adjudication regarding Native American water rights of the Apache and Yavapai in the basin; 5) findings of hydrologic research on the connections between groundwater and surface water and between the Upper and Middle Verde groundwater; 6) recognition of legal conflicts over the application of the Endangered Species Act to the Verde River and over identification of subflow, and 7) investigation of the nature of natural resource planning models already existing within the Verde Basin and of the need for additional hydrologic modeling efforts.

The results of this assessment and analysis have been: 1) the creation of a Decision Support System (DSS) model for the Prescott AMA with the support of the Yavapai County Water Advisory Committee; and 2) facilitation of an adaptive management retreat with the Yavapai County Water Advisory Committee (WAC) in order for the watershed group to overcome planning obstacles and conflicts and to establish more effective planning methods for addressing watershed conflicts over water appropriation and management. SAHRA researcher Kevin Lansey has been working with social scientists Robert Varady
and Anne Browning-Aiken in the Verde to establish the Decision Support System model with the Prescott AMA.

The complex historical, ecological, legal, political, economic, and social factors of the Salt Verde watershed are explored in Jennifer Shepherd’s UA master’s thesis, “Science, Uncertainty, and Decision-making in the Verde River Watershed,” which was completed during the past year as part of project activities. In the thesis, Shepherd analyzes relevant watershed management documents, media coverage, court cases, the dialogue and information presented at watershed group meetings, and interviews with local stakeholders to decipher the role of knowledge and science in the decision-making process in the Verde River Basin in the hope of uncovering ways in which the process might be improved.

In addition, we achieved the following during the past 10 months:

- Completed Verde Basin Conflict Assessment and Analysis (A. Browning-Aiken)
- Presented a poster, “Verde River Watershed Associations: Past, Present, and Future of Collaboration for Sustainable Water Use and Environmental Protection,” for SAHRA and other annual meetings (L. Stauber)
- Presented a poster, “Knowledge, Science and Decision-making in the Verde River Watershed,” for SAHRA and other annual meetings, (J. Shepherd)
- Facilitated planning for DSS model for water resource management decisions in the Prescott AMA with Yavapai County Water Advisory Committee (A. Browning-Aiken, and SAHRA researcher K. Lansey)

**Plans for next reporting period**

Based on the earlier Verde Basin environmental conflict assessment, we have found that integrated water resource management within the basin faces obstacles in strategic action planning that SAHRA physical science (particularly DSS), and Udall Center support (with environmental conflict mediation and strategic planning) can remediate. Science that is relevant and that solves real problems is critical for decision makers in the Verde Basin who are attempting to resolve water allocation challenges. Our research in watershed management issues and capacity building provides SAHRA physical scientists and economists the opportunity to tie their work to the needs of water managers and policymakers. Our research within the regional Southwest provides a model for other watersheds, as well as a context in which SAHRA scientists can collaborate with real stakeholders to produce socially and economically useful water-management tools. With these goals in mind, we propose the following steps:

- Strengthen efforts to unify or at least coordinate work by disparate watershed councils, in the context of the larger, statewide Arizona Rural Watershed Initiative, in order to establish a regional, multijurisdictional water-management authority.
- Convene two workshops, retreats, or public meetings per year to help achieve this goal.
- Strengthen SAHRA’s presence in the Verde Basin through such specific scientific projects as a Verde River flow model and measurement of consumptive uses in the Verde
- Work with stakeholders to develop, refine, adapt, and demonstrate use of models for integrated management
- Continue to disseminate innovative results of work at national and international conferences and fora; and publish in journals, books, and venues
- Seek additional funds to support the above work.
Implementation of legal recognition of surface-groundwater links
Maddock, McHugh (UA-HWR)

Arid western states primarily apply the doctrine of prior appropriation (“first in time, first in right”) to surface waters, but these states differ on how to appropriate ground water resources. Historically, most state systems have treated surface water and ground water as two separate systems. The hydrologic principle of capture, in which groundwater pumping captures water directly or indirectly from a stream or river*, is particularly important since most western states’ water policies do not comply with this hydrological reality. Most states now have recognized the hydrologic connection and are beginning to apply laws that provide instruction on how to deal with groundwater users that are essentially pumping surface water. Most states have also begun to utilize computer models in order to help apply these laws. Western water policy began with little to no understanding of the surface water/groundwater system as a whole. These laws that separate the two “types” of water have become entrenched into the communities, and the legislature and courts are struggling to adjust the laws to recognize the hydrological reality. The research method proposed will gather and summarize all state laws which pertain to groundwater/surface water interaction and examine the studies and models that are being used to aid in applying these laws. Research will also include a description in layman’s terms of groundwater principles, especially the principles governing capture.


Activities and Results

Water policy for specified western states has been extensively researched. Models or studies associated with applying these policies have also been gathered. State policies governing the appropriation of both surface water and groundwater have been summarized for the states of Arizona, New Mexico, Colorado, Nebraska, Kansas, Oregon, and Texas. These summaries specifically refer to state statutes and court cases pertaining to the surface water/groundwater interaction. Policy evolution is also noted in these summaries. The Arizona Department of Water Resources’ guidelines for determining “subflow” and the cone of depression as requested by the courts in the Gila River adjudication has been summarized. Contacts are being made in reference to several studies or within the state agency that deals with water permitting. Summarization and examination of models and studies is in the beginning phase.

Many states are beginning to rely on groundwater models to determine if a proposed withdrawal is within that state’s designated area or zone. Extensive hydrogeological studies are also being performed to get the best and most up-to-date physical information for these computer models and conceptual models of the system.

Plans for next reporting period

Summarization of western states’ water policies pertaining to the surface water/ground water interaction is approximately 80% complete. Examination and analysis of computer models and studies is in the beginning phase. Along with a description of groundwater principles in laypeople’s terms, this research will provide an up-to-date synopsis of the current understanding of the physical system and the current state laws that apply to the system. Examination of the representation of the physical reality in the legal system will provide lawmakers a tool for assessing the need for adjustment in the legal realm. The research will provide not only a one-stop reference for anyone interested in the current policy regarding the surface water/ground water interaction, but also a jumping board for those who are interested in other aspects of western water policy. The examination and analysis of the current models and studies being used by different states will compare and contrast the models in order to determine their effectiveness. Compiling all of these models and studies will also provide decision-makers with an easy reference guide.
Assessment of institutional structures for demand side management integrated modeling

Brookshire (UNM)

To develop a demand-side management model, four broad categories of effort must be undertaken. First, the behavior of household, industrial, commercial, institutional and agricultural users must be understood within a variety of price regimes. This must be done at the micro level in order to fully recognize and account for the diversity of preferences within and across groups. Second, the behavior within and across a variety of institutional structures must be understood both in the short- and long-run setting (capital is fixed versus being substitutable). Examples would be block pricing versus peak pricing versus type-of-use pricing. Third, the goals of the policy-making bodies must be identified and understood. That is, do policy-making bodies seek efficient outcome or use some other policy objective? Finally, the demand behavior for the market side must be integrated into an overall modeling framework that includes physical conditions as well as the appropriate institutional objectives and institutional structures.

Activities and Results

For the first category, projects on the experimental analysis of consumer demand and a survey of disaggregated demand are underway (see sub-area 2 below), and will address the behavior for residential, industrial, and commercial users. The third category is a new initiative for dynamic simulation modeling. The fourth category, integrated modeling, is a new initiative for Years 4 and 5. The new initiatives are proposed to start at a low level of effort; it is anticipated that they will become part of the next 5-year proposal.

Plans for next reporting period

The present project is a new initiative, proposed to address the behavior within alternative institutional structures. There are two sub-components to this proposed effort. First, the issue of water banking and/or water marketing is to be explored. The market framework for re-allocating water is developed conceptually, but little has been done to operationally explore the nature of banking or marketing allocation schemes. Second, the behavior of consumers and others within alternative pricing regimes remains unexplored in pricing regimes that reflect the scarcity value of water.

Water markets and banking are being set forth as possibly desirable allocation structures. Our recent efforts have involved determining the extent of water banking legislation and implementation in the Western U.S. Further, we have pursued data that speak to the operational nature of observed water markets. We propose to further pursue the data collection effort that is represented in Brookshire, et al. (2002) and develop a series of experimental water markets and water banking institutions. The experimental laboratory setting at UNM is ideal for research in these areas. Further, the basin-wide setting is ideal. We have developed cooperative relationships with many of the stakeholders in the area and we envision that they would be part of the overall design process.

Alternative pricing regimes are being debated. The EPA (1997, p.21) reports that 49% use a uniform rate structure, 2% some type of flat fee, 16% a declining rate, 11% an increasing rate, and less than 1% a peak rate structure. As we discuss elsewhere, the behavior of consumers and others for alternative pricing regimes is being explored. The proposal to explore alternative pricing regimes builds upon this work and is necessary for an integrated model to be used by policy makers. Also of interest is consumer response whereby pricing regimes may generate alternative behavior when the possibility of capital substitution exists. Not only are we interested in how consumers react to alternative prices and pricing regimes, but also the capital substitution that they might undertake in the case of a conservation program.

We propose to design a series of experimental protocols that eventually would be linked to the TA5 effort on experimental analysis of consumer demand. The protocols would build upon our access to the Albuquerque Water Wise data set, and would involve residents of Albuquerque in the actual experiments. We would approach relevant individuals in the governments of Albuquerque and Santa Fe (and others to be identified) for aid in designing the protocol.
Year 4 will be a low-level effort. Design of the experimental protocol will be undertaken for both projects. In Year 5 we will begin implementing the experimental protocols. These efforts follow the pattern of development that has been used in the initial disaggregated demand.

2. Behavioral aspects of water markets and water banking

This focus area has developed survey instruments that enable us to compare residents’ actual water consumption through water bills and low-cost, high-resolution water meter loggers with their responses to changes in price, institutions, or education in an experimental setting. Individual research efforts include:

- Experimental analysis of consumer demand
- Survey of disaggregated demand
- Socio-economic factors affecting residential water demand
- Data gaps, hybrid modeling and sustainability

**Experimental analysis of consumer demand**

*Brookshire, Chermak, Krause (UNM)*

The overall goal of the demand-side management is to provide understanding of individual water demand behavior for consumers (agricultural, industrial, institutional, commercial and households). This project specifically focuses on household demand behavior, and is connected to other SAHRA projects through the modeling and the evolving Rio Grand/Rio Bravo Modeling team. The research will add a behavioral component to the integrated modeling for the exploration of scenarios for the Rio Grande/Rio Bravo Scenarios Task Group.

The science question inquires into the behavioral aspects of individual demand behavior. This has four sub-components: 1) Do consumer characteristics underlie and thus drive demand behavior, thus creating a heterogeneous demand for water? 2) Can the historical observed behavior be calibrated with behavior in a context-specific laboratory setting? 3) What price response do we observe for ranges of prices outside current pricing domains? and 4) What will the behavioral response be if long- and short-term considerations are possible? (e.g., convert to xeriscape yard).

We have used historical data and experimental settings to determine the role of characteristics and responses to alternative pricing regimes. We observed that a heterogeneous demand for consumers does indeed exist, and we found an alignment of historical data (household water bills) and behavior in the laboratory in a set of context specific experiments. The project has assembled a unique data set that enables us to evaluate disaggregated consumer demand for the demand side of the demand-side management model. Two critical questions have been addressed. First, what is the nature of heterogeneous preferences? This is an essential element for modeling consumer behavior in a variety of urban settings. Second, the historical data has been successfully but preliminarily calibrated with laboratory behavior, setting the stage for the exploration of alternative behavioral response to differing pricing regimes. The behavioral estimates will eventually be incorporated into the Rio Grande/Rio Bravo Integrated Modeling Team effort.

**Activities and Results**

Sets of experiments were conducted in the fall of 2001. This data was analyzed in the latter part of our Year 2 efforts and in our Year 3 efforts. The heterogeneous demand preferences efforts have been detailed and will be published this year (Krause, Chermak, and Brookshire, forthcoming). The calibration efforts were documented and presented at the American Economic Association meeting, as well as the 2nd World Congress of Environmental and Resource Economists (see Krause et al, Water Consumption,
in Presentations section of Section VIII). Beyond data analysis, a refined set of protocols is being
developed for further calibration and the exploration of behavior under differing pricing regimes. The
calibration efforts involve linking household use to parameters in the laboratory, thus furthering our
exploration of the calibration issue. The pricing protocols are a new design within Year 3 efforts.
Specifically, coupling the calibration efforts to a series of price regimes that more likely reflect the scarcity
value of the water will be designed. This set of experiments will be conducted in the fall of 2002.

In a link to the TA5 project, “Survey of Disaggregated Demand,” census data has been merged with the
survey data (see the project report below) with the Albuquerque household data from the historical
records and the Albuquerque household participants. This will ultimately provide a data platform for the
overall Demand Management Model, as driven by econometric estimates of household disaggregated
demand activity.

Several papers are either in press or were published during the past year, including a paper (Krause, et
al., in manuscript) in which we suggest a way to augment existing studies with experimental data, a first
step in an effort to align experimental responses to real-world data. If experimental results can be
generated that are consistent with actual water consumption, we can extend the price, and thus the
predictive range of the models, outside the current price ranges.

Some of the research was also presented publicly at the Southern Economic Association Meetings, the
American Water Resources Association, and the 2nd World Congress of Environmental and Resource
Economists (see Krause, Chermak, and Brookshire, Demand for Water, in Presentations section of
Section VIII). In this paper we find differences in demand that are correlated with a variety of social and
cultural factors, including age, ethnicity, political affiliation, religious affiliation, and risk preferences. We
use these demand estimates to construct an incentive-compatible non-linear pricing schedule for a case
in which the regulator is faced with a reduction in available supply.

Plans for next reporting period

The next logical steps for the experimental disaggregated demand effort are as follows. First, further
 calibrate the laboratory with the experimental data. Specifically, the experiments need a set of parameters
whereby the contextual water decisions in the laboratory can be linked to actual household decisions.
Essentially, this is a matter of linking decisions - such as yard watering choices - to a choice in the
laboratory that is realistic and appropriately scaled. Second, after the calibration is complete, the
framework will be used to explore alternative price regimes that are “institutional free” (see project report
for “Assessment of Institutional Structures for Demand Side Management Integrated Modeling” for a
discussion of this issue as a new initiative). A set of experiments will be designed and implemented in
Year 5 that will allow the household to “react” to alternative price regimes in a short- and long-term
context. Finally, the preliminary work will be undertaken in Years 4 and 5 for extensions of the household
consumer demand effort into Mexico.

At some scale it is anticipated that the SAHRA Rio Grande effort will produce, at a minimum, a dynamic
simulation model that can be queried using the scenarios that are to be developed by the “Scenario
Group.” One of our new proposed efforts is to directly address how to embed the disaggregated
behavioral market model into the existing Rio Grande hydrologic model produced by Sandia National
Laboratories. The model is currently a lumped model, which will eventually need to be disaggregated into
individual river reaches. This effort is proposed as a newly identified research proposal, a new initiative
for the integrating within the dynamic simulation model.

The calibration and the exploration of alternative price regimes are already underway. Our goal is to
implement the calibration effort in the late fall of 2002 or early spring of 2003 (Year 4). Preliminary testing
of the basic price regime protocol will occur in the spring of 2003. By the end of 2003 (Year 4), the overall
protocols should be implemented and tested. It is not possible to know what glitches will occur, but our
goal is to complete the consumer disaggregated market demand effort by the end of Year 4. Also,
integrating the consumer demand estimates into an integrated modeling framework will be part of the efforts in Year 5 and beyond.

The initial efforts with Dr. Robert Varady and the Udall Center will begin in Year 4 and continue into Year 5. We propose to pursue a study of the disaggregated demand for household water in Mexico. In conversations with Dr. Varady over the last year, he has indicated, based on stakeholder contacts, that the Udall Center has a project that could be undertaken. It is our understanding that Dr. Browning-Aiken will facilitate this effort.

A study of the economics of water consumption patterns in communities on the Mexican side of the San Pedro River basin will be of use in further understanding disaggregated consumer demand. Any modeling of river systems that cross borders addressing demand management issues will require this information. We know of no such investigations. The existing investigations for consumer demand in other countries are of the same aggregate nature that motivated the current ongoing disaggregated demand study in Albuquerque. Thus, this would be a unique study and be important for integrated modeling.

It will be among the first such analyses conducted in a cross-border setting. It will supplement other ongoing social sciences activities in the basin, thus effectively leveraging other sources of funding currently available to the research team.

Several communities offer wonderful opportunities for the study. The largest and economically most important is the city of Cananea, Sonora, Mexico, near where the river arises. Cananea is the home of North America’s largest copper mining operation and a diverse population that relies heavily on the mine. From recent surveys administered by the Udall Center, residents are known to be concerned about both the availability and quality of their drinking water. There is little if any documentation of how households supply their water needs or how much they pay. Few homes can count on permanent, full-time, piped water delivery, and what water is provided is of poor quality, partly because of old infrastructure, partly because of contamination from the mining facility. Naco, right on the border, is the next largest community. Like Cananea, it was the subject of a Udall Center water-use perception survey in 2000-2001. Finally, a number of ejidos are situated along the river and can serve as sample communities for the valuation survey. The survey will take full account of water-quality issues, recognizing that quality and concomitant concern for human health are important factors in family water-purchasing behavior and strategies.

We propose to develop the survey instrument during Year 4 enabling the design of experiments for Year 5. To help do this, we will convene focus group meetings with residents and other stakeholders in the communities to be studied. These meetings will allow important input from citizens and help assure that the survey and its results will respond to local needs and be based on valid premises, as well as motivating the experimental design for a disaggregated demand study.

Survey of disaggregated demand
Brookshire, Chermak, Krause (UNM)

The overall goal of demand-side management is to provide understanding of individual water demand behavior for consumers (agricultural, industrial, institutional, commercial and households). This project focuses upon industrial, commercial and institutional demand behavior. A significant amount of work has been done regarding agricultural demand for water, which we ultimately draw upon at a later date (see project report for “Data Gaps, Hybrid Modeling, and Sustainability” for this effort in the context of the Conchos River).

Using econometric modeling at the firm level, we inquire into the behavioral aspects of industrial, commercial, and institutional demand behavior. The questions are quite similar to the household behavior issues discussed in the project report immediately above, which is a companion project. That is, what are the characteristics that drive water demand by industry, institution and commercial user? The disaggregated market demand for water (as distinct from the disaggregated non-market demand for water
to be discussed the project report “Economic Valuation of Riparian Flyways”) has five aspects – households, industrial, commercial, institutional and agricultural.

**Activities and Results**

At this time, we intend to rely on the Albuquerque data set for the institutional, commercial and institutional disaggregated demand estimates, and will merge data where appropriate to enhance the data set (e.g., Census of Manufacturing). The data set has been assembled beyond the ‘raw’ data given to us by the City. Preliminary econometric regressions have been run. The Albuquerque data set provides information on the industrial, commercial and industrial use of water. Manipulation of this data set has been extremely time intensive. A significant effort has been made to identify this information in the overall data set. This effort started in earnest around January 2002. Initial econometric estimates have resulted in the demand for water from these disaggregated sectors.

The econometric results are preliminary, but promising. As expected, quantity demanded is negatively correlated with price. We also find correlations between quantity demanded and the climatic variables of temperature and precipitation. Also as expected, there are statistical differences in usage between different meter sizes. These results indicate a more micro-level study would be potentially beneficial. Thus, we will expand the data set to include more firm-specific factors, such as SIC codes.

**Plans for next reporting period**

The behavioral estimates will eventually be incorporated into the Rio Grande/Rio Bravo Integrated Modeling Team effort. The next logical steps are to complete the analysis. Significant data identification and merger issues remain. As mentioned previously, this involves the linkage of the industries to specific SIC codes and other information that will enhance the underlying behavioral model. Inquiries will be made to obtain a similar data set from other areas.

We do not propose at this time to undertake the agricultural sector within this project; instead we propose to address the agricultural sector in the development of the dynamic simulation effort in the Conchos River basin as Year 4 and 5 initiatives. A significant amount of work in the extant literature has been done regarding agricultural demand for water, which we will draw upon within that project.

At some scale it is anticipated that the SAHRA Rio Grande effort will produce at a minimum a dynamic simulation model that can be queried using the scenarios that are to be developed by the “Scenario Group.” One of our new proposed efforts is to directly address how to embed the disaggregated behavioral market model into the existing Rio Grande hydrologic model produced by Sandia National Laboratories. The model is currently a lumped model, which will need to be disaggregated into individual river reaches at some point. This effort is proposed as a newly identified research proposal for integrating within the dynamic simulation model.

The econometric estimates will be available for integration into the Rio Grande/Rio Bravo modeling efforts by the end of Year 4. They will be written up in a draft manuscript and as a poster. The papers will most likely be finalized in Year 5. The demand estimates will be incorporated into modeling frameworks (Year 5).

**Socio-economic factors affecting residential water demand**

*Woodard (UA-HWR)*

Econometric and engineering-based studies over the past few decades have failed to produce a clear, detailed understanding of domestic water uses, and how various socio-economic factors, including price and conservation programs, influence domestic demand. For example, we understand in general that higher prices reduce demand, but not how. Do people cut back more in outdoor uses than indoor? Do they irrigate less frequently, or for shorter periods of time? Are clothes washers and dishwashers run less often, with fuller loads? Do they take shorter showers, or fewer showers, or install low-flow
showerheads? This project is developing and deploying low-cost high-resolution water meter loggers to identify and quantify specific domestic water demands within individual households over extended periods of time. By measuring domestic water flow at the 0.1-gallon, 0.01-second resolution, water use traces are generated which reveal particular water uses and details such as frequency of toilet flushing, length of showers, gallons of water used per load of laundry, and frequency and duration of outdoor irrigation. When extended for years, impacts of weather, climate fluctuations, and price changes can be directly observed. Also, household reactions to various water conservation programs can be observed. The overall goal of the demand-side management is to provide understanding of individual water demand behavior for consumers, within a private good setting. Field tests to date suggest that the data gathered by this approach will directly address the questions posed above, and will integrate with the survey work and experimental economic laboratory work to enhance this understanding.

Activities and Results

SAHRA resources were used to develop and prove the concept, produce, and field test data logging equipment, develop and test the necessary software, and compare various battery options and data storage and retrieval mechanisms. The US Bureau of Reclamation support allowed for the purchase and assembly of 60 meter/logger/sensor systems, additional field testing, and development of long-term field power options. Audubon Society support is being used to install some 50-60 meters and sensors in middle-and upper-class ranchettes in the Sonoita/Elgin region of Arizona and gather and analyze the data for two years. Support from Cochise County will allow another 20 low-income ranchettes along the Upper San Pedro River to be logged.

Three field testing sites were established with cooperation of Tucson Water, and some 10 meters have been installed in the Sonoita/Elgin area in cooperation with the Audubon Society’s Research Ranch. Data analysis supports the belief that this methodology will provide the degree of resolution and insights necessary to make a major advance in modeling and forecasting residential water demand.

Results to date are limited to the data collected through field testing. We clearly have sufficient resolution to not only distinguish between types of water usage (e.g., toilet flushing, showering, laundry), but also have the resolution to discern important details of usage, such as: which toilet in the household is being used and how often is it double-flushed; what is the duration of the shower and is a low-flow showerhead being used; and is the clothes washer being run with a full or partial load, and with cold or warm water. See http://www.sahra.arizona.edu/research/TA5/demand_trace.html for a sample meter trace, with labeled water uses.

Plans for next reporting period

The next steps are installation of the remaining meters and loggers in Sonoita and Elgin, selecting participants in the Upper San Pedro, and establishing the data retrieval and analysis process. Beyond that, there are several potential areas in which the work can be expanded, including:

(i) logging of newly constructed homes in three different price ranges in the metropolitan Tucson area (preliminary agreement reached with local water providers);
(ii) modification of software and hardware to allow wireless relay of data (City of Phoenix support offered);
(iii) modification of hardware and software to allow the PDAs to operate as intelligent, updated irrigation controllers that open and close irrigation valves based on downloaded weather data (proposed project with Phoenix Water and Tucson Water); and
(iv) modification of software and hardware to allow the PDAs to serve as data loggers for other field instruments, and trigger samplers on command (being pursued with Jon Petti and summer REU student).
Data gaps, hybrid modeling and sustainability
Brookshire, Chermak, Burness (UNM)

The science question for this project involves issues of modeling, data gaps, and integrated modeling from an economic perspective across disciplines. Modeling efforts include a dynamic analysis of the interacting incentives for private versus habitat water use in the context of a mountain front recharge system such as the Upper San Pedro river basin. A concurrent effort involves hybrid modeling that attempts to bridge the gap between hydrologic models and economic optimization by imposing economic benefit functions on a finite element model of interactive groundwater/surface water use. Since SAHRA is ultimately concerned with sustainable water use in semi-arid environments, we also investigated the economic implications for sustainable use and the meaning of the word “sustainable” in an operational context. Data gaps were explored in the context of benefit transfers. Finally, the nature of urban water pricing and western water markets were preliminarily explored.

This project explored issues of hybrid modeling, data gaps and integrated modeling. Significant data gaps were identified in the effort. For instance, the efforts on the urban water demand revealed the lack of variation of prices for policy purposes across the country; the water market paper identified how little is really known about water markets in the West; the benefit transfer papers reveal that a central issue as yet unaddressed by SAHRA is the uncertainty effects of population growth relative to other data uncertainties. The hybrid modeling papers raise issues that will have to be addressed in policy design regarding the needed anticipation of future demands. Although the UNM group considers this phase of the project finished, new initiatives are proposed below that involve modeling within the dynamic simulation platform.

Activities and Results

During the past year we completed a series of manuscripts, drawing on efforts achieved during Years 1 and 2. Some have been accepted for publication, some will remain as white papers.

Plans for next reporting period

Efforts on the Economic Modeling and Data Gaps project have led us to propose two new initiatives. Both ultimately involve using the dynamic simulation modeling platform.

Sub Area 1
Traditional economic models normally assume that a public decision maker’s objective is to maximize social welfare. Given this objective we can provide water policy makers with integrated management tools to assess the effectiveness of policy alternatives. However, the assumption of social welfare maximization is just one of several objectives that may be relevant. For example, equitable allocation may be more appropriate in some cases, or a combination of equitable distribution up to a specific level of consumption, followed by social welfare maximization after that point, or a sustainable water use plan. Different objectives most likely will result in different efficient policy tools.

The research will provide a tool with which to assess the impact of varying public objectives. The unique aspect of the tool is not only the recognition of varying objectives but also the incorporation of these objectives with the integrated behavioral and physical science models that have and are being developed in SAHRA. This will provide the decision maker with a more accurate tool with which to assess decisions as well as provide an educational tool for the public.

The research program is composed of three parts. Part I will compile the objectives of water utility decision makers. Work already completed within SAHRA in both the U.S. and Mexico will provide the basis for this. Where necessary, a survey of additional policy makers will be completed to provide a comprehensive perspective of policy makers’ objectives for water usage in semi-arid climates. Part II will integrate the objectives into socio-scientific models of water allocation developed within SAHRA. These results will provide the basis for Part III, which is the development of a computer-based interactive tool.
that can be used by policymakers and stakeholders alike to assess resource management plans under the appropriate policy objective.

Sub Area 1 will provide a tool with which to assess the impact of varying public objectives. The unique aspect of the tool is not only the recognition of varying objectives but also the incorporation of these objectives with the integrated behavioral and physical science models that have and are being developed in SAHRA. Without the interdisciplinary platform provided by SAHRA, the work proposed in this area could not be accomplished in a form that would be particularly beneficial. This will provide the decision maker with a more accurate tool with which to assess decisions as well as provide an educational tool for stakeholders in general. The anticipated deliverables include a manuscript as well as the computer-based analysis tool.

Sub Area 2
Conversations with Juan Valdés and Javier Aparicio (IMTA) have resulted in a tentative agreement to collaborate on modeling in the Conchos River region. Dr. Aparicio has a Stella-based model for Mexico with which Dr. Valdés is working. The model would be converted to the dynamic simulation platform and the U.S. side of the Rio Bravo River would be added. This sub-project will serve as vehicle for integrating the substantial literature on agricultural demand for water into a dynamic simulation format.

Sub Area 2 will provide a tool for analyzing alternative international water allocation schemes. The interesting aspect of the area is the heavy emphasis on the agricultural area. SAHRA has to date not fully addressed the issues at the border. This would address one of the more general issues of efficient and equitable distribution of shared waters along an international border. For Year 4 the primary effort would be writing a proposal for possible funding from the U.S. and Mexico. Also the modeling of the Conchos using dynamic simulation mentioned in Section 4 will be continued and will be the basis for the integration.

3. Non-Market Valuation

This focus area proposes to examine the influence of other types of valuation on stakeholders’ water demands and choices. This and the previous focus area provide a scientific evaluation of stakeholders’ water choices and suggest where and how policy and management changes might be more effective. There is one active project within this sub-area:

Economic valuation of riparian flyways
Brookshire, Chermak (UNM)

This project addresses the value of water in an integrated framework. The goal of this proposed research is to link the understanding of the science of the relationship between water availability, habitat health, and the valuation of both birds (diversity of population size) and water as resources.

Activities and Results

A draft proposal was prepared by Dr. David Brookshire, but has not yet been circulated. Initial proposal writing suggests that this is a far larger project than anticipated and far more costly.

Plans for next reporting period

This effort is intended to eventually be a separately funded project. We aim to complete and submit the proposal in January 2003. As mentioned above, the cost and complexity of the proposal is greater than originally anticipated.
A critical need is for the work of Julie Stromberg and Arriana Brand to be started. We propose that money be allocated to these individuals to begin their collaboration. We have not had time to discuss their interest in this notion, as it comes out of the draft proposal writing stage.

4. Water Resources and Management Operations

This focus area links the research from the prior TA5 areas with the findings from other thrust areas in modeling systems developed collaboratively with water managers. These system dynamic models act as frameworks for integrating physical and social science into decision tools for the management of scarce water resources. The individual research efforts include:

- Drought preparedness plan for the Rio Conchos basin
- Extending URGWOM to include dissolved oxygen using demand-side management
- A surface water - groundwater mass balance model for the Verde River basin using demand-side management
- Evaluating Sierra Vista conservation alternatives using demand-side management
- Dynamic Simulation Model for the Albuquerque basin
- Multi-objective water resources management optimization model for the San Pedro river basin

Drought preparedness plan for the Rio Conchos basin
Valdés (UA-CEEM), Aparicio (IMTA)

The characterization of droughts poses a significant problem for hydrometeorologists and water resources engineers. One of the reasons is because droughts can last longer and extend across larger areas than other climatic extreme events. Droughts in the Conchos River basin are of great interest to both the U.S. and Mexico because of the International Treaty of 1944 regarding the sharing of the waters of the Rio Bravo/Rio Grande watershed.

The general objective of this research is to create a decision support system (DSS) for the Rio Conchos basin that will help to simulate and improve water resource management and planning. The DSS will help to clarify to the decision-makers what is necessary in order to increase the water supply and reduce the water demand both in the short and long term through the analysis and applications of various scenarios. Drought indices were developed to characterize droughts in semi-arid and arid regions. We also provide statistical approaches to examine the spatial influence of droughts and to estimate the return periods of droughts. The results of this research provide a framework for sustainable water resources management in the basin.

Activities and Results

The previous years were focused on analyzing temporal and spatial extents of droughts as well as estimating the relative frequencies and recurrences of droughts in the Conchos River basin. During the current reporting period the characterization of the droughts was completed with a bivariate representation of the drought severity and duration. In addition a forecasting model was developed that outperforms others statistical models in the application case, the Conchos River Basin. These characterization and forecasting components will be used in the development of a decision support system for the basin using system dynamic techniques. This decision support system will allow the consideration of socio-economic indicators for the basin and for the Lower Rio Grande/Bravo basin in conjunction with the research being carried out by other members of TA5.

In addition to completing the characterization of droughts, a forecasting model for droughts was developed. The forecasting model provides indexed regional drought forecasts for the Conchos River basin. This model is based on dyadic wavelet transforms and artificial neural networks. Preliminary results of the model are promising as may be seen in the following section, and we plan to continue the
development of the forecasting model. Improved forecasts of the indexed drought will allow water resources decision makers to develop drought preparedness plans far in advance to mitigate drought impact. Another graduate student is spending his summer getting familiar with this particular catchment.

The coupled (ANN-DD) forecasting model developed in this reporting period provides significant improvements for forecasting PDSI compared to the traditional regression model and popular nonlinear neural networks. The figures below show the performance of the proposed model compared with other forecasting models. The climatological average was used as baseline. Several forecasting skill scores were used to measure the performance of the models. As shown in the figures, the coupled model has a better performance than the other models. One of the reasons is the weakness of other forecasting models to adequately represent the innate long-term memory of the PDSI, which is highly dependent on antecedent soil and atmospheric moisture conditions. Regarding the development of DSS, which will be based in a dynamic simulation model, an initial model representing the main characteristics of the Conchos basin is expected to be finished by the end of the summer.

Plans for next reporting period

In the first three years, the drought characteristics and predictability in the Conchos River basin have been examined. In Year 4 we expect to finalize the characterization and predictability issues of droughts in semi-arid and arid regions. We will focus on the implications of droughts in the region and on the development of a drought preparedness plan. During Year 4, we plan to determine the frequency of major droughts in the historic record. This will be accomplished by including paleoclimatologic data in the analysis. Using system dynamics, the representation of the basin will be completed and connected with the model developed by IMTA for the Mexican portion of the Rio Grande/Rio Bravo. The next logical step is to continue working on the definition of the principal characteristics and the creation of the DSS. These activities are to be held together with the activities mentioned in sub-area 2 (see above).

The following is a rough timeline for planned accomplishments:

- **Fall 2002**  Completion of the first version of the dynamic simulation representation of the Conchos River Basin. Complete development of forecasting model and addition of paleoclimatologic data to drought characterization.
- **Spring 2003**  Incorporation of connections with the overall model of the Bravo, and definition of scenarios for simulation. Completion of the final version of the dynamic simulation model. Determination of the economic and other social parameters of the basin in collaboration with IMTA researchers.
- **Fall 2003**  Simulation runs using the final version of the model. Development of first version of drought preparedness plan for the basin.
- **Spring 2004**  Drought preparedness plan for the basin.
Extending URGWOM to include dissolved oxygen, using DSM
Lansey, Varvel (UA-ENG)

Water resources management decisions affect a broad community and tools to assist all constituents in that community will be valuable in transmitting the rationale for, and understanding the potential impact of, decisions. Dynamic simulation modeling is a tool that can provide a link between technical and scientific information and decision-makers. To demonstrate the utility of this approach, a lumped-sum, mass balance model for simulating surface water flow and dissolved oxygen concentrations on the upper Rio Grande River has been created for technical decision-makers.

Activities and Results

The Upper Rio Grande (URG) water operations group has a total of 8 objectives that are being considered by different subgroups. Water quality in terms of arsenic, algae, and total sediment load is an issue in northern New Mexico, and salinity concerns have been voiced in the southern portion of the state. We have developed a dissolved oxygen simulation model using a dynamic simulation model. A water budget from Cochiti reservoir through Elephant Butte reservoir has been developed and calibrated for a fifteen-year record on a monthly time step. Calibration of the dissolved oxygen component is nearing completion. Kyle Varvel, CEEM MS student, is finalizing his thesis and will defend in August 2002.

The components of the river model (stream segments and reservoirs) have been developed as generic components and can be applied to any system. Mr. Varvel’s responsibilities were expanded to develop a first level model of the Rio Conchos for use in a management model with the drought management effort in SAHRA. Data availability is a major difficulty in Mexico, but a simple model has been programmed and will be calibrated for local gains and losses.

The primary result of this year has been the near completion of the Upper Rio Grande Water Quality model. The range of the model is the Cochiti reservoir to Elephant Butte reservoir. Screen shots from the model’s mass balance component are shown in Figure 1. Inputs can be easily modified using the slide bars and dials as shown in the figure on the left, while output can be displayed graphically or in tables (right figure). This model allows operators to consider the impacts of water quality when making release and diversion decisions.

As discussed above, the components of this model are written in general form in order to be easily applied to other locations, e.g., Rio Conchos. The water quality model mass balance component will serve as the basis for salinity modeling in the URG. It is anticipated that the water quality model can also...
be transformed to represent salinity. If desired, the basis model can be extended to the entire Rio Grande basin. Such large-scale modeling may be helpful to understand mechanisms.

The major contribution of this research direction has been the adoption of dynamic simulation (DS) as an integral component of SAHRA. Several investigators have been involved in this area and, as noted, DS should provide a mechanism to link SAHRA science and water resources decision making. The current emphasis is on assisting decision makers in planning for a sustainable water supply. This ability is particularly critical for the State of Arizona.

**Plans for next reporting period**

The general use of dynamic simulation (DS) can link SAHRA science with stakeholders. In the short term, we propose that the primary application area for DS modeling/water resources management will be the Upper San Pedro (USP) watershed in southeast Arizona. This application will complement the Sandia URG work in New Mexico.

During Year 4 a dynamic simulation (DS) model will be developed that includes potential conservation measures. Modules will be written for water balance and costs. Appropriate interfaces will be developed in collaboration with the USPP report. During Year 5, the DS model will be extended to include response function relationships for USPP most preferred groundwater models and riparian zone integrity measures. Interfaces will be extended as needed and reported. Future efforts will be to extend the model to include alternative groundwater model relationships. This option is desired by USPP due to lack of agreement on best model. Sensitivity and uncertainty analyses also are desired by USPP members.

The following is a rough timeline of proposed activities for this and the two projects described immediately below:

- **Fall 2002** Water supply data collected and DS lumped community model constructed (January 2002).
- **Spring 2003** Demand data collected and DS model for community constructed (June 2002).
- **Summer 2003** Calibration of models with field data on aquifer scale and develop time series of future inflows/demands (August 2003).
- **Fall 2003** Incorporate cost relationships for conservation measures and make preliminary model runs (December 2003).
- **Spring-Summer 2004** Spatial disaggregate groundwater pumping and impacted riparian areas. Develop response function relationships (August 2004).
- **Fall 2004** Inclusion of riparian zone integrity measures as model output given groundwater levels and model testing (December 2004).

**A surface-groundwater mass balance model for the Verde River basin using dynamic simulation modeling (DSM)**

*Laney, Bowen (UA-ENG)*

Water resources management decisions affect a broad community, and tools to assist all constituents in that community will be valuable in transmitting the rationale for, and understanding the potential impact of decisions. Dynamic simulation modeling is a tool that can provide a link between technical and scientific information and decision makers. The DSM model approach is being applied for policy level settings in the Verde basin. The Verde basin model is slow in developing due to time commitments of an unfunded graduate student.
Activities and Results

Population growth in the Prescott area has stressed the limited available water resources. Several groups have formed with the goal of water resources management. They are receiving additional support from the Arizona Department of Water Resources (ADWR) to become better organized. We have discussed the development of a decision support system based upon a water balance model developed in dynamic simulation. They are receptive and willing to collaborate. The initial effort is focusing in the Prescott Active Management Area. After initial discussions, this project has proceeded very slowly due to limited availability of Ms. Bowen. The major effort has been collection of water availability and supply data for the region.

The major contribution of this research direction has been the adoption of dynamic simulation (DS) as an integral component of SAHRA. Several investigators have been involved in this area and, as noted, DS should provide a mechanism to link SAHRA science and water resources decision making. The current emphasis is on assisting decision makers plan for sustainable water supply. This ability is particularly critical for the State of Arizona.

Plans for next reporting period

Work within the Verde basin will continue as student time and availability permits. A basic water balance model that can identify critical components and possible solutions continues to be the first objective of this work.

The following is a rough timeline of proposed activities for this and the two projects described immediately above and below:

- **Fall 2002** Water supply data collected and DS lumped community model constructed (January 2002).
- **Spring 2003** Demand data collected and DS model for community constructed (June 2002).
- **Summer 2003** Calibration of models with field data on aquifer scale and develop time series of future inflows/demands (August 2003).
- **Fall 2003** Incorporate cost relationships for conservation measures and make preliminary model runs (December 2003).
- **Spring-Summer 2004** Spatial disaggregate groundwater pumping and impacted riparian areas. Develop response function relationships (August 2004).
- **Fall 2004** Inclusion of riparian zone integrity measures as model output given groundwater levels and model testing (December 2004).

In the original proposal, a main objective of SAHRA was to assist communities with water resources planning. Unbiased science to improve these decisions is clearly a major contribution and we are working toward that end. A long-term concern is the relative emphasis on science versus tools for decision makers and stakeholder involvement. If water resources remain a priority, water resources planning concerns exist in other regions within Arizona and can provide long-term connections in the state. The Verde River basin is water-limited in certain sectors, and water allocation and impacts of groundwater pumping on riparian zones and endangered species is of interest to many constituents. The Phoenix and Tucson regions and their local utilities must also make planning decisions about how best to use their resources and maintain a sustainable water supply. See for example David Modeer’s article in *H20 Tucson* (Tucson Water Newsletter). As an acceptable understanding (from a decision maker perspective) is achieved in the San Pedro basin, these other locations offer opportunities for SAHRA to have an impact within Arizona.
Evaluating Sierra Vista conservation alternatives using dynamic simulation modeling (DSM)  
_Lansey (UA-ENG), Roach (UA-HWR)_

Water resources management decisions affect a broad community and tools to assist all constituents in that community will be valuable in transmitting the rationale for, and understanding the potential impact of decisions. Dynamic simulation modeling is a tool that can provide a link between technical and scientific information and decision makers. The DSM approach is being applied for policy level settings in the San Pedro river basin.

Activities and Results

Significant time has been spent building links with the Upper San Pedro Partnership and developing their buy-in to the modeling approach. Several proposals will be submitted in early July to extend the San Pedro work. The large-scale San Pedro model can serve as a link between the science elements within SAHRA and with the science results and decision-makers.

The Upper San Pedro Partnership (USPP) is a consortium of 20 agencies and interest groups that are resolved to managing the limited water resources in their watershed. Water demands are dominated by domestic, industrial, and environmental uses. Decisions for short- and long-term allocations are pressing. SAHRA and others are improving knowledge of water demands and distribution. With Dr. David Goodrich's assistance, we have begun a dialogue on their needs for a general decision support system for regional water management decisions. The USPP is very receptive to the dynamic simulation modeling and contributing to the development of a model for their region. The first question that they are interested in answering is what conservation measures should be instituted to move toward safe yield. Jesse Roach (a UA graduate student) developed a prototype model for demonstration purposes. He has shifted from this project and a new student has not been identified for summer/fall 2002.

The major contribution of this research direction has been the adoption of dynamic simulation (DS) as an integral component of SAHRA. Several investigators have been involved in this area and, as noted, DS should provide a mechanism to link SAHRA science and water resources decision making. The current emphasis is on assisting decision makers plan for sustainable water supply. This ability is particularly critical for the state of Arizona.

Plans for next reporting period

The overall DSS development will be completed in the five tasks described below. Each task requires two major efforts: data collection and computer programming. Valid input information and model calibration is critical for DSS acceptance and use. The USGS, USPP, ADWR, University researchers, and local communities have collected water availability and consumption data for over 30 years. Within each task detailed below, appropriate data will be documented by source and accuracy in the DSS database. Most information will be static and stored in spreadsheets. If necessary, more complex databases that are compatible with the dynamic simulation model will be used.

The first four tasks are related to the development of the DSS that links water consumption with environmental demands. The primary water use (outside of riparian ecosystem demands) is municipal use. The USPP has developed a set of alternative conservation measures that are being examined to bring the community to a safe yield without groundwater mining. The first major effort is to provide a tool that will allow evaluation of these alternatives including their costs (Tasks 1 and 2). The dynamic simulation model will allow selection of different management options, such as reducing residential demand, water reuse, and allowable population growth.

Using a dynamic simulation modeling platform, a graphical interface will be developed to modify input and key evaluation criteria can be displayed in several formats. Simple user interfaces such as slider bars
can be moved to define a desired input (see Part I). The model is then executed by a single mouse click and the results are displayed in graphical form for this example. Total consumption and aquifer overdraft can be shown as a function of time. Based on results, inputs can be quickly modified to examine alternative decisions and re-executed. These interfaces can be tailored with graphics, photographs, etc. to be more visually appealing. As noted, dynamic simulation is not simply representing a water balance; other information can be presented in alternative forms such as tables or single indices (e.g., total cost, water reduction/dollar of investment, riparian zone condition for various locations).

The remainder of the DSS component of this project is to enhance the basic model through improved spatial detail and incorporation of uncertainty. Task 3 will focus on spatial disaggregation of groundwater withdrawal and recharge. This effort will provide answers to the question of the impact of municipal use on the riparian corridor. The interaction between groundwater inflow/outflow and groundwater levels in the riparian zones will be determined using available groundwater models and imbedded in the DSS (Task 3). Based upon the groundwater levels, riparian zone condition will be evaluated using the relationships developed in first component of this study (Task 4). This task will then provide a direct link between the water use and riparian zone sustainability.

Task 5 is listed as a final separate task but it will be completed throughout the project. The data input/output interface will also be developed in conjunction with the USPP to best present the desired model results.

This work will link with ongoing work in the San Pedro basin including work on riparian integrity, data collection, and groundwater modeling. As noted above, this type of model can serve as the integration tool to bring the various science projects together. In addition to the clear connection by including models (or simplifications of them) in the DS model, other aspects of coordination will be the variability of annual groundwater recharge and generating of time series of future basin inflows.

The following is a rough timeline of proposed activities for this and the two projects described immediately above:

- **Fall 2002** Water supply data collected and DS lumped community model constructed (January 2002).
- **Spring 2003** Demand data collected and DS model for community constructed (June 2002).
- **Summer 2003** Calibration of models with field data on aquifer scale and develop time series of future inflows/demands (August 2003).
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- **Fall 2004** Inclusion of riparian zone integrity measures as model output given groundwater levels and model testing (December 2004).

During Year 4, a dynamic simulation (DS) model will be developed that includes potential conservation measures. Modules will be written for water balance and costs. Appropriate interfaces will be developed in collaboration with a USPP report. During Year 5, the DS model will be extended to include response function relationships for USPP’s most preferred groundwater models and riparian zone integrity measures. Interfaces will be extended as needed and reported. Future efforts will be to extend the model to include alternative groundwater model relationships. This option is desired by USPP due to lack of agreement on the best model. Sensitivity and uncertainty analyses are also desired by USPP members.
Dynamic simulation model for the Albuquerque basin
Tidwell (Sandia), Webb (Sandia), Woodard (UA-HWR)

There is an urgent need to assure sustainable water supplies to meet demands, which are increasing with population, affluence, and environmental concerns. Structural, technological solutions, although necessary, are increasingly costly and take time to develop and implement. On a more immediate basis, efficient water management practices must be pursued. This is made more difficult by the highly dispersed responsibility for resource management, resulting in a piecemeal approach. Additionally, management practices must fully appreciate the interconnections, feedbacks, and time delays among watershed subsystems (e.g., precipitation, runoff, groundwater discharge, evapotranspiration, pumping, recharge) that operate over a range of spatial and temporal scales. To better address these problems, adopting a holistic, systems-level approach is being adopted. Specifically, systems dynamics is used as a decision support framework in which we integrate the natural system with other systems including economics, demographics, and ecology. The resulting decision models are couched in the context of the legal, political, and social constraints that limit the decision process. Currently, project participants are developing a prototype decision support model for the Middle Rio Grande Basin. This model incorporates the basic components of water supply (basin inflow, recharge, evaporative losses, etc.) and water demand (municipal, agricultural, and industrial).

Activities and Results

Enhancements of the prototype decision support model for the Middle Rio Grande Basin that have been completed or are well under way include:

a) Improving the evapotranspiration functions
   i) Establishing cooperative relationship with the US Bureau of Reclamation, US Army Corps of Engineers, New Mexico Interstate Stream Commission, City of Albuquerque, and other stakeholders and decision makers.
   ii) Calibrating the model against historical data for basin outflows and groundwater depletion.

b) Developing integrated user-friendly interfaces to allow real-time analysis of alternative water management practices in the basin.

c) Converting the model to the current software version being used by other SAHRA researchers.

Specific results cannot yet be reported, as the research is still ongoing. However, perhaps the most important achievement of this project is that the model generated considerable interest among SAHRA researchers as an integrating approach and a DSS tool. It catalyzed half a dozen other DSM efforts involving modeling of various water parameters in the Upper and Middle Rio Grande, the Upper San Pedro, the Conchos, and the Upper Verde.

Plans for next reporting period

The model is by definition an integrative device. It is generating connections with the NMT work on salinity in the Middle Rio Grande (Phillips, Hogan, et al), and with water demand work at UNM (Brookshire et al).

In the forthcoming year, we intend to increase the spatial area covered by the model, including downstream to Elephant Butte Reservoir. We will also change the time step of the model from annual to monthly to incorporate seasonal effects. The model will be improved by adding economic relationships and by adding at least one water quality parameter (salt). The model will be published on the Web, and we will host a workshop in fall 2002 for researchers throughout the western U.S. who are using DSM to model natural resources, including water.
Multi-objective water resources management optimization model for the San Pedro river basin

Yeh, McPhee (UCLA)

This research has two main goals. The first goal is to develop a Decision Support System (DSS) that merges knowledge from diverse disciplines and simulation tools in a practical, meaningful decision-making environment. The second goal is to assess the reliability of management decisions made using DSS and to evaluate data sufficiency for management purposes. Our research approach combines groundwater simulation with multi-objective optimization to generate trade-off curves among competing objectives in groundwater management. Multi-objective decision-making techniques can be used to select the most desirable pumping policies. Our research aims to developing a method to evaluate uncertainty in the decision space with respect to parameter uncertainty, which in turn is related to the quantity and quality of data used to calibrate the model. Key results for the reporting period include the establishment of a working relationship with the Upper San Pedro Partnership and the formulation of the multi-objective optimization problem to be used in the management model.

Activities and Results

In the first three years of our research, we have selected the San Pedro River Basin, in the U.S. Southwest, as the candidate basin for the development of a DSS. The overall framework for the DSS has been built, linking a simulation model with an optimization model. The linkage uses the response matrix to replace the groundwater flow model in the optimization problem. A multiobjective management model with three conflicting objectives has been proposed and submitted to the main stakeholder organization in the Upper San Pedro River Basin, the Upper San Pedro Partnership (USPP). Potential for integration with other SAHRA researchers has been identified, and research activities are being coordinated between the USPP, UA and UCLA. Our research goals and the way in which they are being carried out aim at bridging the gap between sciences, decision-makers and planning. The DSS will integrate knowledge from diverse disciplines such as hydrology, numerical modeling, social science and operations research.

Activities during Year 3 have focused mostly on communicating our research plans to Basin stakeholders and decision managers, and in formulating a multi-objective optimization problem that reflects the needs and priorities of these actors, for inclusion in the DSS environment. To formulate a multi-objective function that incorporates hydrologic, economic and ecological values, we need to identify desirable states of the hydrologic system, and express them in mathematical terms and as a function of the output of the simulation model. In the initial stage of management model formulation, feedback from stakeholders is fundamental to ensure that research results will be meaningful and useful. A field trip to Arizona and Sonora was conducted in November 2001. On that trip, we attended a meeting of the advisory committee of USPP, where initial contacts were made. The SAHRA Annual meeting in February 2002 provided a forum to enhance those contacts and further acquaint USPP representatives to the nature of our research. This led to a one-hour presentation made to the USPP Technical Committee on April 2002. The presentation allowed us to describe our research, in detail, to representatives of most of the 18 member agencies of the USPP.

Potential for integration with other SAHRA researchers was identified. Based on system dynamics, Kevin Lansey at UA is working on a DSS for the San Pedro Basin. The UA model is intended to evaluate broad water demand and supply decisions using lumped functional relations at a regional scale to evaluate fluxes and storage changes. Both approaches may be coupled to perform fast, interactive analysis with the UA model, and detailed pumping policy optimization with the UCLA model.

The outcome of the above meetings and presentations is a management model proposal that was submitted to the USPP in May 2002. The proposed management model includes: 1) an economic objective that minimizes costs of supply, treatment and conservation; 2) an ecological objective that maximizes groundwater heads in specified locations so that riparian vegetation is preserved; and 3) a maximum pumping objective that seeks to evaluate explicitly the trade-off of pumping against the two other objectives.
Although initially groundwater quality objectives were considered in the analysis, our interaction with stakeholders suggests that water quality is not a relevant issue in the U.S. portion of the basin. Therefore, our initial research approach has been updated and will include only groundwater flow simulation.

**Plans for the next reporting period**

Once the management model is fully developed and linked with the simulation model, it will be possible to obtain a set of non-inferior solutions and find desirable pumping policies, taking into account the multiple conflicting objectives that have been identified. Since decisions made with DSS are based on results obtained using a simulation model, the next logical step is to assess the reliability of those decisions by evaluating the parameter uncertainty that affects the simulation results.

The concept of Management Equivalent Identifiability – MEI – (Sun and Yeh, 1990) will be extended to the San Pedro Basin, and to the case in which model parameters are correlated. MEI purports determining sets in the parameter and decision spaces, so that all acceptable parameter vectors lead to acceptable decision vectors. Acceptable parameter vectors are those that provide a good fit of the simulation model to observed data. Acceptable decision vectors need to be defined in terms of the optimal policy uncertainty that decision-makers are willing to allow.

Parameter uncertainty is closely linked to the quantity and quality of data used for model calibration; model reliability analysis leads to conclusions about the sufficiency of data for management purposes. If model parameter uncertainty leads to unacceptable dispersion in the decision space, and on the other hand the calibrated model adequately fits the historical data, then we can conclude that data is insufficient for calibration from a management point of view.

We will develop a method for experimental design that considers management objectives. Experimental design for parameter estimation traditionally seeks to minimize some type of norm of the parameter covariance matrix, which in its approximation is a function of the Jacobian matrix of state variables with respect to model parameters. First-order approximation will be used to derive the covariance matrix of management decisions, as a function of the sampling design. Therefore, it is possible to specify sampling locations so as to minimize uncertainty in the management decisions obtained with the DSS.

This research should continue to be supported by SAHRA because it aims to provide a powerful tool for information management, specifically developed for the sustainable water resources management in the southwest U.S. and other semi-arid areas. The DSS is capable of merging ongoing research on riparian vegetation demands, hydrology, human demand scenarios, etc., and provides an opportunity for narrowing the gap between practitioners and scientists. Uncertainty analysis is a major concern in engineering and science research, since models are broadly used in decision making in areas such as water right allocations, zoning, risk analysis, etc. Therefore, understanding the implications of data quantity and quality over water resources management decisions has important consequences from the point of view of resource allocation and conflict resolution.

The project integrates with at least three major areas of research within SAHRA. First, research on water demands of riparian vegetation at the San Pedro River Riparian Corridor can be input as constraints or objectives to the management model. If functional relations are developed linking water table levels, vegetation areal coverage, etc., objective functions involving the extent of the San Pedro Riparian National Conservation Area could be developed. Second, current research on DSS using system dynamics simulation (Kevin Lansey at UA) can be successfully coupled with our proposed DSS, since each of them deals with the problem of water management at different spatial scales, with different levels of aggregation. Third, demand-side water management studies being carried out by SAHRA researchers will provide potential demand scenarios, within which our DSS can be run, so as to optimize particular features regarding pumping and recharge policies.

The following is a rough timeline of proposed activities:
December 2002  Prepare a manuscript on management models.

December 2003  Prepare a manuscript on model reliability analysis and data sufficiency evaluation.
5.1 Institutional Analyses and Social Assessment
- 5.1.1 Extraordinary drought evaluation for the Rio Grande/Bravo basin (Project No. 5.06)
- 5.1.2 Institutional analysis and social assessment of the Upper San Pedro river basin (Project No. 5.07)
- 5.1.3 Institutional analysis and social assessment of the Salt Verde river basin (Project No. 5.08)
- 5.1.4 Implementation of legal recognition of surface-groundwater links (Project No. 5.09)
- 5.1.5 Assessment of institutional structures of demand-side management integrated modeling (Project No. 5.17)

5.2 Behavioral Aspects of Water Markets/Banking
- 5.2.1 Experimental analysis of consumer demand (Project No. 5.01)
- 5.2.2 Survey of disaggregated demand (Project No. 5.02)
- 5.2.3 Socio-economic factors affecting residential water demand (Project No. 5.03)
- 5.2.4 Data gaps, hybrid modelling and sustainability (Project No. 5.16)

5.3 Non-market Valuation
- 5.3.1 Economic valuation of (riparian) flyways (Project No. 5.04)

5.4 Water Resources and Management Operations
- 5.4.1 Drought preparedness plan for the Rio Conchas basin (Project No. 5.06)
- 5.4.2 Extending URGWOM to include dissolved oxygen using DSM (Project No. 5.16)
- 5.4.3 A surface water - groundwater mass balance model for the Verde River basin using DSM (Project No. 5.11)
- 5.4.4 A surface water - groundwater mass balance model for the Verde River basin using DSM (Project No. 5.11)
- 5.4.5 Dynamic Simulation model for the Albuquerque basin (Project No. 5.13)
- 5.4.6 Multi-objective water resources management optimization model for the San Pedro river basin (Project No. 5.14)
III. EDUCATION

1a. Education Objectives

Our broad educational vision remains unchanged. The three overarching and cross-cutting goals in SAHRA’s educational efforts are to 1) improve hydrologic literacy at all levels; 2) integrate research and education; and 3) move beyond business as usual. These goals will be described in greater detail below. First, by improving hydrologic literacy we mean to affect the ability and actual practice of applying sound hydrologic principles to problems ranging from basin-scale water management to public policy debate. Additionally, we will encourage public participation in terms of both individual action (like conservation) and public participation in water-related issues (like growth). Second, by integrating research and education we want to recognize and promote the bi-directional incorporation of SAHRA research into all our educational programs, which necessitates broad science personnel participation in these efforts both within and beyond the university, as well as wide-spread opportunities for teachers, students and the public to participate in and appreciate Center activities. Finally, by moving beyond business as usual we want to acknowledge the difficulty in moving from our traditional roles toward ones that require boldness, innovation, collaboration, and public service. Obviously, these goals are self-reinforcing, as are the projects that are describe below.

Stakeholders

The audience or primary stakeholders that SAHRA’s education program recognizes include the traditional ranks of the postdoctoral and graduate student. Undergraduate students are recognized as being critical future leaders and opinion makers who have much to gain in terms of basic hydrologic literacy skills. More technically able students are the prime recruits for future graduate study, whether their interests lie in science, policy or education. Where possible, it is advantageous to work with those individuals who have the greatest lifetime impact. Certainly, our classroom teachers have this large multiplier effect so they are critical SAHRA stakeholders. Their students, likewise, are important to our mission of widespread hydrologic literacy because of the subtle influence children can have on adults around them. Needless to say, water management professionals are important users of SAHRA research products and services and require advanced and rather specific training to transform our academic and research ideas into new operational standards. The public is the final major stakeholder. It is important to reach them because not all water policy is based on technical detail. Thus without an educated public, SAHRA’s mission can never fully be satisfied. There are many overlaps between education and knowledge transfer stakeholders, particularly within these last two categories. One group of stakeholders who are critically important but implicitly involved in all these activities are SAHRA research scientists. Finally, we are targeting Native Americans by building career pathways that will support indigenous decision making and tribal sovereignty.

<table>
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<tr>
<th>Table 1: Education Matrix</th>
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<td><strong>What \ Who</strong></td>
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<td><strong>New Courses</strong></td>
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<td><strong>Career Paths</strong></td>
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<td><strong>Research Opportunities</strong></td>
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<td><strong>Extended Learning</strong></td>
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Management and Organization

An education matrix (Table 1) provides a convenient framework for relating the various education stakeholders to generic program objectives. In general, SAHRA seeks to advance its educational goals
by developing new courses targeted to various stakeholder constituencies and by supporting career pathways from one level of educational engagement to the next. Further, SAHRA seeks to promote an array of research opportunities to foster an authentic and deeply ingrained appreciation and knowledge of its activities. More informal knowledge transfer activities might be termed extended learning or community service opportunities. These will typically engage university students in short-duration, Center-supported and coordinated knowledge transfer efforts into the community to both further the students’ community involvement and to give them experience communicating their knowledge to a radically different, but highly receptive group. We are leveraging SAHRA funds wherever possible and actively solicit non-SAHRRA funding to support these activities.

1b. Performance and Management Indicators

These programs can be judged to be successful by their persistence and gradual growth in numbers served and quality of product. Successful programs will be offered at multiple locations and will be shared with diverse audiences through publications and presentations. Successful programs will garner positive participant reviews. The most successful activities are likely to attract outside financial support.

Educationally, one goal is for teachers to turn to the SAHRA web page for the latest water education activities and workshop information. Likewise, for knowledge transfer, one goal is for the public to accept SAHRA personnel and scientific findings as desired and objective components in future water issue debates. Both of these goals are difficult to measure although web traffic, meeting participation and participant feedback will provide positive indications of success and direction for improved implementation.

Several uniform assessment tools are being developed so that we might better track and service our various constituencies. These constituencies include program participants such as teachers and potential recipients of participant learning such as students. One set of tools will assess changes in hydrologic literacy while another will be fairly open-ended and designed to assess water-related attitudes.

Specific indicators include:

- List / Number of participants (teachers, students) in education programs and potential recipients (students, families) of participant learning
- List / Description of impacts of education programs on participant understanding and activity
- Summary of feedback on implementation from education program participants
- List of education collaborations
- List of publications and presentations on education programs
- List of education products developed

1c. Problems

Although much progress has been made in the last 10 months, some problems described last year persist. These include low workshop participation, poor linkage with core research activities and assessing the breadth of educational participation away from Tucson. A major effort is underway to better utilize the SAHRA web site to facilitate linking and promoting our various activities. Several of our collaborators were unable to participate with us this summer because of complications due to drought conditions and the resulting forest fires. We continue to explore ways to improve our partnership with NAU. Graduate recruitment continues to be challenging without fully funded research assistantships, although most open positions are currently filled by first and second-year students.

2a. Internal Education Activities

Our overall goals in course development are to improve hydrologic literacy, integrate state-of-the-art research findings and venues into basic course material and to provide inspiration and motivation to the student.
Graduate Seminar (HWR696)
Led by: Bales & Washburne
Intended Audience: SAHRA graduate students
Impact: 10 UA students/yr; Center-focused curriculum
Narrative: This one unit seminar class is taught every spring to help assimilate new graduate students into the interdisciplinary focus of SAHRA. Post-docs contribute by reviewing the innovative science and relevant water management issues within their areas of expertise. Participating students learn more about how their project integrates with the Center by making presentations to the rest of the class covering a topic of particular interest. SAHRA scientists lead discussions of fundamental research, management and policy issues that the students will face during their tenure with the Center.

Undergraduate Water Issues course (HWR203)
Led by: Ekwurzel, Washburne
Intended Audience: Non-science undergraduates
Impact: 100 UA students/yr; general education program with some Center content
Narrative: This is a mid-size (50 students) Tier 2 general education (required natural science) course at the University of Arizona that we teach every semester. The class is mostly non-science majors. The class goals are to improve the students’ hydrologic and scientific literacy, instill life-long learning and job skills and prepare the students for dealing with as yet undefined water issues in their future. The class is relatively unstructured, from the students’ perspective, although the course is broken into two-week modules which concentrate on issues related to the major themes of: water quantity, watersheds, water quality, water law, ground water, water conflicts and water sustainability. Class reading is drawn from industry and government fact-sheets and reflective essays about current regional water issues. A variety of activities are integrated into the 75 minute class period. Most classes begin with a focus image think-pair-share activity, which is used to introduce new concepts and terminology. A variety of in-class activities engage the students in data collection, analysis and group simulations. The students’ math skills are stimulated by the basic calculations and conversions required within these activities. In many cases, SAHRA science plans can be used to explain the historical development or current needs of various water management applications. We have just begun to encourage the further development of the graduate TA’s teaching skills by sharing the lecture duties for this lively class.

SAHRA Campus Seminar Series
Led by: Woodard
Intended Audience: University water research community
Impact: approximately 8 seminars/yr x 30 in audience; Impacts both internal and external communities
Narrative: No professional or academic education experience is complete without a forum for the intellectual exchange and debate about current developments and controversies in the field. This need is particularly acute for a large interdisciplinary group such as our own. In conjunction with the Department of Hydrology and Water Resources (HWR) and the Assistant Director for Knowledge Transfer, we are promoting the collegial exchange of professional views in a regular seminar series. Many of these lectures will be video taped for distribution within our Center. This year, we will receive supplemental funding from the Army Corps of Engineers to enhance the professional development aspect of these seminars by bringing in outside guest lecturers to cover a wider range of topics than is possible from local resources.

MS in Water Resource Engineering (MSE) Professional Degree Program
Led by: Valdés
Intended Audience: mid career water professionals
Impact goal: 2 new participants/year; New graduate degree program
Narrative: This degree program was set up in collaboration with all three Arizona state universities (UA, ASU, NAU) to facilitate mid-career academic and professional advancement. An academic program was forged from offerings (particularly distance learning courses) from the three universities and an intensive one-year on-campus stay to pick up key specialty courses and develop rapport with a faculty advisor. In place of a traditional thesis, a professional report related to the student’s work situation would serve as the capstone project. While interest in this route is expected to be light, it will greatly facilitate the career advancement for a few mid-level water resource managers.
Spring Snow Field Camp (HWR 696F)
*Led by:* Brooks
*Intended Audience:* SAHRA graduate students
*Impact:* 10 students/yr; New course with Center-focused content
*Narrative:* This new field course covers the basics of snow formation in the atmosphere, distribution on the land surface, and metamorphosis through the season. The basics of avalanche dynamics, water supply issues, and streamflow generation are also covered. The course has several organizational meetings but then meets for the week of Spring Break in the San Juan Mountains of Colorado where snow is studied first-hand. Finally, the course participants contribute to a SAHRA-related snow survey of the upper Rio Grande basin.

Graduate Research Assistantships / Community Service
*Led by:* Washburne
*Intended Audience:* SAHRA graduate students
*Impact:* 40 RA/TA's/yr, 100 hours of community service; external mentoring and leadership
*Narrative:* SAHRA funds over 40 graduate RA's and TA's to provide the research support and scientific innovation necessary for such a large and diverse Center. Because their specific activities and accomplishments are chronicled elsewhere, the focus here is on some of the unique opportunities this group enjoys. To promote interdisciplinary understanding and friendships, most SAHRA graduate students are seated in two large office spaces. Most students are required to take one core course that covers the philosophy and an overview of the goals and objectives of the Center (HWR696), co-taught by the Deputy Director. Graduate students are further encouraged to take part in some extracurricular community service project or something that extends their learning outside of class. Examples of some current opportunities are helping to mentor undergraduate interns, staffing the SAHRA public display at professional or professional development meetings, becoming involved with inquiry and research development programs in surrounding school districts, and helping to support special water-related activities (such as Sabino Canyon Days) with cooperating schools.

Research Experiences for Undergraduates (REU)
*Led by:* various researchers
*Intended Audience:* science undergraduates at SAHRA-related institutions or affiliates
*Impact:* 15 undergraduates/yr; Center-related career/research experience
*Narrative:* NSF has provided supplemental funding for 15 separate summer or semester-long REU’s over the current fiscal period. These programs have been aimed at attracting highly motivated undergraduates to experience our research environment. This past summer saw the completion of several successful REU experiences, with valued research coming from the solute, riparian and vadose zone research efforts. We are currently developing REU support to improve mentoring, assessment and follow-up. A complete report on our REU efforts has been prepared for NSF.

Undergraduate Internship Program
*Led by:* Washburne, Austin
*Intended Audience:* non-science undergraduates at SAHRA-related institutions or affiliates
*Impact:* 8 undergraduates/yr; Center-related topic or career exploration
*Narrative:* In order to stimulate creative ideas and provide support for non-expert students to explore a wide range of projects related to water sustainability in semi-arid regions, SAHRA provides funding to undergraduates who develop a project proposal with a non-SAHRA faculty member. These proposals are fairly simple and of limited duration, but do provide the student with a realistic proposal process experience. Several creative projects are currently being funded including one that is promoting campus water harvesting and one that is exploring ways to use industrial reclaimed water for revegetation projects around maquiladoras in Nogales, Son. Mexico.
High School Intern Program

*Led by: Woodard*

**Intended Audience:** High school students headed to UA  
**Impact:** 8 interns/yr; Center-related career/research experience  
**Narrative:** Eight outstanding high school juniors and seniors were recruited from local schools to participate in various field and database support roles this past summer. The program was a great success, particularly in terms of a project that had several of the interns programming and debugging a data collection system using hand-held personal data assistants (PDA’s). Several of the interns who worked for us this summer have entered the University and continue working with us as undergraduate assistants, thus supporting our career pathways objectives.

Environmental Hydrology (FOR/GGG 340)

*Led by: Aregai Tecle (NAU)*

**Intended Audience:** undergraduate environmental studies majors  
**Impact:** 20 students/yr; New course with some Center content  
**Narrative:** Aregai Tecle developed an undergraduate emphasis area in rural water and watershed management. The course and the emphasis area are meant to promote the objectives of SAHRA and meet student needs. Environmental Hydrology was developed and approved in 2001 as a forestry, geography and honors course. The course consists of a 3-credit hour lecture and 1 credit-hour laboratory/field experience. The course is being taught this fall as a web-enhanced course, and there is a plan to develop it as a web-based course in the near future.

Science Education Research

*Led by: Elizabeth Hancock*

**Intended Audience:** SAHRA researchers & educators; teachers  
**Impact:** under development  
**Narrative:** Science education research is an activity that affects both how we operate our programs and their effectiveness. In a broader sense, science education research affects how we all approach the critical job of education. While much of what an STC does is orientated toward near-term practical objectives, Center programs also provide the perfect test-bed for studying how various groups react to and are influenced by advanced interdisciplinary research and understanding. SAHRA has been engaged in basic science education research over the past year in collaboration with the UA College of Education and Barb Austin, who has been interviewing REU and other undergraduate interns to determine what affect their participation with the Center has had on their appreciation of science and on their general level of hydrologic literacy. More importantly, we expect our newly hired education postdoc, Elizabeth Hancock, to continue this work and begin new efforts to more uniformly and consistently gather participant feedback, facilitate student-faculty integration, and help our many education and knowledge transfer activities to take better advantage of science education research literature.

2b. External Education Activities

Integrating Inquiry and Issues in Water Science  
*(I$^3$H2O, formerly Hydrologic Literacy Workshop, HWR599L)*

*Led by: Madden & Uyeda (Local HS teachers/trainers)*

**Intended Audience:** High School science teachers in the SW  
**Impact:** 6 trained this year in Tucson; goal of reaching 26 next year  
**Narrative:** This two-week workshop for high school teachers is aimed not only at increasing their hydrologic literacy, but also to give them much needed experience engaging in inquiry themselves, developing authentic research skills and analyzing complex (interdisciplinary) information. We were able to hold small workshops with the help of two master teachers and many hours of preparation. The regular class sequence is to review some basic concepts, have them read about several on-going issues or conflicts, introduce the Seek/Solve/Create/Share methodology in the context of a water quality problem and finally to work through a week-long problem-based learning (PBL) module constructed around a regional water management plan developed by a small group. SAHRA science and policy work is being integrated into this workshop. We hope to use SAHRA’s distributed network of researchers to support and
stay in contact with these teachers who are implementing what they have learned. This has been a successful joint effort between the SAHRA core office and the UA College of Education.

**Student-centric Program for learning About Semi-arid Hydrology**  
*(SPLASH, formerly WISE, HWR101C)*  
*Led by: Hancock, Woodard & Washburne*  
*Intended Audience: High school teachers interested in providing integrative science alternatives*  
*Impact: under development; 8 teachers and 80 students (Fall 2002)*  
*Narrative: Most water education materials are developed at the K-9 grade level. With the growth of charter schools, systemic science education reform, integrated and inquiry-based environmental science curricula, there is greater demand for a year-long, AP-level water science course that qualifies for basic university science credit and promotes early recruitment into undergraduate hydrology major programs. This course builds on our other course development and knowledge transfer efforts, particularly our website. The first pilot program in 3-4 schools will be in place for the 2002 fall semester. The development of this course is a collaborative and jointly funded endeavor between four water centers at the University of Arizona: SAHRA STC, Center for the Benign Manufacture of Semiconductors (CBMS) ERC, the Arizona Water Resources Research Center (WRRC), and the Water Quality Center (WQC). The course will integrate state-of-the-art water science, technology-rich and inquiry-based activities and regional field trips. There are many opportunities for graduate student support and community service learning. We hope to expand this program to other SAHRA cities within three years. Obviously this effort satisfies our developing career pathways objective.*

**Research Experiences for Teachers**  
*Led by: Washburne; Scheall*  
*Intended Audience: K12 science teachers*  
*Impact: under-development; approximately 5 teachers next summer*  
*Narrative: Like undergraduates, teachers too benefit from a full immersion research experience. Such an experience provides critical career, focused content and a very basic understanding of how science is done that teachers can, in turn, share with their students. Fieldwork in the hydrologic sciences is often constrained by the whim of seasonal weather patterns so it is difficult to plan teacher-scientist interactions strictly on the calendar. One opportunity we will explore the feasibility of is to invite teachers along on regularly scheduled departmental field camps. While the timing of these camps is not ideal for most teachers, the intensity and camaraderie that go along with an outdoor-based field experience should be attractive. There are three two-week camps in our current program focusing on: Snow hydrology, Surface water and Vadose hydrology.*

**SAHRA/Project WET Collaboration**  
*Led by: Flowers, Schwartz (WRRC)*  
*Intended Audience: K12 science students in SAHRA’s region of interest*  
*Impact: under-development; possibly 30 schools by next year*  
*Narrative: Water sustainability is often tightly tied to population growth. In Arizona, much of this growth is occurring in the Phoenix Basin within Maricopa County. SAHRA has been able to leverage state funds to support a water education specialist to serve this large metropolitan area. Our initial goal was to help facilitate area-wide Project WET (Water Education for Teachers) development. Over the coming months this specialist will become more involved with supporting other water education projects, improving our awareness of pending water legislation, and working with the press to highlight SAHRA-related research.*

**SAHRA/GLOBE Collaboration**  
*Led by: Washburne, Ferré, & Nijssen*  
*Intended Audience: K12 science students in SAHRA’s region*  
*Impact: under-development; possibly 30 schools by next year*  
*Narrative: This major new initiative ties together several previous strands of our education effort. The goal of the collaboration is to leverage the resources and abilities of both partners to more effectively sample environmental phenomena at wide space and time scales in SAHRA’s areas of interest. Essentially, this partnership requires significant buy-in and participation at all levels throughout SAHRA as well as in the schools located in our areas of interest. Global Learning and Observations to Benefit the Environment*
(GLOBE) students will be tasked with regular and special sample collection while SAHRA scientists and students will work with the schools to show how the student measurements can be integrated with their scientific datasets for a more complete physical picture of the water balance and water quality. The initial focus areas are the Rio Grande, San Pedro and Four Corners areas. A salinity and water solute sampling program is being set-up this Fall along the Rio Grande. Native American schools throughout the Four Corners region, where we have existing teacher training and support efforts, will be tasked to evaluate their regional hydroclimatology within the constraints of GLOBE and SAHRA.

**Passport to Learning – Water Cycle module**

*Led by: Steve Russell (Biosphere 2 Center)*

**Intended Audience:** middle school students

**Impact:** Possibly 5-10,000 students on class tours per year

**Narrative:** SAHRA supplied curriculum development funds to enhance an existing water cycle component in their standard middle school tour. This extension addresses selected aspects of hydrology and water use in southern Arizona. In particular, the relationships between water and other ecosystem processes are examined. This supplement is computer-based, which should enhance its impact. The enhanced module was introduced during the past year. SAHRA also supported the development of a three-dimensional hydrologic system model at Biosphere 2, which opened during the summer of 2002. The model will be part of tours for the general public and K-12 student groups.

**Environmental Education Outreach & Institute for Tribal Environmental Professionals (EEOP/ITEP)**

*Led by: Mansel Nelson (NAU)*

**Intended Audience:** Native American K-12 Teachers

**Impact:** 8 jointly funded workshops

**Narrative:** SAHRA provides travel and participant support matching funds to two pre-existing programs based at NAU to develop, demonstrate and support K-12 water resources and water quality education throughout the Four Corners region. Eight workshops and many on-site demonstrations were given to K-12 teachers and students. The purpose of this partnership is to train teachers who will incorporate the teaching of water and water quality in their science curriculum, and to stimulate students to learn about water and water quality problems that affect their tribal areas. Additionally, we believe this early exposure to water issues and science is crucial to recruiting more college-bound students into our degree program. A brief summary of workshops and knowledge transfer supported, in-part by SAHRA, over the last 10 months are:

1. **Tribal Schools Ecological Monitoring Program (TSEMP) workshop involving a three-day long education program organized and given in cooperation with The Nature Conservancy (TNC) and Navajo Nation Environmental Protection Agency (NNEPA).** However, only three educators from the Navajo Nation took the workshop. Participants learned the GLOBE hydrology protocols, macroinvertebrate sampling, and stream ecology. Schools currently involved in the TSEMP program include Tse Ho Tso Middle School (3 teachers), Chinle High School (2 teachers), Navajo Pine High School (1 teacher), St. Michaels Elementary School (1 teacher), and Tsaile Elementary School (1 teacher).

2. **Summer Scholars program (6/03/02 to 06/30/02).** This program was organized in collaboration with four school districts and it provided Middle School students with an emphasis in environmental science, mathematics, and technology a one-week on-campus, residential experience. The Summer Scholars program involved four one-week sessions and reached 140 students.

3. **A one-day Summer Institute on Youth Opportunity Program** was given to 24 students from the Navajo Nation. During the workshop students participated in a panel discussion concerning the current status of Navajo Nation’s surface and ground water systems. The discussion included the importance of the role of the community in water protection and why it is important to protect the existing water supplies.

4. **Protective Circle.** In this program, the EEOP staff visited 15 schools on Navajo Nation to provide classroom presentations and teacher workshops. During the visits, the EEOP staff gave presentations on solid waste and water contamination issues. The EEOP staff also used ground water models to teach students and educators about the importance of proper handling household hazardous wastes in order to keep contaminants off ground water.
2c. Professional Development Activities

Several workshops were organized to plan, coordinate and discuss early progress between SAHRA researchers and their stakeholders. These are discussed under Knowledge Transfer and the appropriate Thrust Area headings. Below, a few of the professional development activities carried out in collaboration with the SAHRA education program are highlighted.

**Tribal Watershed Training Workshop (NAU/FOR499)**
*Led by: Laurel Lacher & Johnathan Long (White Mountain Apache Tribe)*

**Intended Audience:** Tribal watershed managers and technicians

**Impact:** 8 last year; 12-15 next year

**Narrative:** SAHRA provided key participant support (scholarships) to an affiliated group (White River Apache Tribal Environmental Affairs Office), which developed and piloted an invigorating two-week summer workshop devoted to improving tribal environmental watershed management practices. The first summer field course offered by the Tribal Watershed Training Program (TWTP) was held in June 2001 at a remote facility on the Fort Apache Indian Reservation owned and operated by the White Mountain Apache Tribe. The course hosted eight tribal member participants from the natural resources programs of five tribes in Arizona and New Mexico. The Watershed Analysis and Management field course focused on the interconnections of natural systems and on the fundamental scientific tools required for understanding those systems. Each morning’s “classroom” lectures and demonstrations were followed by afternoon field trips to sites specifically designed to reinforce concepts presented in the lectures. Specific areas of emphasis included map reading and aerial photo interpretation, geology, soils, landscape analysis, hydrology and climate, channel morphology, riparian restoration, and land-use practices and management. At the end of the week, participants were asked to utilize some of the tools learned during the week in making group presentations to address thematic questions posed by the instructors at the beginning of the week. Students taking the course for college credit (through NAU) were required to submit a paper on a watershed analysis topic of their choice four weeks after the end of the field course. Catered meals and evening recreation contributed to a relaxed yet invigorating atmosphere for both the participants and instructors. Formal evaluations conducted throughout the week and video documentation of the course demonstrate the participants’ enthusiasm for this method of learning, and support the continuation of this course and possibly the development of others to address the needs of tribes and their members. Support for this year’s course was provided by US EPA, the Cooperative Institute for Research in Environmental Sciences (CIRES) at CU Boulder, SAHRA, the US Geological Survey, Northern Arizona University, and the White Mountain Apache Tribe. This summer’s program was cancelled due to extreme drought and the largest forest fire in Arizona history that started near where the workshop was held last year.

**Northern Arizona Watershed Collaborations**
*Led by: Aregai Tce (NAU)*

**Intended Audience:** Tribal and agency watershed managers

**Impact:** A presence and working relationship with tribal and other local watershed activists

**Narrative:** We have developed a strong collaboration to study soil and water salinity as well as the nutrient content and the productive capability of Hopi tribal lands. The Hopi Tribe provides in-kind contributions in the form of a hydrologist and soil and water sampling equipment. We are working to develop collaborations with NAU’s Center for Environmental Sustainability and the Navajo Nation to study land management impacts on water and water quality in the Coconino Plateau and the Navajo Reservation, respectively. Further, we are developing a partnership with the US Forest Service to study the relationship between forest management and wildland hydrology and water quality. We also have funds from the Bureau of Land Management and the Arizona State Prop 301 to study related problems. In addition, we are developing partnerships with local, regional and national environmental groups such as the Nature Conservancy, the Grant Canyon Trust, the Grand Canyon forest partnership, the Sierra Club and other groups. This will help us to view and address our water resources-related educational and research activities in a holistic framework.
2d. Integration of Research and Education

Education and research are naturally linked with a continuum of student-scientist interactions and independent research thinking occurring throughout the undergraduate-graduate-post doctoral experience. This, however, is business as usual. SAHRA fully expects its students and researchers to work together on the scientific challenges we have set for ourselves, but the expectation does not end there. We expect that both students and scientists will participate in the many extended educational opportunities we provide for them. In fact, the full suite of activities listed above is not possible without contributions from all levels of SAHRA participant.

One important Center product is a new, interdisciplinary curriculum at the university level. Such products are only possible with the participation of key frontier researchers, like Paul Brook’s new spring snow field course and the tempered but different perspectives of Roger Bales and Jim Washburne in our SAHRA graduate seminar course.

It is also important to get faculty participation in education activities outside of the realm of normal university life. We are pleased that two new departmental and Center faculty, Ty Ferré and Bart Niessen, have taken the time to participate as co-investigators with Jim Washburne in the K-12 GLOBE program and to become involved in an inquiry mentoring project with the local school district, TUSD.

SAHRA education staff have coordinated or participated with many school programs over the last year, but these programs would not be viable without the wide and gracious support of departmental students. These programs place our students in basic supervisory positions that allow them to safely experience the joys and rewards of K12 science education without a total commitment. Among the programs that have benefited from the participation of Center personnel are judging during the Southern Arizona Science and Engineering Fair, activity leaders for Daughters on Campus Day, field guides for the Esperero Canyon Middle School’s Sabino Canyon Experience, and supervisors for the water quality section of the local Science Olympiad.

We are particularly proud of two students’ extraordinary efforts to integrate research with education. Kyle Blasch, a non-SAHRA student funded through a USGS internship, came to SAHRA last September with a proposal to greatly expand the hydrologic component of their visitor center display through a unique collaboration between SAHRA, the US Forest Service, the US Geological Survey and the area’s docent naturalists. Through his catalytic efforts, this project should be completed in the next few months. Karletta Chief, a SAHRA Ph.D. candidate and Navajo Indian, has worked closely with SAHRA education staff to represent the Center at several environmental education conferences for Native American educators and to help us translate our hydrologic literacy message so it is more culturally appropriate.

2e. Significant Changes

Our emphasis for the coming year is to improve and expand our current programs. One key to this will be a major expansion of our education/knowledge transfer web site to better serve a wide variety of users. Julie Luft, our primary education collaborator in the UA College of Education has decided to relocate to UT-Austin effective August 10. While we will miss her expertise, this allows us to develop new ties to a new generation of science educators campus-wide. This effort is sure to progress rapidly as we have recently hired a new education post-doc from Florida State University, Elizabeth Hancock. We are currently exploring collaborative public education efforts with Debra Colodner at the on-campus Flandrau Science Center. As was stated in last year’s report, we expect to continue to slightly shift our emphasis away from supporting generic hydrologic literacy towards a greater emphasis on more active promotion of fundamental SAHRA science concepts and themes.
2f. Outreach

Several opportunities came up over the last 10 months where SAHRA was asked to attend or participate in other meetings or conferences for the explicit purpose of informing other groups about our activities. What follows is a list of these events.

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
<th>Group</th>
<th>Location</th>
<th>Audience</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/14-15/01</td>
<td>AHS Annual Meeting - poster</td>
<td>AZ Hydrological Society</td>
<td>Tucson, AZ</td>
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<tr>
<td>9/29/01</td>
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<td>Esperero Canyon MS</td>
<td>Tucson, AZ</td>
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<tr>
<td>10/19/01</td>
<td>ASTA Annual Meeting - poster</td>
<td>AZ Science Teachers Assn.</td>
<td>Phoenix, AZ</td>
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<tr>
<td>12/4/01</td>
<td>UA Extension Retreat - talk</td>
<td>AZ Cooperative Extension</td>
<td>Tucson, AZ</td>
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</tr>
<tr>
<td>12/10-13/02</td>
<td>AGU Fall Meeting - poster</td>
<td>Am. Geophysical Union</td>
<td>San Francisco</td>
<td>1000's</td>
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<td>Science Olympiad Students</td>
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<td>2/2-3/02</td>
<td>Native Eyes Conf. – pamphlet</td>
<td>Science and Math Center</td>
<td>Tucson, AZ</td>
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<tr>
<td>2/25-28/02</td>
<td>SAHRA Annual Mtg - Poster</td>
<td>SAHRA visitors</td>
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<tr>
<td>5/2-4/02</td>
<td>CEA-CREST Annual Mtg - Poster</td>
<td>Cal State-LA collaborators</td>
<td>Pasadena, CA</td>
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<tr>
<td>5/14-16</td>
<td>Rivers Symposium – activities</td>
<td>GEWEX</td>
<td>New Orleans</td>
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<tr>
<td>6/6/02</td>
<td>PAG Water Education Mtg.</td>
<td>Pima Assn. of Governments</td>
<td>Tucson, AZ</td>
<td>25</td>
</tr>
</tbody>
</table>
IV. KNOWLEDGE TRANSFER

1a. Knowledge Transfer Objectives

SAHRA’s knowledge transfer (KT) objectives a year ago were as follows:

- developing working relationships with various stakeholders to better understand their needs and solicit ideas and suggestions to guide SAHRA’s research efforts;
- communicating research findings and making available to water resources managers and policy makers in semi-arid areas the decision support models, data sets, and tools that result from our research; and
- improving water resources management and furthering hydrologic literacy by identifying, sorting, validating, and making available in useful formats existing information.

Another objective which we have begun to aggressively pursue is as follows:

- helping water professionals expand and improve their skills and knowledge base through continuing education opportunities for working professionals.

In addition to pursuing this new objective, we have continued to evolve and broaden our KT emphasis. We continue to enhance internal KT, but have focused on improving KT with water resources professionals and developing KT initiatives with stakeholders. The largest increase in KT activity involves projects and products targeting the general public (e.g., our Web-based News Watch Service and Residential Conservation information, Rural Water Resource Centers, Sabino Canyon Visitor Center display and press briefings). We continue to seek areas where potentially useful information is not currently available from other sources, and to integrate content components so as to create synergies.

Our international activities also are broadening in scope and geographic coverage. A year ago, emphasis was placed in three areas:

- studying the impacts of privatization and decentralization of water and land resources in developing countries;
- looking at trans-boundary water issues, which include international borders, state borders, and Indian reservations; and
- studying water management issues in northern Mexico, including the Conchos and upper San Pedro basins.

A great deal has been accomplished in these areas, and they will continue to be pursued for at least the next two years. We are, however, moving beyond a focus on northern Mexico. An example of this is our current exploration of joint training opportunities with the new UNESCO Regional Centre for Training and Water Studies of Arid and Semi-Arid Zones (RCTWS) in Egypt. Other possibilities in North Africa and other semi-arid regions are being evaluated.

Across the spectrum of KT beneficiaries, we continue to identify areas of critical water information that lack effective dissemination mechanisms, and work to provide this in specific areas. These information clearinghouses will serve not only Southwestern water resources professionals, stakeholders, and general public, but the same types of people and organizations around the world. An example of our commitment to this is ongoing efforts to add more languages to those covered by our Web-based News Watch service.
1b. Performance and Management Indicators

Performance and knowledge indicators are based primarily on quantifying demand for the information produced. Thus, we are beginning to monitor the number of people, and their institutional affiliations, that access various types of information made available via workshops, through our Web site, at various public displays, and in print. Some examples of monitoring include:

- our Web site monitors usage and generates statistics including: numbers of visitors (over 1,000 per week during the last year, and currently about 350 per day); where they are located; where they arrive at the site; search terms used to land on various pages; pages viewed per visitor (average is 6), what browsers they are using, etc.;
- new electronic kiosks developed for Rural Water Resource Centers and the Sabino Canyon Visitors Center will record similar usage statistics;
- recording the number of copies of various flyers, pamphlets, reprints, etc. that are produced and given away.

We also need indicators of the **quality** of the knowledge and information being transferred, such as its usefulness, how current it is, and whether it fills an otherwise unmet need. This is more of a challenge, since people are more likely to share compliments than criticisms. Thus, we must continually challenge KT recipients to tell us how we can better meet their needs. In addition, we are endeavoring to characterize the impacts of knowledge transfer programs on participant understanding and activity.

1c. Problems Encountered

SAHRA has become a large and complex entity, involving over 200 persons, 11 universities, and numerous agencies, state and local governments, and organizations. Many research projects started over the last two years are now producing significant findings. Also, education efforts begun over the last two years are starting to bear fruit. Simply keeping track of who is doing what has become a significant challenge.

We have met this in part by continuing to automate all database entry, and by having all reporting requirements within SAHRA met through Web-based forms. As a result, information rarely has to be provided more than once, and increasingly, reports are at least partially self-generated.

We continue to develop mechanisms for efficient and effective internal knowledge transfer. Supplemental funds from NSF were used to fund videoconferencing facilities at three key partner institutions (New Mexico Tech, University of New Mexico, and Arizona State). One is currently operational, and the others are expected to be complete in August 2002.

Given the large and growing volume of Knowledge Transfer needs and opportunities, human resources were stretched very thin a year ago. A number of new hires have greatly improved this situation. These include:

- hiring a data base specialist in December 2001;
- hiring a curriculum specialist to assist SAHRA and three other UA water centers with education and knowledge transfer activities in Maricopa County (metropolitan Phoenix) in February 2002;
- hiring a graphic artist/Web developer in May 2002;
- hiring an education/knowledge transfer post-doctoral research associate in June 2002;
- hiring a full-time editor (while retaining our part-time Water News Watch editor) in July 2002; and
- hiring students to help with various Knowledge Transfer tasks.
In addition, some members of the nearly complete team of postdoctoral research associates have assisted in some KT areas. Overall, we are tremendously better staffed to meet KT challenges than we were just six months ago.

2a. Knowledge Transfer Activities

<table>
<thead>
<tr>
<th>Knowledge Transfer Activity</th>
<th>Informal Experiential Displays and Sites for the General Public</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Gary Woodard</td>
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</tbody>
</table>

Participants

<table>
<thead>
<tr>
<th>Name and Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Kyle Carpenter, Brad James, Mary Black, SAHRA</td>
</tr>
<tr>
<td>2 Sarah Davis, Jeff Klas, U.S. Forest Service</td>
</tr>
<tr>
<td>3 Kyle Blasch, Chris Smith, Dan Evans, USGS</td>
</tr>
<tr>
<td>4 Susan Pater, Jeff Schalau, Cooperative Extension</td>
</tr>
</tbody>
</table>

SAHRA is developing two types of Knowledge Transfer displays/outlets that target the general public.

**Informal Experiential Displays** take advantage of large concentrations of people in settings that provide opportunities to informally educate them through entertaining experiences. At the request of the US Forest Service, and with the assistance of the USGS, which is helping provide real-time data on streamflow, weather, and flood and fire danger, SAHRA is completing a public display, electronic kiosk, and Web site for visitors to Sabino Canyon. This desert mountain canyon, located just north of Tucson, receives 1.4 million visits per year. Visitors range from tourists traveling from Europe and Asia to Tucsonans taking advantage of the canyon’s hiking trails. The displays contain information on Sabino Creek, an ephemeral stream that rises in the Sky Island mountaintops and descends through several biomes to the Sonoran Desert. The kiosk and Web site will display near-real-time data from weather stations at the top, center, and base of the canyon that are operated by SAHRA, USGS, and the Forest Service, respectively.

The goal of this project is to educate people on desert streams, addressing basic issues as: Where does the water come from? Why does the flow stop part of the year? What are the conditions that produce flash floods? How does elevation affect climate, flora, and fauna?

The outcomes we seek include: attracting a large percentage of the estimated 350,000 persons who pass through the Visitors Center annually to the static displays and electronic kiosk; having a large percentage of local residents who call the Center staff for information on streamflow and weather and access that information via the Web site; and luring people who visit the Web site for weather and streamflow information to other parts of the Web site that explain the hydrology and biology of the stream.

**Rural Water Resource Centers**, by contrast, serve members of the public who are actively seeking information on local water conditions, issues, and resources. The ultimate goal is to have one in each rural county. Currently, Centers are being completed in Cochise County (Upper San Pedro River) and Yavapai County (Verde River). Developed in cooperation with Cooperative Extension offices, each Center will have a collection of print and electronic publications and data bases, some developed specifically for that county. Users will be able to carry away pre-printed materials, custom printed information, and CD-Rs, as well as email information to themselves and others.

The goal is to serve diverse populations, including educators, home owners, and policy makers who seek specific information relevant to their local basins.

Outcomes will be measured in terms of numbers of users and the amounts and types of information they receive. This information will guide the design and implementation of the next three Centers to be...
developed in 2003.

<table>
<thead>
<tr>
<th>Knowledge Transfer Activity</th>
<th>Professional Development</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Gary Woodard</td>
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</tbody>
</table>

Participants

<table>
<thead>
<tr>
<th>Name and Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Bonnie Colby, Agricultural and Resource Economics, U of Arizona</td>
</tr>
<tr>
<td>2 John Thorson, Special Master, Gila River Adjudication, retired</td>
</tr>
<tr>
<td>3 Don Davis, Juan Valdés, Don Slack, UA MEng. Program coordinators</td>
</tr>
<tr>
<td>4 Mark Dunning, Duane Bauman, US Army Corps of Engineers</td>
</tr>
</tbody>
</table>

SAHRA’s Committee on Integration hosted a series of science integration meetings in Tucson that led to a proposal for a river basin focus. As a result, three workshops were held:

- Integrative Modeling meeting in Albuquerque September 20-21, 2001;
- Rio Grande river basin science workshop in Taos, NM on June 6-7, 2002;

Another workshop sponsored by SAHRA was:

- Model Parameter Estimation Experiment (MOPEX) workshop, April 8-10, 2001, in Tucson.

Upcoming workshops include a follow-up Rio Grande river basin workshop on September 26-27, 2002, and a Dynamic Simulation Modeling workshop on November 1-2, 2002 in Tucson.

SAHRA has co-sponsored a number of short courses and symposia, including:


SAHRA has taken the lead in developing, with the Departments of Hydrology, Civil Engineering, and Agricultural and Biosystems Engineering, a Master’s program for U.S. Army Corps of Engineers employees, in water resources planning. This degree program is designed for mid-career Corps employees who desire to pursue a masters degree while only being away from their home offices for a single semester. The program is expected to serve a handful of students in Fall 2002, and substantially larger numbers in Fall 2003.

SAHRA’s seminar series brings two distinguished speakers to the University of Arizona each semester to present a seminar on a topic of widespread interest and to spend a couple days talking with SAHRA researchers and visiting labs and field sites.

SAHRA is jointly funding and contributing to publication of the 2nd ed. of Indian Water Rights: Negotiating the Future, by Bonnie Colby and John Thorson. The book, to be published in December 2002, will form the basis for SAHRA’s first Executive Training Program, in Spring of 2002. The second Executive Training Program will address hydrologic and legal connections and disconnects between groundwater and surface water.

SAHRA’s static displays, electronic kiosks, and printed materials are used at professional conferences...
to spread word about SAHRA, develop new partnerships, and recruit students. Conferences and meetings where SAHRA has had major displays in the last 10 months include:

- Arizona Hydrologic Society (Sept. 2001)
- New Mexico Annual Water Conference (Dec. 2001)
- Annual AGU meeting (Fall 2001)
- Arizona Science Teachers Convention, Phoenix (Oct. 2001)
- ADEQ Year of Clean Water Celebration, Nutrioso, AZ (June 2002)

<table>
<thead>
<tr>
<th>Knowledge Transfer Activity</th>
<th>International Activities</th>
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<tbody>
<tr>
<td>Led by</td>
<td>Diana Liverman, Gary Woodard</td>
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<tr>
<td>Participants</td>
<td></td>
</tr>
<tr>
<td>Name and Organization</td>
<td></td>
</tr>
<tr>
<td>1  Paul Wilson, Agricultural and Resource Economics, U of Arizona</td>
<td></td>
</tr>
<tr>
<td>2  Juan Valdés, Civil Engineering, U of Arizona</td>
<td></td>
</tr>
<tr>
<td>3  Bob Varady, Udall Center, U of Arizona</td>
<td></td>
</tr>
<tr>
<td>4  Margaret Wilder, U of Arizona</td>
<td></td>
</tr>
<tr>
<td>5  Tereza Cavazos, U of Arizona</td>
<td></td>
</tr>
<tr>
<td>6  Nicolas Pineda, Colegio de Sonora</td>
<td></td>
</tr>
<tr>
<td>7  Jose Luis Moreno, Colegio de Sonora</td>
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Tereza Cavazos (postdoctoral fellow with ISPE/CLIMAS) completed a project on Climate and Climate Variability of the Conchos Basin, Chihuahua, Mexico and submitted for publication a paper with the following abstract:

- The Rio Conchos basin lies in the arid/semi-arid part of the Mexican state of Chihuahua, where major cities such as Ojinaga, Chihuahua, Camargo, Jimenez, Delicias, and Parral are growing rapidly due to increasing industrialization. Water supply management creates great challenges at the binational level, especially during times of extended droughts such as those of the 1950s and 1994-1998. Thus, understanding the climate of the basin, its variability and the possibilities for seasonal predictability are fundamental for water management and planning in the basin. In this paper we present the climatology and precipitation variability of the Conchos River basin and the Bolson de Mapimí referred here to as the Conchos-Mapimi region. Special attention is given to the possible atmospheric and oceanic factors responsible for extended droughts. It is found that the current atmospheric and oceanic anomalies are typical of those of extreme drought years over the study area.

Juan Valdés and Paul Wilson are supporting and working with Jesus Gastulum, a PhD student from Conchos, Mexico. They are developing a Dynamic Simulation Model of the Conchos basin that includes factors affecting the frequency, areal extent and severity of drought. Working closely with colleagues from Mexican colleges, the goal is a decision support tool that will help policy makers improve management of the basin’s water resources, currently a source of friction between the US and Mexico.

SAHRA researchers Margaret Wilder, Nicolas Pineda, Jose Luis Moreno and Diana Liverman wrote a paper on the restructuring of water management in Mexico. This paper describes recent changes in Mexican water management and their impacts on local agricultural and municipal areas in Sonora, Mexico.

Margaret Wilder has completed her PhD by defending her dissertation on water in Sonora. She previously published two related articles:

- Margaret Wilder, The "new water culture" and ejidal producers in the Yaqui Valley, Sonora,

Soroosh Sorooshian and Hoshin Gupta made a number of presentations around the world on SAHRA’s mission and activities. These include presentations at conferences in the Netherlands, United Kingdom, France, Switzerland, United Arab Republic, and Egypt. A complete list of presentations by SAHRA-related researchers is provided in Section VIII.

Several SAHRA researchers, including Diana Liverman and Bob Varady, presented a one-day seminar to the Mexican National Water Commission on 9 November 2001. Simposio sobre la Problemática Ambiental en Cuencas de México y Estados Unidos de América focused on institutional and policy questions related to trans-border water issues.

Diana Liverman also has been working on a number of initiatives on water policy with collaborators in Mexico and Brazil including a study of water resource vulnerability to climate change (supported by EPA), and on the restructuring of water management in Mexico (with SAHRA’s Mexico partners supported by the Hewlett Foundation).

<table>
<thead>
<tr>
<th>Knowledge Transfer Activity</th>
<th>Joint Activities with Other Water Centers</th>
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<tbody>
<tr>
<td>Led by</td>
<td>Gary Woodard</td>
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<tr>
<td>Participants</td>
<td></td>
</tr>
<tr>
<td>Name and Organization</td>
<td></td>
</tr>
<tr>
<td>1  Kerry Schwartz, Arizona Water Resources Research Center</td>
<td></td>
</tr>
<tr>
<td>2  Deb Young, Susan Pater, Cooperative Extension</td>
<td></td>
</tr>
<tr>
<td>3  Sally Clements, ERC for Environmentally Benign Semiconductor Manufacture</td>
<td></td>
</tr>
<tr>
<td>4  Jo Falls, Tohono Chul Botanical Park</td>
<td></td>
</tr>
<tr>
<td>5  Jim Washburne, SAHRA</td>
<td></td>
</tr>
<tr>
<td>6  Gregg Garfin, Barbara Morehouse, Institute for the Study of Planet Earth</td>
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Voters in the State of Arizona approved an increase in the sales tax in November 2000 to increase funding of education. While 85% of these funds are earmarked for K-12 education, the remaining 15% is distributed to the state’s community colleges (5%) and three state universities (10%). Each university selected a small number of program areas to receive increased funding. The University of Arizona selected water resources as one of its targeted areas.

These additional funds are distributed to four water centers at the UA, including SAHRA. Some 80% of those funds support targeted research, but the four Centers agreed to each contribute 20% to a Joint Water Education and Outreach program. This program is coordinated by Gary Woodard and managed by SAHRA’s Business Office.

The goals of the joint program are to enhance hydrologic literacy at all grade and age levels by funding projects and programs that take advantage of synergies among the four Centers. For example, a curriculum specialist was hired to more effectively bring the Centers’ programs to Maricopa County (Phoenix metropolitan area). Other projects include support of Rural Water Resource Centers (described above), cross-training of water education specialists, and programs for the legislature and other decision-makers.

In conjunction with the Institute for Planet Earth (ISPE), SAHRA is hosting a series of occasional press briefings in Tucson, Phoenix, and Albuquerque. The goal is to more effectively use the newspaper and TV media to convey basic information on hydrology and climate to the general public.

The first press briefing was on July 22, 2002, in Tucson. It featured five researchers presenting studies...
and forecasts tied to drought, its causes, and its effects. Representatives of two newspapers, two television stations, and 1 periodical attended (see Appendix D for resulting news stories).

<table>
<thead>
<tr>
<th>Knowledge Transfer Activity</th>
<th>Internal Information Sharing</th>
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<tbody>
<tr>
<td>Led by</td>
<td>Kyle Carpenter</td>
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<tr>
<td>Participants</td>
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</tr>
<tr>
<td>Name and Organization</td>
<td></td>
</tr>
<tr>
<td>1  Steve Schroeder</td>
<td></td>
</tr>
<tr>
<td>2  Jill Gibson, SAHRA</td>
<td></td>
</tr>
<tr>
<td>3  James Hogan, SAHRA</td>
<td></td>
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<tr>
<td>4  Gary Woodard, SAHRA</td>
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A number of searchable databases have been added or expanded on the administrative (private) side of SAHRA’s Web site to meet information-sharing and integration objectives. Increasingly, these are accessible through, or selectively displayed on the public side as well. They include:

- a database of people associated with SAHRA (public side);
- a projects database on all discrete research, education, and knowledge transfer efforts;
- a bibliography on the hydrology literature of the Rio Grande;
- a bibliography on the hydrology literature of the Upper San Pedro;
- a bibliography on the hydrology literature of the Upper Verde;
- digitized “classic” reference works;
- glossary of all terminology used in the various disciplines within SAHRA;
- water-related quotes data base searchable by hydrologic subject, type of source, key word, author, and date (public side);
- annotated photo collections (public side);
- set of PowerPoint presentations; and
- a calendar of SAHRA activities (public side).

We currently are creating an intranet to pull together and make more usable all the administrative tools developed to date. This will also allow easier off-campus access.

We have begun to automate the remote logging of data from field research sites. This will enhance the quality of the data, more quickly identify instrument problems, and save considerable labor.

We have expanded our lending library of digital cameras, video cameras, video digitizing and editing, and audio recording equipment for capturing SAHRA-related activities.

<table>
<thead>
<tr>
<th>Knowledge Transfer Activity</th>
<th>Web-based Information Clearinghouses</th>
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<tr>
<td>Led by</td>
<td>Kyle Carpenter, Gary Woodard</td>
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<tr>
<td>Participants</td>
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<tr>
<td>Name and Organization</td>
<td></td>
</tr>
<tr>
<td>1  James Hogan, SAHRA</td>
<td></td>
</tr>
<tr>
<td>2  Louise Shaler, SAHRA</td>
<td></td>
</tr>
<tr>
<td>3  Beery Adams, SAHRA</td>
<td></td>
</tr>
<tr>
<td>4  Rechel Bartholomew, SAHRA</td>
<td></td>
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<tr>
<td>5  Brad James, SAHRA</td>
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</tbody>
</table>
SAHRA has developed a number of comprehensive searchable databases of useful information for water managers, educators, and the general public. These include:

**News Watch Service**
This Web site allows users to search for news items on water issues in semi-arid and arid areas by topic, date, and geographic area. Items are culled from over 100 Web sites, as well as press releases and reports being solicited from major water policy and research organizations. The items are summarized in English from their original languages (English, French, Spanish, Italian, Greek, Farsi). The Web site highlights major breaking stories and offers shortcuts to the most recent stories in several topic areas.

**Conservation Information**
A Web site aimed at both homeowners and water conservation professionals is now on SAHRA’s Web site. Content will continue to be added over time. The design of this Web resource reflects SAHRA’s philosophy that material targeting the general public must not only be useful and easy to use, but attractive and entertaining.

**K-12 Curriculum Clearinghouse**
A searchable database on hundreds of K-12 water-related curriculum materials was created during the summer of 2001. The user interface allows users to search for materials based on subject, media type, grade level, cost, and other factors. Intended for use by schoolteachers, the database also is being used to determine where SAHRA should focus new curriculum development efforts. In September 2001, Jim Washburne attended a national conference on the NSF-funded Digital Library of Earth Science Education (DLESE). Because of the substantial overlap between SAHRA’s and DLESE’s database structure, the decision was made to modify SAHRA’s structure to conform to DLESE. This work is currently underway. Currently, the Grades 9-12 portions of the database are being enhanced and utilized to guide development of curriculum modules for a high school science course in semi-arid water resources.

**River Basin Bibliographies**
A bibliography of hydrologic reports, articles, maps, data sets, etc. for the Rio Grande has been recognized as an important resource for SAHRA researchers. We have compiled ~1000 references and made this database available over the website. In May 2002, similar efforts were begun for the Upper San Pedro and Upper Verde river basins. These bibliographies will be available to the general public by Fall 2002.

**Digitizing Historic Reports and Other Publications**
An outgrowth of our Rio Grande bibliography effort was the recognition of many historic reports on the Rio Grande. These reports provide a wealth of information about the past conditions (hydrologic, geochemical, and socio-economic) within the basin. These reports are difficult to obtain but are potentially very useful to many SAHRA and non-SAHRA researchers. In order to make these reports publicly available we have begun to scan, convert to pdf and post them on our website. Our initial effort focused on a 1938 report on Regional Planning of the Upper Rio Grande by the National Resources Council. In addition to scanning the entire report and converting it to pdf files, the associated maps were scanned, digitized and reproduced as well. Also, a searchable database on the 500+ tables, charts, photos, and other figures was compiled. More recently, key documents from the Upper San Pedro and Verde river basins have been digitized for posting, along with water organization newsletters going back 20 years.

**Isotopes and Hydrology**
We have developed an isotope hydrology information resource on SAHRA’s website ([http://www.sahra.arizona.edu/programs/isotopes/](http://www.sahra.arizona.edu/programs/isotopes/)). This resource contains a clickable periodic table that links elements with isotopes useful in hydrology to web pages that provide basic information about that isotopic system as well as important hydrologic applications. For carbon it has information about $^{12}$C, $^{13}$C and $^{14}$C, how these isotopes are measured, how much it costs for an analysis, and details about the major applications of these isotopes in hydrology. The site also includes information on different
types of isotopes and methods of analysis. We hope that this background information will complement isotopic research within SAHRA. Much of the web page content was developed by students in Brenda Ekwarzel’s Isotope Hydrology class at the UA. This material was reviewed and edited by undergraduate physics major Jessica Ubry under the guidance of Research Associate James Hogan.

**Virtual Field Trips**
At the USGS, Tucson, Stan Leake and Chris Duffy have collaborated on developing “virtual field trips” in the southwest for scientific, stakeholder and public use. The website for the Rio Grande: [http://cataractis.cee.psu.edu/riogrande/](http://cataractis.cee.psu.edu/riogrande/), is a result of this effort.

SAHRA has been more closely monitoring traffic at its Web site to gauge the demand for various types of information, judge where marketing efforts need to be concentrated, determine how people come to the site, and provide similar types of useful feedback.

**Web Site Visitors: June 2001 - June 2002**

<table>
<thead>
<tr>
<th>Month</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visitors</td>
<td>3,500</td>
<td>4,000</td>
<td>4,500</td>
<td>5,000</td>
<td>5,500</td>
<td>6,000</td>
</tr>
</tbody>
</table>

**Browser Versions Used**

- Internet Explorer: v4 - 1%, v6 - 90%
- Netscape: v4 - 2%, v6 - 5%
- Other: 16%

<table>
<thead>
<tr>
<th>Knowledge Transfer Activity</th>
<th>Recruiting the Next Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Led by</strong></td>
<td>Gary Woodard, Jim Washburne, Julie Luft</td>
</tr>
<tr>
<td><strong>Participants</strong></td>
<td></td>
</tr>
<tr>
<td>Name and Organization</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Alison Charney, Melissa Tom, Jessica Guggi, Tucson H.S., now UA College of Engineering</td>
</tr>
<tr>
<td>2</td>
<td>Warren Grantham, Jessica Jensen, Mountain View H.S., now UA College of Engineering</td>
</tr>
<tr>
<td>3</td>
<td>Chelsi Remme, Pavla Senkyrikova, Grant Shreve, Jon Katz, Josh McCord, Amphi H.S., now UA</td>
</tr>
<tr>
<td>4</td>
<td>Sam Swift, Catalina Foothills H.S., now UA</td>
</tr>
</tbody>
</table>

Very few young people enter college planning on a career in some water resources field. Rather, hydrologists, watershed scientists and others generally come to the field indirectly, from such disciplines as geology or environmental science. A related phenomenon is the dearth of challenging earth sciences courses at the high school level, and little enthusiasm by high school science teachers for integrating water resources-related curriculum materials in their existing classes.

SAHRA has targeted high school teachers and promising science students in an effort to increase the potential number and quality of young people entering water resources fields. These efforts include development of a K-12 water curriculum clearinghouse (discussed elsewhere), maintaining a listserv for K-12 science teachers in Arizona that are interested in water-related topics, developing a high school
course on Water in Semi-arid Environments (see SPLASH, TA6), and selected knowledge transfer activities to high schools with diverse populations.

The most fully developed effort to date is the Summer Program for Learning About Semi-arid Hydrology (SPLASH). This program, now in its second summer, recruits outstanding high school seniors and juniors from high schools with diverse populations and exposes them to a summer of fieldwork, lab work, and knowledge transfer activities.

The result of this program was an understanding of how diverse and challenging the fields of hydrology and water resource management are, and an appreciation of how "real" scientific research is planned and conducted. A significant side benefit of the program was the significant amount of assistance provided by the summer interns to our researchers in the field and in the labs.

Nearly all the graduating high school seniors are now freshmen or sophomores in the University of Arizona’s College of Engineering and are working as REU students on specific research projects. Five of them are women and two are minorities.

2b. Outcomes or Impacts

SAHRA is now 30 months old, with many research activities beginning to show significant results. Impacts on water resource management are still probably premature. Much of the scientific knowledge that results from our research is reflected in new or improved models of portions of the hydrologic cycle; these in turn are now being integrated in basin-scale models and incorporated into social science and DSS work.

In the areas of Education and Knowledge Transfer, there are some signs that SAHRA is starting to have an impact. Whether these efforts are reproducible and sustainable has yet to be demonstrated.

We see a growing demand for our research, education and KT efforts. The Nature Conservancy has expressed a desire to base future land purchases on SAHRA-provided groundwater/surface water models that predict the degree to which river flows and riparian vegetation will be protected or restored by changes in water uses. The New Mexico State Engineer’s Office has asked that we enhance their URGWOM model through development of compatible dynamic simulation models that provide information on water quality variables, including salinity and dissolved oxygen. Water providers in the Sierra Vista area of the Upper San Pedro are interested in a DSM on selecting conservation opportunities.

Other areas where DSMs are being developed or planned are the Verde River in Arizona, the Conchos Basin in northern Mexico, and additional reaches of the Rio Grande in New Mexico and west Texas. These models not only integrate a variety of existing knowledge and new research findings, they also help to identify pieces of the hydrologic cycle or water budgets where future research is needed.

2c. Plans

We will build on the success to date in making SAHRA’s Web site an information clearinghouse for several types of information critical to water resources managers in arid and semi-arid areas. Our K-12 efforts will continue to focus on high school science teachers and their most promising students, using summer internships, and a high school water resources course aimed at priming the pipeline that produces the next generation of water resource managers.

We will continue to develop visually appealing and entertaining, as well as useful and informative, Web sites, displays and kiosks for the general public.
SAHRA will begin its Executive Training Program in Spring 2003 with a short course on Indian Water Rights.

We will continue to expand and leverage our new News Watch service. We hope to summarize Arabic stories, in addition to the current seven languages. We will offer an email-based subscription service to those News Watch stories that match one’s topical and geographical interests.

A newsletter will be published beginning in Fall 2002 on a schedule of three or four issues per year, and distributed to several hundred subscribers, including university water researchers, teachers involved in water-related projects, water resources managers, water policy experts, and other elected officials, including state legislators in Arizona and New Mexico. Each issue will highlight a topic of current interest, beginning with the ongoing drought and forest fires, and their relevance to and impact on SAHRA research in particular, and to water issues in general. The newsletter will be mailed and posted in pdf format on the Web site to widen readership, particularly in other countries.

We will fully utilize our new video conferencing capabilities at ASU, UNM and NMT. Software has been developed in-house to help use these facilities to improve communication among SAHRA researchers.
V. PARTNERSHIPS

1a. Partnership Objectives

Our partnership objectives remain essentially the same.

We endeavor to form lasting relationships with universities, government research labs and agencies, commercial labs and consulting firms, state and local agencies with water management responsibilities, as well as NGOs, Irrigation Districts, and educators to produce mutually beneficial interchanges of data, information, and human and capital resources to further our goal of improving the science of hydrology and water resources. This includes giving stakeholders a key role in defining the scenarios that drive our integrated research agenda. It also involves increased efforts at leveraging our resources through various creative arrangements with a variety of partners and cooperators.

1b. Performance and Management Indicators to Assess Progress

- List / Number of partners
- List / Description of projects undertaken with partners
- List of data, information, and human and capital resources interchanged with partners

1c. Problems

SAHRA continues to have numerous opportunities to partner with many diverse organizations. The challenge remains one of managing the rate of growth, and bringing new partners into SAHRA in a controlled way that leverages our resources, creates synergies for all concerned and contributes to integrating our activities.

2a. Partnership Activities

<table>
<thead>
<tr>
<th>Organization Name</th>
<th>Shared Resource</th>
<th>Involvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Atmospheric Sciences Research Center (ASRC)</td>
<td>Jungle Research Group</td>
<td>Over the years the JRG has been developing a comprehensive data acquisition and post processing routine for high-resolution data. They have allowed us access to their algorithms and we have customized it for our purposes. We have a collaborative agreement for ongoing development and refinement of the analytical techniques involved. Dr. David R. Fitzjarrald and Dr. Ricardo Sakai from JRG have provided valuable help in the data acquisition aspect of our project. The Jungle Research Group (JRG) at the Atmospheric Sciences Research Center (ASRC), University of New York at Albany studies the micrometeorology of vegetated surfaces. They measure the exchanges of radiation, heat, water vapor, momentum, and carbon dioxide between earth’s surface and the atmosphere, which typically involves placing sensitive instrumentation on a tower located in some remote place, and letting it run for a long period of time. Their research is therefore very similar to our subalpine project and lends itself to similar methodologies.</td>
</tr>
<tr>
<td>2 Arizona Hydrologic Society (AHS)</td>
<td></td>
<td>SAHRA works with AHS to facilitate school-scientist collaborations, mentoring and education, mostly during their annual meeting. AHS is the primary statewide organization for water professionals. They are also active in promoting educational knowledge transfer among their membership.</td>
</tr>
<tr>
<td>3 Arizona Project WET (Water Education for Teachers)</td>
<td></td>
<td>SAHRA jointly funds a WET support staff and shares a Maricopa Water Education Specialist through leveraged funds. WET and SAHRA collaborate on hydrologic literacy efforts. WET is strongest at the K-8 grade levels and SAHRA is concentrating on grades 9-12.</td>
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<tr>
<td>4 Arizona White River Apache Tribe</td>
<td></td>
<td>SAHRA funded 5 watershed workshop scholarships in 2001. A massive wildfire on the reservation in June 2002 caused this program to be temporarily suspended. Laurel Lacher, Tribal Hydrologist, has developed outside funding through EPA and other sources to coordinate and operate a two-week summer workshop for the professional development of tribal environmental specialists. A significant amount of this training is watershed-based.</td>
</tr>
<tr>
<td>5 Asociación Regional Ambiental de Sonora-Arizona/Sonora-Arizona</td>
<td></td>
<td>Linking ARASA scientific research needs with SAHRA and other researchers. Building the capacity of ARASA to answer ARASA is a binational organization focused on environmental issues in the Upper San Pedro River Basin. The group organized in response to concerns about local...</td>
</tr>
</tbody>
</table>
Regional Environmental Association (ARASA) | science questions, especially about basin hydrology and water resource management, through assisting in grant writing for operational expenses, management training, environmental conflict management and by promoting the collaboration of ARASA with other Mexican environmental NGOs. | water quality and delivery problems but extended its scope to other environmental issues. The group describes itself as "a non-governmental organization convened for the improvement, investment and conservation of the regional ecosystem though education, investment and scientific research."

6 Audubon Society’s Appleton Research Ranch | Providing indirect funding, in-kind support, data, and logistical support for logging water usage of some 60 "ranchettes" in the Sonora/Elgin area. Assisting with installation of meters & loggers; joint selection of study participants | The Audubon Society is interested in improving the understanding of domestic water demand for "ranchettes." This is the largest uncertainty in the water budget for the Sonora/Elgin basin in southern Arizona.

7 AzTEC - Arizona Teacher Education Coalition | Some teachers have received hydrologic literacy training and instructional material. | This program helps recruit talented teacher candidates into mathematics and science education, improves the quality of instruction for mathematics and science teachers during teacher preparation, improves the clinical experiences that exist for preservice mathematics and science teachers, develops effective induction programs for mathematics and science teachers, and participates in creating a clearinghouse of best practices. This is a state-wide program funded largely through the US Dept. of Education.

8 Bureau of Applied Anthropology (BARA) | Several BARA students are taking part in our undergraduate interns program and we have loaned water quality equipment to a Native American outreach program. | BARA coordinates several efforts aimed at studying regional communities. By leveraging some of these efforts with SAHRA, both groups are better able to serve their constituencies, particularly those along the U.S.-Mexico border.

9 Bureau of Reclamation, Lower Colorado Office | Funding development of hardware and software to use low-cost PDAs as high-resolution meter loggers for disaggregation of domestic water demand. Providing money for equipment, student wages, etc. | The Bureau of Reclamation’s conservation program supports efforts at improved understanding of factors of domestic water demand, and identifying the most effective and cost-effective water conservation targets.

10 CEA-CREST, Cal. State University, L.A. | We have purchased a low-level scintillation spectrometer with supplemental funds for joint use in this collaboration. Also use of stable and radiogenic isotope analytical facilities at Univ. of Arizona for sample from field area for the Hueco Bolson project on age and origin of groundwater supplying El Paso and Cd. Juarez. | Joint NSF GLUE-Grant to collaborate on Rio Grande groundwater modeling and Regional mesoscale land-atmosphere modeling. CEA-CREST promotes the development and testing of theories predicting natural and anthropogenic changes in ecosystems, with a particular emphasis on Southern California and the southwest U.S.

11 Central Arizona-Phoenix LTER | Contributes personnel (Lewis, Grimm). | The LTER is interested in working with SAHRA on educational efforts, understanding of hydrology in central AZ basins.

12 Cochise County | Cochise County is providing funding, data, and logistic support. | Cochise County is interested in determining the water use patterns of private well owners near the Upper San Pedro River. They are cooperating in high-resolution meter logging on 20 rural "ranchettes" along the Upper San Pedro River.

13 Collaborative for the Advancement of Teaching Technology and Science | We are funding two SPLASH CATTS fellows and two GLOBE CATTS fellows. | SAHRA is leveraging its support of local classroom teachers involved in the GLOBE and SPLASH projects through this NSF-funded, K-12 partnership program.

14 Columbia University, Biosphere 2 Center | Stable isotope laboratory and field equipment. B2C has also received scholarship grant funding that will make hydrologic literacy programs available to students in Pinal, Pima and Maricopa Counties that have large under-represented populations. | Dr Guanghui Lin and his staff (Postdoc - Joost vanHaren, Tech - Danielle Pierce) have been collaborating with TA3 in using stable isotopes to determine plant water sources and partitioning of carbon sinks and sources. Collaborative efforts also aim to improve the hydrologic literacy of visitors through collaborative efforts to develop display and tour materials that contrast the unique hydrologic aspects of Biosphere 2's and Southern Arizona's environment. Biosphere 2 is also involved with determining carbon fluxes and sources.

15 ECOSTART | SAHRA has provided travel money to Anne Browning-Aiken as she was organizing this network as well as funded teacher to participate in GLOBE training in Tucson. | ECOSTART is a binational exchange program that employs environmental education to build grassroots capacity in northern Mexican communities to address environmental problems. Water resources and hydrologic literacy is one issue SAHRA and ECOSTART have in
| **16** | **El Paso Water Utilities** | Well samples. **El Paso Water Utilities are coordinating well sampling in the Hueco Bolson.** |
| **17** | **Elephant Butte Irrigation District (EBID), Las Cruces, NM** | Use of SAHRA’s Farm Model will allow EBID to estimate supply and demand per farm and irrigation season and will help in operational decision making. **The Farm Module will be applied to the EBID from November 2002 (see TA4).** |
| **18** | **GEWEX-CEOP** | CEOP/Mt. Bigelow database **The Mt. Bigelow eddy correlation tower is a CEOP high-altitude semi-arid reference site. As such, SAHRA research around this site will benefit from the coordinated database that will be accumulated by CEOP over the next 2-year intensive observational period for this site.** |
| **19** | **GLOBE** | SAHRA sponsors schools in its field areas to get GLOBE training as part of an effort to set up collaborative regional environmental monitoring networks. **We promote authentic science and research through support and encouragement of GLOBE teachers and training in our area of interest.** |
| **20** | **IAEA - Isotope Hydrology Section** | SAHRA, through the Rio Grande solute balances project, is participating in this CRP. Data collection activities will be coordinated so that intercomparison of large river basins may be possible. **IAEA is initiating a coordinated research program (CRP) on “Design Criteria for a Network to Monitor Isotope Composition of Runoff in Large Rivers”** |
| **21** | **IBWC (International Boundary and Water Commission)** | Well samples. **IBWC / CILA has assisted in coordinating well sampling on the Mexican portion of the Hueco Bolson.** |
| **22** | **IMADES (Instituto del Medio Ambiente y el Desarrollo Sustenable)** | Eddy covariance instrumentation, scaffold tower. IMADES has been involved with intensive field measurement campaigns. **Dr. Watts has been collaborating with us, lending his expertise and field support for making eddy covariance measurements of understory evapotranspiration.** |
| **23** | **IMTA (Mexican Institute for Water Technology)** | Exchange of information, joint authorship of papers and presentations. Also a member of the scientific committee for the First International Symposium on Transboundary Water Management **Collaboration in the development of a drought preparedness plan for the Conchos River basin, Mexico.** |
| **24** | **ITSON (Instituto de Tecnologia de Sonora)** | Field equipment (eddy covariance system, meteorological instrumentation) **Dr. Garantuza collaborates in micrometeorological research (TA3 mesquite study) through his participation in understory flux measurement campaigns.** |
| **25** | **NAU/ITEP/EEOP** | SAHRA is one of several sources that helps to support a wide range of activities that are offered and also provides the program coordinator, Mansel Nelson, with travel support for school follow-up visits. **Trains, supports and mentors Native American teachers in the Four Corners region. Training has been through GLOBE and Project WET.** |
| **26** | **NM Master of Science Teaching Program** | SAHRA runs a two-week workshop for teachers on hydrologic literacy and teaching science. The program was cancelled this summer due to under-enrollment caused by a conflicting course. **This is one of the most active teacher professional development programs in New Mexico, particularly for science teachers.** |
| **27** | **NM State Engineer Office** | Data related to Rio Grande Basin watershed management. This office operates the URGWOM model **Stakeholders interacting with the Rio Grande River Basin science team and providing guidance on water resource management issues for the Rio Grande Basin.** |
| **28** | **NOAA/ATDD** | Instruments, technical advice. **NOAA/TDD provides all of our soil temperature probes.** |
| **29** | **New Mexico Interstate Stream Commission** | We are currently working with both these groups on a limited basis. Mainly we are sharing some data and samples. We have analyzed several well samples collected through these projects to quantify our saline groundwater end member. NM-ISC is considering providing funds to extend our current research activities to tie more closely with these existing efforts. **The New Mexico Interstate Stream Commission is charged with managing New Mexico’s water resources. The NM-ISC has recently funded two projects that are closely tied to the Rio Grande salinity study. One project (led by Rob Bowman at NMT) is studying water resources in the Socorro basin, the other project (run out of the NM-WRRI) is examining salinity in the Mesilla Basin in southern New Mexico.** |
| **30** | **New Mexico Tech** | Socorro, NM Cooperative Trench Study – Soil samples were collected from four vertical sections, two beneath established vegetation and two lacking surface vegetation. 32Si interpretations will benefit from the extensive data (e.g. total Cl, root density, soil properties) collected by New Mexico Tech researchers. **We are sharing data to take a closer look at the surface regime where detailed investigations of vegetation impact on recharge can be investigated.** |
| 31 | Pima Association of Governments (PAG) | SAHRA attends special water education meetings of the water quality committee to promote Center activities. | PAG holds regular meetings of area professionals interested in water quality issues. |
| 32 | Prop. 301 Water Centers: Engineering Research Center for the Environmentally Benign Semiconductor Manufacturing (ERC-EBSM), the Water Resources Research Center, and the Water Quality Center | Joint activities include sharing staff, establishing rural water resource centers and planning policy maker briefings. | A consortium of 4 UA water centers, including SAHRA, receiving State of Arizona Prop. 301 funds and jointly pursuing an education/knowledge transfer program. |
| 33 | Sandia National Lab | Sandia is funding a 2.5-year PhD fellowship in conjunction with SAHRA that includes summer internships. SAHRA and Sandia are jointly sponsoring a DSM workshop, and cooperating in other attempts to broaden the use of DSM in water resource management. | Sandia and SAHRA are interested in using DSM to develop integrating models of water supply and demand in the Middle Rio Grande. Both organizations also share the desire to develop the use of DSM in managing water resources and education. |
| 34 | Science and Math Education Center (SAMEC) | We are exploring ways to collaboratively manage some workshops and working together for greater campus and regional visibility. | SAMEC operates a popular newsletter and listserv that are invaluable for contacting active science teachers. SAHRA is better able to work with the larger UA outreach community through its participation with SAMEC. |
| 35 | Science Teachers and Reformed Teaching (START) | Several SPLASH teachers are participating in this program (Uyeda & Fletcher). | START builds leadership capacity in Southern Arizona among secondary science teachers through one-week summer workshops on inquiry and then follow-up meetings for classroom support. Primary funding is through an Eisenhower grant. |
| 36 | Scripps Institution of Oceanography, UCSD | SAHRA provides the major funding for our postdoctoral hydroclimatologist, which thus focuses his work on the US southwest. In addition, Scripps has requested another ECPC postdoc to provide relevant information from various global change experiments that may be pertinent to the SAHRA project. | All of the SAHRA activities are developed in collaboration with the Scripps Experimental Climate Prediction Center, which is an Applied Research Center funded mainly by NOAA Office of Global Programs. A goal of the Scripps ECPC is to develop an integrated global to regional climate seasonal prediction system that can be utilized by regional application centers. As part of this effort, we are developing a daily to seasonal atmospheric and macroscale hydrologic prediction system for the Southwest. We are also developing global change experiments that will eventually be used to drive macroscale hydrologic models for the Southwest. |
| 37 | Sevilleta Long Term Ecological Research (LTER) Site | The Sevilleta LTER has contributed salary (Ph, graduate student, and technicians), supplemental equipment funding, and field crew time. | Rainfall manipulation plots at the Sevilleta Wildlife Refuge are a key element of the current Sevilleta research program. |
| 38 | Tucson Unified School District | Several SAHRA faculty have taken part in TUSD-sponsored inquiry institutes. Discussions on additional leveraging and collaboration are underway. | Gail heads TUSD's urban systemic initiative call the DESSERT project. Rachel is DESSERT's university facilitator. We work together to promote school-science collaborations between the district and SAHRA. |
| 39 | UA Cooperative Extension | Establishing rural water resource centers; developing searchable databases on research in the Upper San Pedro, Verde basins; developing conservation content for Web site. | Working together on various education and knowledge transfer projects in rural Arizona. |
| 40 | UA Dept. of Hydrology & Water Resources | Summer field camp opportunities. | Among other things, SAHRA has requested that K-12 teachers be allowed to participate in departmental field camps. Dennis Scheals is the field camp supervisor. |
| 41 | UA Flandrau Science Center | This collaboration is currently under development. | Flandrau is currently expanding its programs for students and the public and has expressed interest in collaborative program development with SAHRA. |
| 42 | UA Institute for the Study of Planet Earth (ISPE) | Academic and government research ties and media contacts. | Joint press briefings in Tucson and Phoenix tying hydrologic and climatologic research to current weather and water issues. |
| 43 | US Army Corps of Engineers | Jointly developing water resources planning version of MEng degree, including seminar course. | Developing version of MEng degree for outstanding mid-career Corps staff as part of professional development activities. |
| 45 | US Army, Ft. Huachuca | Providing meteorological measurement | Ft. Huachuca is a member aenenv of the Upper San Pedro
<table>
<thead>
<tr>
<th><strong>46 USDA-ARS, Southwest Watershed Research Center</strong></th>
<th>Support at three remote sites along the San Pedro River Partnership and is a primary supporter of the San Pedro National Riparian Conservation Area Water Needs research being conducted in collaboration with SAHRA.</th>
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<tr>
<td><strong>47 USDA-ARS, US Salinity Laboratory (USSL)</strong></td>
<td>A variety of SWRC resources are being utilized to enhance the collaborative SAHRA research effort. The SWRC operated Walnut Gulch Experimental Watershed (WG EW), a key shared facility for SAHRA. This experimental watershed is arguably the most densely instrumented semi-arid watershed in the world and is an important outdoor laboratory for SAHRA research. Research knowledge, observation, and understanding from the WG EW are being used in a variety of SAHRA activities, ranging from rainfall characterization, infiltration, ephemeral channel recharge, to erosion. SWRC instrumentation (rain gauges), facilities (shops, labs, housing for visiting scientists, and students), and vehicles are utilized by SAHRA collaborators. The USDA-ARS-SWRC is a major partner in SAHRA on many fronts. It has been conducting research on semi-arid hydrologic and watershed processes in the Southwest for nearly 50 years. The mission of the SWRC is very comparable to the mission SAHRA, and the SWRC has operated the Walnut Gulch Experimental Watershed (WG EW) for nearly as long. The WG EW is a key “shared facility” utilized by SAHRA to enhance and further its research capabilities.</td>
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<tr>
<td><strong>48 US Forest Service</strong></td>
<td>Jointly developing display, kiosk and Web site. SAHRA and the Forest Service are working with USGS to improve the public’s understanding of the hydrology of Sabino Creek.</td>
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<tr>
<td><strong>49 US Geological Survey (USGS)</strong></td>
<td>They have provided us with the equipment used to taking soil core samples. The soil core samples were sent to the USSL for analysis, to provide us with the soil hydraulic properties of our sites. The soil hydraulic properties from our site will also be used by USSL research group for expansion of their database for semi-arid pedotransfer functions. The USSL has analytical facilities that are equipped for rapid organic and inorganic analysis of soil, water, and plant samples. The USSL provides critical expertise and knowledge on infiltration theory and capabilities for automated soil hydraulic analysis. Their research focus is to develop pedo-topo-vegetation transfer functions to estimate soil hydraulic properties at different spatial scales.</td>
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<tr>
<td><strong>50 USGS - Albuquerque Basin Study</strong></td>
<td>We have collaborated with the USGS to analyze some of their samples to constrain the &quot;saline groundwater&quot; end member for our river salinity project. The USGS has undertaken extensive sampling of groundwater wells in the Albuquerque basin.</td>
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<tr>
<td><strong>51 USGS - NASQAN Program</strong></td>
<td>For the IAEA River Basin study, we are joining our isotopic data sets to provide full coverage of the Rio Grande basin. NASQAN Program monitors water quality in the lower Rio Grande (El Paso and below). Their work complements SAHRA research activities. We are exploring the possibility of producing a joint paper on water quality in the Rio Grande, covering the full basin. We are also exploring the possibility of undertaking a joint effort to examine issues of water quality on the Rio Conchos.</td>
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<tr>
<td><strong>52 USGS, Tucson Office</strong></td>
<td>Jointly developing displays, kiosks and Web site and enhancing gauges for Sabino Canyon. SAHRA and the USGS are working with the Forest Service to improve the public’s understanding of the hydrology of Sabino Creek.</td>
</tr>
<tr>
<td><strong>53 Universidad de Sonora - Hermosillo (UniSON)</strong></td>
<td>Administrative support (computers, etc.) With sabbatical support from SAHRA, Dr. Castellanos has been working with Dr. Williams’ group on using stable isotopes to determine plant water sources.</td>
</tr>
<tr>
<td><strong>54 Upper San Pedro Partnership</strong></td>
<td>The Partnership sponsors funding for postdoc and lab techs for TA3 along with Community watershed organization consisting of 20 federal, state and municipal agency representatives.</td>
</tr>
<tr>
<td><strong>55</strong> Upper San Pedro Partnership</td>
<td>Partnership sponsors funding for post-doc and lab tech for TA3 along with some funding for equipment needs</td>
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<tr>
<td><strong>56</strong> Water Educator's Roundtable</td>
<td>SAHRA maintains the group's listserv and has offered to spearhead other leadership and data collection activities.</td>
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<tr>
<td><strong>57</strong> Yavapai County Water Advisory Committee (WAC)</td>
<td>Development of a modflow model with the Prescott Active Management Area (key stakeholder in the Yavapai County WAC) and facilitation of the Yavapai County WAC adaptive management retreat to assess the council's effectiveness in addressing water management problems.</td>
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**2b. Plans for the Next Reporting Period**

Whether measured in terms of participants, partnerships, or projects, SAHRA has become a large, complex organization. We do not plan to actively seek out new partnerships over the next year, although we will consider all partnership activities that come along. Our efforts will be focused instead on developing and deepening existing partnership relations. By becoming more familiar with the goals, interests and resources of our various partners, we are able to find synergistic opportunities, such as the current collaboration among the US Forest Service, US Geological Survey, and SAHRA in developing Sabino Canyon knowledge transfer displays and Web content. The one area where SAHRA will seek out new partnerships is International Activities, particularly in areas beyond Mexico.
VI. DIVERSITY

Many of SAHRA’s objectives are aimed at improving the current state of water management and operations throughout our areas of interest, which are focused on the Southwest U.S. and Mexico. Our efforts are aimed not just on improving the state of the science but on the practice of science as well. Thus, a key group of stakeholders are water managers and officials responsible for water operations or policies. While no firm statistics are available, we believe that the key diversity needs in these positions will most likely be filled by women, Hispanics and Native Americans.

Objectives

SAHRA’s primary diversity objective is to improve the hydrologic literacy and technical ability of tribal members and their water management agencies. This is because of the importance of developing tribal sovereignty and control over many critical water supply and water quality issues that confront the tribes throughout the southwest. Our strategy is to focus on career pathway development from the K-12 level to the University system through teacher workshops, summer programs, undergraduate internships, support networks and graduate study.

Similar programs are in place in the area around our centers of research for local high school students, which have the potential to recruit into our program the predominately Hispanic student population that characterizes these schools. Most of our teacher training programs are too new to provide specific classroom diversity/impact statistics. We will assess the diversity and impact of these programs starting this Fall.

Many women find advanced studies in hydrology to be particularly rewarding because of their interest in the environment, analytical analysis, and the flexibility of many employers. Recent departmental and SAHRA statistics reveal a significant number of women are naturally attracted to this field (35% and 37%, respectively). We will monitor this participation rate and try to increase SAHRA’s percentage of women graduates.

A third and newest diversity initiative is related to a collaborative GLUE supplementary grant between SAHRA and CEA-CREST. Our partnering institution is the California State University – LA. We expect this collaborative effort will give our projects greater visibility and enhance the recruiting potential from this diverse and similarly focused state college.

Performance and Management Indicators to Assess Progress

All of our programs will attempt to gauge the level of participation from under-represented communities. Many of our educational efforts are focused on particular interest groups or have a high potential to benefit the diversity targets identified above. Every effort will be made to encourage the recruitment of a diverse student and intern population from each partner.

Specific indicators include:
- List / Number of individuals and groups participating in SAHRA’s activities identifying sex and ethnicity
- List / Number of members of SAHRA identifying sex and ethnicity
- Description of SAHRA’s efforts to involve diverse individuals and groups

Problems

Native American students have many demands placed on them and face significant social, family and cultural barriers to completing a formal graduate degree in a natural science, such as hydrology. While we do not have any simple solutions to these well-documented issues, we plan to work closely with the small number of students we have to provide the support and encouragement to continue in this field.
Accomplishments

The following table summarizes the diversity of SAHRA participants. The “Non-faculty” category is made up of research scientists and other professionals. The “Other” category is made up of visiting faculty, pre-college students and otherwise classified participants.

<table>
<thead>
<tr>
<th>Table: SAHRA 2002 Diversity Statistics</th>
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<tr>
<td>Gender</td>
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<tr>
<td>Faculty</td>
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<td>Non-Faculty</td>
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<td>Staff</td>
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<td>Postdocs</td>
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<td>Graduates</td>
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<td>Teachers</td>
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<td>Others</td>
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<td>Total</td>
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Participant Highlights

SAHRA’s total participants grew from 193 last year to 222 this year, an increase of 13%. A majority of our non-faculty participants are female (87%) and a majority of our undergraduates are female (68%). More than a third of our postdocs and graduate students are female. A slightly larger percentage of our participants classify themselves as "white" this year (79%). The largest ethnic group we have is Asian (12%) followed by Hispanics (7%), which is almost exactly where those two groups ranked last year. Asians make up 17% of the graduate student population, due to many students from the Middle East and China that find our program valuable. Our citizenship statistics are very comparable to last year’s numbers, with 76% of our participants being US citizens.

Plans

Our plans for the next year are to better assess how the array of programs described above are functioning and work on developing better contacts, particularly at the community and junior college level.

Impact

The impact of these programs or activities on enhancing diversity continues to grow. K-12 classroom impacts will begin to be significant this year, as will opportunities for professional development. We are already making a positive impact on females in the field of hydrology.
VII. MANAGEMENT

1a. Organizational Strategy & Structure

There have been no major changes in the Center organization during the past year. The Executive Committee (EC), consisting of 13 members (see below), conducts the overall planning of SAHRA. The EC is responsible for setting the vision and goals of SAHRA and for overseeing planning and coordination of the science, education and knowledge transfer activities. The executive committee meets once a month by phone conference, with every third meeting held in-person at the University of Arizona. Decision making is by consensus with ultimate authority and responsibility carried by the Director and Deputy Director. Coordination and integration within and across the Thrust Area science activities is carried out by the TA leaders mentioned above with the major assistance of the TA postdoctoral research associates (PDRAs). The group of PDRAs constitutes a “shadow” executive committee, which is extremely important to achieving the goals of planning, critical self-review, cross-disciplinary integration, and coordination with other non-SAHRA funded projects and activities. Each week, the postdoctoral research associates meet as a group with Bales, Gupta, and other senior researchers to discuss various ongoing science activities. Major ideas and initiatives that emerge are presented before the EC for discussion and approval.

External advice and oversight is provided by the (currently) seven-member External Advisory Board (EAB). The EAB meets at least once per year to provide feedback to the executive committee; this year’s written comments are in the Appendices. One EAB member (Peggy Woods) resigned in February 2002. Administrative affairs are managed primarily by the Associate Director, with assistance from the two Assistant Directors and the (currently) 10-person administrative support staff, who meet weekly to ensure communication and coordination of activities. The relevant TA leader and postdoctoral research associate coordinate the individual TA activities via email and periodic TA meetings. Several SAHRA-wide workshops and meetings are held each year to bring researchers together across disciplines. Finally, all SAHRA scientists, students and stakeholders gather each spring at the annual meeting in Tucson to meet, share and discuss scientific results, and conduct center-wide discussion and planning.

Executive Committee:
Soroosh Sorooshian (UA, Director), Roger Bales (UA, Deputy Director, Leader TA1), Hoshin Gupta (UA, Associate Director, Science and Administration), Gary Woodard (UA, Assistant Director, Knowledge Transfer and Outreach), James Washburne (UA, Assistant Director, Education), Fred Phillips (NMT, Leader TA2), David Goodrich (USDA-ARS/UA, Leader TA3), Larry Winter (LANL, Leader TA4), Juan Valdés (UA, Co-leader TA5), David Brookshire (UNM, Co-leader TA5), Julie Luft (UA, Leader TA6/Education), Diana Liverman (UA, International Cooperation), and Stan Leake (USGS).

Post-Doctoral Research Associates:
Constance Brown (TA1), James Hogan (TA2), John Villinski (TA3), Luis Bastidas (TA4), Anne Browning-Aiken (TA5), Elizabeth Hancock (TA6/education). Coordination and integration assistance is provided by postdoctoral researcher Martha Whitaker.

External Advisory Board (see also section 3 below):
Kenneth Schmidt (Kenneth D. Schmidt and Associates, EAB Chair), Susan Avery (CIRES), John Bernal (Pima County Public Works Dept.), Peter Eagleson (Massachusetts Institute of Technology), Charles Howe (University of Colorado), Devendra Lal (Scripps Institute of Oceanography), and Harold Mooney (Stanford University). Peggy Woods (Head of the Science Department at Amphitheater High School) resigned February 2002 due to over-commitment.

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 (editor, part time), and two work-study student
helpers. Additional administrative support is provided by Corrie Thies (administrative associate to Sorooshian), and Cas Sprout (administrative assistant to Bales).

<table>
<thead>
<tr>
<th>Goals of SAHRA Management</th>
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<tr>
<td>Develop and implement a strategic plan to carry out the mission of the Center</td>
<td>a. Establish an executive committee</td>
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<td>b. Develop and periodically update a strategic plan</td>
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<td></td>
<td>c. Establish an external advisory board (EAB)</td>
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<td>d. Integrate recommendations from EAB, SAHRA science teams, and SAHRA stakeholders into the plan</td>
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<td>e. Integrate NSF oversight team recommendations into the plan</td>
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<td>f. Design and implement a mechanism for project selection and performance evaluation</td>
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<td>g. Design and implement a mechanism for integration of projects across disciplines and institutions</td>
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<td>h. Organize and conduct a Center-wide annual meeting</td>
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<tr>
<td>Support and facilitate SAHRA research, education, and knowledge transfer activities.</td>
<td>a. Acquire, manage and maintain infrastructure (space, furnishings, computer systems, communication network, supplies, laboratories and field sites)</td>
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<td>b. Recruit and maintain scientific, technical, and administrative staff</td>
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<td>c. Create and maintain a physical and psychological organizational environment that is exciting and rewarding for Center staff so that organizational stability is maintained and staff turnover is minimized</td>
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<td>d. Manage finances (budgeting, accounting, disbursement)</td>
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<td>e. Support preparation of grant proposals to NSF and other funding sources</td>
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<td></td>
<td>f. Manage communication</td>
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<td>g. Manage information (collecting, organizing, disseminating)</td>
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<td>h. Coordinate activities (meetings, workshops, report preparation, project reviews)</td>
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<td></td>
<td>i. Coordinate and prepare documentation</td>
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<td>j. Recruit and support students towards achieving their educational and professional goals</td>
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<tr>
<td>Meet the contractual obligations to NSF</td>
<td>a. Coordinate and prepare reports (work plan, annual reports, continuation proposal) and respond to requests for information</td>
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<td>b. Coordinate and conduct site visits</td>
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<td>c. Develop and maintain database</td>
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<tr>
<td>Promote the activities of the Center at the local, regional, national, and international levels</td>
<td>a. Develop and maintain a Web site</td>
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<td>b. Feed information to the public, professionals, and the media</td>
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<td>c. Represent the Center through participation (including presentations) at conferences, meetings, and visits to other organizations/institutions</td>
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<td>d. Participate in key committees and research initiatives</td>
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Work toward post-NSF sustainability

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<tbody>
<tr>
<td>a. Support preparation of grant proposals to non-NSF funding sources</td>
<td>b. Seek and nurture cooperative/collaborative relationships with other organizations and individuals</td>
</tr>
<tr>
<td>c. Develop, maintain and leverage infrastructure (field sites, laboratories, equipment, etc.) that are valuable resources for the water resources community at large</td>
<td>d. Create and maintain a physical and psychological organizational environment that is exciting and rewarding for Center participants and which promotes creativity, growth and long-term involvement</td>
</tr>
<tr>
<td>e. Create and maintain an organization that is externally considered to be valuable to the water resources community and therefore worthy of continued existence</td>
<td></td>
</tr>
</tbody>
</table>

1b. Performance and Management Indicators

The goals of management are to:

a) Develop and implement a strategic plan to carry out the mission of the Center
b) Support and facilitate SAHRA research, education, and knowledge transfer activities.
c) Meet the contractual obligations to NSF
d) Promote the activities of the Center at the local, regional, national, and international levels
e) Work towards post-NSF sustainability

The following indicators can be used to measure the performance of management in achieving the goals listed above:

a) Performance indicators related to strategic planning (descriptive)
   Performance related to strategic planning is measured by the success of management in creating an organizational structure that enables and facilitates the Center to carry out its mission. In this regard, we believe SAHRA management to have been quite successful. An executive committee of 13 members meets monthly to engage in strategic planning. An external advisory board and an NSF oversight team review Center activities and provide feedback, and SAHRA integrated-science teams design and coordinate research activities. A science integration committee reviewed the structure of Center research and proposed significant revisions aimed at enhancing integration and collaboration. A project review process is being implemented to fine-tune the directions of SAHRA science. A basin-centric strategy is being implemented to enhance and ensure science integration across disciplines and institutions. A Center-wide meeting and numerous integrative workshops are held every year to ensure communication and sharing of information.

b) Performance indicators related to support for research, education, and knowledge transfer activities.
   - List / Descriptions of Center infrastructure (space, furnishings, computer systems, communication network, supplies, laboratories and field sites)
   - List of scientific, technical, and administrative staff
   - Statistics regarding staff turnover
   - Description of structures developed and used to facilitate management of finances (budgeting, accounting, disbursement)
   - Number / List of grant proposals submitted to NSF and other funding sources
   - Description of structures developed and implemented to facilitate communication
   - Description of structures developed and implemented to manage information (collecting, organizing, disseminating)
• Description of structures developed and implemented to coordinate activities (meetings, workshops, report preparation, project reviews)
• Description of structures developed and implemented to coordinate and prepare documentation
• Description of structures developed and implemented to recruit and support students towards achieving their educational and professional goals

c) Performance indicators related to meeting contractual obligations to NSF
Performance related to meeting contractual obligations is measured by the success of management in developing and maintaining a Center database, submitting complete and timely reports (work plan, annual reports, continuation proposal), responding to requests for information, and conducting satisfactory annual site visits. In this regard, we believe SAHRA management to have been quite successful.

d) Performance indicators related to promotion of Center activities
• List of statistics that monitor Web site access and usage
• List / Summaries of information provided to the public- and to the media
• List / Summaries of participation by Center representatives in conferences, meetings, and visits to other organizations/institutions
• List / Summaries of participation by Center representatives on key committees and research initiatives

e) Performance indicators related to achieving post-NSF sustainability
• List / Summaries of grant proposals to non-NSF funding sources
• List / Descriptions of successful/unsuccessful efforts to seek out and nurture cooperative/collaborative relationships with other organizations and individuals
• List / Descriptions of access to and usage of SAHRA infrastructure (field sites, laboratories, equipment, etc.) by non-SAHRA members of water resources community
• Descriptions of efforts (including testimonials) to create and maintain a physical and psychological organizational environment that is exciting and rewarding for Center participants and which promotes creativity, growth and long-term involvement
• Descriptions of efforts (including testimonials) to create and maintain an organization that is externally considered to be valuable to the water resources community and therefore worthy of continued existence

1c. Organizational & Management Problems

We have experienced three major organizational/management challenges during the first two years of existence of the Center. These problems, and the steps we have taken to address them, are discussed below.

A) NSF Scheduling Interferes with Scientific Schedules

In the second Annual Report we mentioned that an inordinate amount of the SAHRA management and administrative team’s time has been devoted to responding to NSF’s requests for reports and information, and that this poses a major challenge to actually getting some real science done, as well as seriously impacting morale. Unfortunately, the situation has not improved during the third reporting period. This year we were directed by NSF to advance the submission date of our Annual Report from October 1 to July 1, to advance the NSF-oversight team site visit to August, and to prepare a year 6-10 renewal proposal for submission by February 2003 (this is only the end of the third year!). The revised reporting date put us in the undesirable position of demanding project reports from SAHRA scientists right in the middle of our major fieldwork season – a major example of poorly planned reporting requirements interfering with the science. Further we are being forced to think about year 6-10 science when our existing science activities are only just beginning to bear real fruit – precisely the time when SAHRA
researchers need to be left alone to make scientific progress, which will ultimately lead to more clarity about the next scientific steps to be taken.

[Recommendation to NSF: Involve the Center Management Team in the scheduling of reports to NSF. In particular, requests for information should be scheduled so that they do not interfere with (or take precedence over) the primary mission of the Center, which is production of science].

B) Financial Management & Budgeting

Poor compatibility between the financial reporting structure provided by the University and that required to properly manage the Center continues to be a problem, but we have learned to work with it. Budgeting complications are now caused mainly by expanding science interests and by increasing salary rates that could not have been properly anticipated during writing of the proposal. We continue to explore additional sources of funding, including proposal writing and funding from the state of Arizona.

The original proposal for the Center requested and was awarded only approximately $16M of the maximum possible $20M that could have been requested. The proposed budget did not include sufficient funds to account for inflation in salaries and other costs, and for certain critical activities such as the development of teleconferencing facilities and development of the knowledge base. SAHRA includes a much larger number of partner institutions than most other STC’s and therefore has greater travel and communication overhead. Further, the science ambitions of SAHRA researchers have expanded considerably as the Center has become established, and as the magnitude of the sustainability problem in semi-arid regions has become better understood.

In response, SAHRA has sought out additional funding to help support these needs.

• Supplemental awards were solicited and obtained from NSF in three areas: REU (Research experiences for undergraduates (onetime $57,500); graduate student support (onetime $319,274); and Center-wide teleconferencing facilities (onetime $32,000).

• An NSF-initiated “glue grant” with Cal State-LA’s Center for Environmental Analysis to develop joint research activities ($517K over 3 years) began Oct 1, 2001 and is in its first year.

• A partnership with Sandia National Labs to jointly develop a dynamic simulation model of the Middle Rio Grande ($90K over 2.5 years) began June 20, 2001 and is in its second year.

• The State of Arizona Board of Regents has made a commitment to provide SAHRA with Arizona Proposition 301 Initiative funds, for development of behavioral water science, education and knowledge transfer activities, beginning July 1, 2001. The second year award of $178,000 was received July 1, 2002. Commitments in future years are expected to increase substantially.

• The Nature Conservancy awarded SAHRA researchers Tom Maddock and Hoshin Gupta a grant to develop an “alternative futures” groundwater-surface water model of the Middle San Pedro River. The grant ($20K over 2 years) began March 14, 2001, and is in its second year.

• The Bureau of Reclamation, Audubon Society and Cochise County awarded SAHRA researcher Gary Woodard grants for analysis of domestic water demand. The grants (total of $55K over 2 years) began Sept 28, 2001 and are in their first year.

• The New Mexico Interstream Commission awarded SAHRA researcher Rob Bowman (NMT) a grant for “Evaluation of Groundwater/Surface Water Interactions in the Middle Rio Grande” for $224,000, 2 Years duration, Starting May 25, 2001.

• The Borders Partners in Action (PACT)/CONAHEC awarded SAHRA researcher Anne Browning a grant for an “Ecostart Bi-National Environmental Education Program,” for $12,000, one year duration, beginning August 2001.

• An Eisenhower grant to support a Student-centric Program for Learning About Semi-arid Hydrology (SPLASH) targeted at high-school students was awarded May 6, 2002, by the State of Arizona Board of Regents (onetime $50,000). Selected high-school teachers are developing curriculum modules for an interdisciplinary science course in water resources.

• An NSF GK-12 fellowship for the SPLASH program (see above) was awarded (onetime $9,000).

• Two CATTS fellowship for the SPLASH program (see above) were awarded (onetime $18,000 for a graduate fellow and $9,000 for an undergraduate fellow).
• A subcontract was awarded June 2002, by Soundprint, as part of a grant from NSF for production of a science radio series on “What If? Predicting, Modeling and Forecasting” (onetime $10,000).
• SAHRA is collaborating with and receiving in-kind support from the US Forest Service and USGS to develop a visitor center display and electronic kiosk to educate the public on “sky-island climatology and desert stream hydrology” (onetime approx. $20,000, beginning Feb 2002).
• A proposal to support research into the non-market economic value of migratory flyways in the San Pedro and Rio Grande basins is under development.
• The Bureau of Reclamation (via Yuma Cooperative extension) provided funds for the development of the “Conservation” portion of the SAHRA website (onetime $4,000).
• A proposal to the NSF ITR Large Grants Program to support research to extend and develop Virtual Watershed Laboratory concept was submitted Nov 9, 2001, but not funded ($12,256,908 over 5 years).
• Proposals on “Modeling Disaggregated Residential Water Demand Using Innovative Technology” were submitted to the Turner Foundation and NSF by SAHRA researchers Brookshire and Cermak, but were not funded.
• A proposal on “Improving methods for Calibration of Advanced Hydrologic Models: Multi-Criteria Approach to Sensitivity Analysis, Parameter Estimation and Performance Evaluation” was submitted to the NSF Division of Earth Sciences, Hydrologic Sciences, by SAHRA researchers Hoshin Gupta, Luis Bastidas and Soroosh Sorooshian, but was not funded.

Other leveraging possibilities are also being actively explored. These additional funding sources will facilitate a more comprehensive implementation of the mission of SAHRA, while spawning offshoots to the primary research initiatives. However, as noted above, several investigators have experienced problems with obtaining funding for proposals and are concerned that this may somehow be related to their close association with the NSF STC.

C) Over-commitment and Scheduling

As reported last year, key Center personnel, namely the members of the executive committee, continue to be over-committed, making it difficult to achieve rapid progress in the direction of scientific integration, mainly because it is difficult to get all the key people to a meeting at the same time. To some extent, the availability of remote conferencing facilities, and the ability to have PDRAs represent (and coordinate with) members of the executive committee is helpful, but it seems to be a fact of STC life that progress can be slow when doing truly multi-disciplinary, multi-institution work.

As far as the next reporting period is concerned, we do not anticipate any major management problems. As mentioned earlier, the main challenges will be to a) establish the knowledge base as a strong foundation linking the research, education and knowledge transfer efforts, b) continue implementation of the scenario model and the integration framework, using this process to bring about even greater cohesion and direction within SAHRA’s activities, c) complete the process of project review to phase out some activities and bring in new ones, d) prepare and submit our second phase renewal proposal, and e) allow the scientists to get some work done.

2. Management and Communication Systems to Bring About Integration

During the first reporting period, efforts to bring about integration were handled mainly by the Executive Committee and the central administrative staff. Integration of SAHRA physical science activities was already quite good, due in part to the “ground up” consensus-based proposal preparation process, and also that the majority of SAHRA scientists had already worked together in inter-disciplinary fashion on issues related to the San Pedro basin under the NASA EOS and SALSA projects. The process was strengthened by recruiting a group of young and energetic postdoctoral research associates to assist the Executive Committee in management and coordination. These PDRAs were placed together in a specially designed office suite to facilitate close working relationships and coordination of activities.
During the second reporting period, more formal procedures to foster integration were implemented, based on feedback provided by the EAB and NSF oversight team. Special attention was devoted to aspects of integrated modeling (TA4), and integration of the physical and behavioral sciences (TA5). A special Committee on Integration, led by the Associate Director, Hoshin Gupta, and consisting of the five thrust area PDRAs, selected members of the EC, and postdoctoral research associate Martha Whitaker (committee coordinator and secretary), reviewed the overall structure of science activities and recommended a conceptual model for integration of SAHRA activities, which included structural changes within each TA (for details, please see the Second Annual Report). In particular, it was decided to a) implement a multi-resolution integrated modeling strategy with a river-basin focus and scope, b) develop a coordinated “knowledge-base” to support and inform SAHRA science, modeling, education, and knowledge transfer activities, and c) develop a clear set of scenarios to drive the integrated science and modeling activities from the “top-down”.

During the current reporting period, a number of meetings and workshops were held which have resulted in a concerted move towards integration of SAHRA science activities around a river-basin focus. Deputy Director Roger Bales led the development of a scenario model that was discussed and refined at the second annual meeting in February 2002 and the “Rio-Grande river basin” science workshop in July 2002. Associate Director Hoshin Gupta and LANL senior research scientist Everett Springer led the development and refinement of the multi-resolution integrated river-basin modeling strategy. In addition, a funding supplement was requested and obtained from NSF to develop the capability for enhanced remote conferencing. Facilities with identical capabilities have been constructed at UA and UNM and are under construction at NMT and ASU. The enhanced remote-conferencing facilities have already made it considerably easier for SAHRA researchers to “meet” and to share information without having to be physically in the same location.

### 3. External Advisory Board (EAB)

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Susan Avery</td>
<td>CIRES, Univ. of Colorado</td>
</tr>
<tr>
<td>2 John Bernal</td>
<td>Pima County Public Works</td>
</tr>
<tr>
<td>3 Peter Eagleson</td>
<td>Massachusetts Institute of Technology</td>
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<tr>
<td>4 Charles Howe</td>
<td>University of Colorado at Boulder</td>
</tr>
<tr>
<td>5 Devendra Lal</td>
<td>Scripps Institute of Oceanography</td>
</tr>
<tr>
<td>6 Harold Mooney</td>
<td>Stanford University</td>
</tr>
<tr>
<td>7 Kenneth Schmidt</td>
<td>Kenneth D. Schmidt &amp; Associates</td>
</tr>
<tr>
<td>8 Peggy Woods – Resigned 2/2002</td>
<td>Amphitheater High School</td>
</tr>
</tbody>
</table>

### 4. Changes to Center’s Strategic Plan

There has been one important evolutionary change to the SAHRA strategic plan during this reporting period. Based on a review and analysis of SAHRA science activities, and the experience gained during two-and-a-half years of operation, we are currently implementing a “River-Basin” focus for coordination of SAHRA science activities. While SAHRA scientists will continue to organize many activities around the Thrust Area themes, the overall project coordination and budgetary decisions will be coordinated around the selected river-basins (Rio Grande and San Pedro/Gila) in order to achieve stronger integration of the science. This strategy appears to already be having positive impacts on the development of SAHRA science.
VIII. CENTER-WIDE OUTPUTS AND ISSUES

1a. Publications


Brookshire, D.S., M. Ewers, P. Ganderton, and J. Little, "Western water markets," (white paper).


Han, J., and J. Roads, U.S. climate sensitivity simulated with the NCEP regional spectral model, J. Climate Change, (in review).


Hibbs, B., F. Phillips, J. Hogan, C. Eastoe, J. Hawley, J. Kennedy, F. Nunez, A. Granados, and T. Kretzschmar, Binational study of the surface and groundwater resources of the Pío Pascual International Corridor in Proceedings, Integrated Transboundary Water


*Kim, T., J.B. Valdés, and J. Aparicio, Frequency and spatial characteristics of droughts in the Conchos River Basin, Mexico, submitted to Water International, IWRA.


Udall Center website weekly electronic news service, San Pedro News and Comment, with U.S. and Mexican articles on water management and policy issues.


* Peer Reviewed

* Not included in 2000-2001 annual report

1b. Conference Presentations

Bardsley, T., and J. McConnell, Investigations toward understanding the spatial representativeness of SNOTEL measurements of snow water equivalent, paper presented at the 70th Meeting of the Western Snow Conference, 2002.


Bardsley, T., and J. McConnell, Understanding the spatial representativeness of SNOTEL measurements, presented at the Western Snow Conference, 2002.

Bastidas, L.A., Multi-criteria to improve parameter estimation in hydro-meteorological and environmental models, seminar presentation at the Department of Civil and Environmental Engineering, Utah State University, April 2002.


Brookshire, D.S., M. Ewers, P.T. Ganderton, and J. Little, Comparisons of water consumer demand characteristics in the Middle Rio Grande”, 2nd Annual SAHRA Meeting, Tucson, AZ, Feb. 2002 (poster), and presented as a paper at the 2nd World Congress of Environmetal and Resource Economists, Monterey, CA, June 2002.


Chen, J., and J. Roads 2002: CRD, ECPC and SAHRA. Presentation to visitors from various Arab countries under the auspices of the State Dept, 2002.


Gupta, H.V., SAHRA: The National Science Foundation Science and Technology Center for Sustainability of semi-Arid Hydrology and Riparian Areas, presented at the SAHRA Rio Grande Workshop, Taos, NM, June 6-7, 2002.


Hogan J., and P. Brooks, conveners of a special session at the Fall AGU on “Water Quality and Biogeochemistry in Arid and Semiarid Regions,” 2002.


Misirli, F., H.V. Gupta, and S. Sorooshian, Improving Bayesian Recursive Estimation (BaRE) of parameters for conceptual rainfall-runoff models, presented at the American Geophysical Union Spring Meeting, Washington, DC, May 2002.


Sorooshian, S., Bounding parameter sets for land-surface models using remote sensing and multi-criteria methods, presented at the European Geophysical Society (EGS) Assembly, Nice, France, April 2002.


Sorooshian, S., Impact of water system management and human demand on water resources, presented at the Graduate Student Summer Program (GSSP) Lecture Series on Climate Change and the Global Water Cycle, Baltimore, MD, June 2002.


Sorooshian, S., L.A. Bastidas, and H.V. Gupta, Bounding parameter sets for land surface models using remotely sensed information and multi-criteria, European Geophysical Union XXVII General Assembly, Nice, France, April 2002.


Uyeda, S., Why do I have to learn this stuff - Introducing hydrologic literacy into the secondary classroom, UA Student Showcase, Tucson, AZ, Nov. 2001.


Varady, R.G., and B.J. Morehouse, Moving borders from the periphery to the center: river basins, political boundaries, and water management policy, paper to be presented at the 1st International Symposium on Transboundary Waters Management, Monterrey, Mexico, Nov. 18-22, 2002.


Yepez, E., D. Williams, R. Scott, G. Lin, J. van Haren, and D. Goodrich, D18O of vapor reveals rapid shift in evapotranspiration sources after a monsoon rain pulse in a semi-arid woodland ecosystem, presented at the 3rd International Conference on Applications of Stable Isotope Techniques to Ecological Studies, Flagstaff, AZ, 2002

* Not included in 2000-2001 annual report
1c. Other Dissemination Activities

SAHRA’s research results are being widely disseminated through national science radio programming. Science reporter Corinna Wu from the American Association for the Advancement of Science’s Science Update interviewed several SAHRA researchers, resulting in four 5-minute pieces. Water in Plants, airing on January 25, 2002 (see www.scienceupdate.com/jan02.html#020125), described how desert plants make the most of limited precipitation. The piece on Low-Flush Toilets that aired March 18, 2002, (www.scienceupdate.com/march02.html#020318), was also adapted as a middle school science curriculum component. The Tree Torture piece airing on April 19, 2002 (see www.scienceupdate.com/april02.html#020419) described research involving an artificial drought created in the San Pedro riparian corridor. Snow Mapping, which aired on May 29, 2002 (see www.scienceupdate.com/may02.html#020529), described remote sensing approaches to measuring snow.

In addition, SoundPrint interviewed several SAHRA researchers for one of its programs on forecasting and modeling. Water is Gold, a 28-minute piece, will air August 23, 2002 (see www.soundprint.org/radio/display_show/ID/1150/name/Water+is+Gold).

SAHRA’s education and knowledge transfer programs will be more widely disseminated as a result of efforts by Dana Flowers, funded by State of Arizona Prop. 301 funds. Ms. Flowers is involved in cross-training water educators from throughout Arizona in each others’ programs and familiarizing them with SAHRA’s programs. She also is developing media contacts and ties in the Phoenix metropolitan area. The first major cross-training effort took place over six days in late July 2002. A media briefing is scheduled for late summer 2002.

2. Awards and Honors

<table>
<thead>
<tr>
<th>Recipient</th>
<th>Reason for Award</th>
<th>Award Contributor</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Kevin A. Dressler</td>
<td>Yearly Student Hydrology Symposium</td>
<td>University of Arizona Hydrology and Water Resources Department</td>
<td>April 4, 2001</td>
</tr>
<tr>
<td>2  Huade Guan</td>
<td>To honor outstanding student posters at the annual meeting.</td>
<td>SAHRA</td>
<td>March 1, 2002</td>
</tr>
<tr>
<td>3  Jennifer Hamblen</td>
<td>Student Poster Contest</td>
<td>SAHRA</td>
<td>Feb. 2002</td>
</tr>
<tr>
<td>4  Anne Kramer Huth</td>
<td>Best departmental oral presentation; includes a check for $200</td>
<td>El Dia del Agua - student research symposium</td>
<td>April 12, 2002</td>
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<tr>
<td>5  Anne Kramer Huth</td>
<td>Best Student Oral Presentation</td>
<td>HWR</td>
<td>April 2002</td>
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<tr>
<td>6  Anne Kramer Huth</td>
<td>Student poster competition</td>
<td>SAHRA</td>
<td>Feb. 2002</td>
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<tr>
<td>7  Sharon Lite</td>
<td>Best student poster at annual meeting of Arizona Hydrological Society, Tucson, Arizona.</td>
<td>Arizona Hydrological Society</td>
<td>September 15, 2001</td>
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<tr>
<td>8  Julie Luft</td>
<td>Outstanding graduate mentor</td>
<td>UA College of Education</td>
<td>Spring 2002</td>
</tr>
<tr>
<td>9  James McPhee</td>
<td>Overall performance in the Master of Science in Water Resources Engineering program</td>
<td>UCLA Department of Civil and Environmental Engineering</td>
<td>June 2001</td>
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<tr>
<td>10 Noah Molotch</td>
<td>Presentation of the proceedings paper: Analysis of the partial variability of snow cover depletion in an alpine watershed, Tokopah Basin, Sierra Nevada, California, U.S.A.</td>
<td>The Western Snow Conference</td>
<td>April 18, 2001</td>
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<tr>
<td>11 John Roads</td>
<td>Roads currently chairs the CEOP WESP working group, the NCEP regional reanalysis scientific advisory committee, and the international RSM workshops. He is a member of the NRC Hydrology Committee, the AGU precipitation committee and was a recent member of the BALTEX scientific advisory committee and the USGCRP Water Cycle Working group.</td>
<td>CEOP WESP</td>
<td>2002</td>
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<tr>
<td>12 Steve Uyeda</td>
<td>1st place, education division, and graduate community outreach award, for graduate poster that dealt with education topics</td>
<td>Student Showcase Comm.</td>
<td>Nov. 10, 2001, Feb. 12, 2002</td>
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</table>
3. Center Graduates

<table>
<thead>
<tr>
<th>Student Name</th>
<th>Degree(s)</th>
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<tbody>
<tr>
<td>Mary Ewers</td>
<td>PHD</td>
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<td></td>
</tr>
<tr>
<td>Joe Little</td>
<td>PHD</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Michelle Walvoord</td>
<td>PHD</td>
<td>5</td>
<td>USGS - Lakewood CO</td>
</tr>
</tbody>
</table>

4. General Outputs of Knowledge Transfer Activities

SAHRA patents, licenses and start-up companies

SAHRA researchers are developing many new approaches and applications in the areas of field measurements, isotopic analysis, numeric methods and modeling. However, little of this innovative and creative work will be protected by intellectual property rights, or engender spin-off economic activity. This is because this work along with most of the data sets, integrative models, and other decision support tools being developed by SAHRA are more in the nature of public goods, and not patentable.

This does not mean that SAHRA won't be protecting some intellectual property with patents, copyrights, or software licenses. Our goal, however, and the way we will measure success, is the degree to which these outputs are quickly adopted and used by agencies and other water resource management institutions.

Some areas of technological innovation include:

- various new uses of remote sensing data
- new application of Electrical Resistance Tomography (ERT) to measure changes in vadose zone water content
- improved variable intensity rainfall simulator
- new application of 32Si isotopic work to quantify paleo-recharge of water through soil
- novel isotopic 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 PDA hardware and original software to create low-cost, high-resolution water meter data loggers to disaggregate residential water demand
- application of scour pans to develop real-time scour sensors in active streams during storm events
- various numerical and modeling advances

5. List of all Participants

<table>
<thead>
<tr>
<th>Participant Name</th>
<th>Category</th>
<th>Gender</th>
<th>Disability</th>
<th>Ethnicity</th>
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<tbody>
<tr>
<td>Roger Bales</td>
<td>Faculty</td>
<td>M</td>
<td>None</td>
<td>Not Hisp. or Lat.</td>
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<td>US Citizen</td>
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<tr>
<td>Luis A Bastidas</td>
<td>Faculty</td>
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<td>None</td>
<td>Hispanic or Latino</td>
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<td>other non-US Citizen</td>
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<tr>
<td>Doug Boyle</td>
<td>Faculty</td>
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<td>None</td>
<td>Not Hisp. or Lat.</td>
<td>White</td>
<td>US Citizen</td>
</tr>
<tr>
<td>Lindy Brigham</td>
<td>Faculty</td>
<td>F</td>
<td>None</td>
<td>Not Hisp. or Lat.</td>
<td>White</td>
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<td>No.</td>
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<td>Title</td>
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<tr>
<td>5</td>
<td>Paul D Brooks</td>
<td>Faculty</td>
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<td>6</td>
<td>David S. Brookshire</td>
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<td>Stuart H. Burness</td>
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<td>8</td>
<td>Janie M Chermak</td>
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<td>9</td>
<td>Bonnie Colby</td>
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<td>Not Hisp. or Lat.</td>
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<tr>
<td>10</td>
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6. Summary Table

| 1 | Number of participating institutions (all academic institutions that participate in activities at SAHRA) | 12 |
| 2 | Number of institutional partners (total number of non-academic participants, including industry, states, and other federal agencies, at SAHRA) | 42 |
| 3 | Total leveraged support (sum of funding for SAHRA from all sources other than NSF) | $521,000 |
| 4 | Number of participants | 166 |
| 5 | Number of affiliates | 56 |

7. Media / Publicity

Please refer to Appendix D.
IX. BUDGET

The budget section has been removed for web versions of the annual report
Appendix A: Biographical Information on New Faculty

Douglas P. Boyle

Assistant Research Professor
Division of Hydrologic Sciences
Desert Research Institute
University and Community College System of Nevada

RESEARCH INTERESTS
Watershed hydrology, integrated modeling of watershed scale processes related to water quantity and quality, streamflow forecasting, GIS, remote sensing, sensitivity analysis, automatic and manual parameter estimation, and multi-criteria analysis.

EDUCATION
Ph.D Hydrology and Water Resources, minor in Systems Engineering, University of Arizona, August 2001
M.S., Hydrology and Hydrogeology, University of Nevada, Reno, 1996
B.S., Aerospace Engineering, University of Southern California, 1989

EMPLOYMENT
Research
2001 - present Assistant Research Professor, Desert Research Institute, Reno, Nevada.
2000 - 2001 Research Associate, Desert Research Institute, Reno, Nevada.
1996 - 2000 Graduate Research Associate, University of Arizona.

Teaching
Instructor, Advanced Surface Water Modeling (Spring 2002), Small Watershed Hydrology (Fall 2001), Hydrologic Field Methods (Spring 2001 and 2002), University of Nevada.
Teaching Assistant, Fundamentals of Hydrology (Spring 1988), University of Arizona.
Teaching Assistant, Hydrologic Fluid Dynamics (Fall 1994), University of Nevada, Reno.

Professional Engineering
1989 - 1993 Assistant in Civil Engineering, El Dorado County Department of Transportation, Placerville, California.

PROFESSIONAL SOCIETIES
American Geophysical Union (AGU)
AGU Surface Water Committee
American Meteorological Society

PUBLICATIONS
Refereed Journals

Book Chapters

Conference Papers and Presentations

Douglas P. Boyle

July, 2002


Appendix B: Center Organizational Chart

SAHRA Management Structure
Appendix C: Minutes of Advisory Committee Meetings

NSF Science & Technology Center for
“Sustainability of semi-Arid Hydrology and Riparian Areas” (SAHRA)
Dept. of Hydrology, University of Arizona
Tucson, Arizona 85721

External Advisory Board
Meeting Minutes
(in conjunction with SAHRA 2nd Annual Meeting)
February 28, 2002
Sheraton Tucson Hotel & Suites, Tucson, Arizona

Slides accompanied this report – for copies of the slides please contact Rannie at SAHRA

PRESENT

Advisory Board: Susan Avery, John Bernal, Devendra Lal, Harold Mooney, Kenneth Schmidt
Executive Committee: Soroosh Sorooshian, Roger Bales, Hoshin Gupta, Gary Woodard,
Jim Washburne, David Brookshire, David Goodrich, Diana Liverman, Larry Winter,
Juan Valdes, Bisher Imam
Research Associates: Constance Brown, James Hogan, John Villinski

PROCEEDINGS

Introductions.

Soroosh: The SAHRA Annual Report was sent to NSF in October, the site visit was held in
November, and we received the NSF site visit report in December (copies are in the notebooks
we handed out). A response is being prepared by Hoshin and Martha Whitaker and will be sent
in the next few weeks.

While mostly positive, the NSF site visit report indicated that the External Advisory Board is not
being well utilized by SAHRA. Need to discuss how the EAB can better work with SAHRA to
reach goals. The Advisory Board needs to help in terms of deciding what role they want to play.

We now have a stable management team: Soroosh, Hoshin, Gary, Jim, Roger, and Thrust Area
leaders. We also have Research Associates in place, who play a pivotal role in integration.
Hoshin has asked the Research Associates to help us to decide how to coordinate the scientific &
social sciences within the Center.

We also have good support staff on board in the main office (Rannie) and the business office
(Jill and Gabe).
Most PIs have now been supported for a couple of years. We have tried to make some adjustments and modifications, and have had to cut back on some partners because of lack of participation, but most have been conscious of their roles within the Center.

**Advisory Board members not attending:** Peter Eagleson could not attend had to meet a book deadline. Chuck Howe is overseas, and was going to try to get here, but decided he couldn’t make it. Peggy Woods resigned from the Board she said she had too many commitments to keep up. Bill Harris said we should consider removing him from the Board he has now gone to Ireland to set up an NSF-like organization in Ireland.

In conversations with Dr. Eagleson, his only comment was that last year the Advisory Board was not sure if work presented was done by SAHRA or work from other (previous) projects. In response to this concern, it takes two years for graduate work to mature last year was too soon, but this year we are seeing this along with some leveraging with other groups.

This year is crucial for us because we need to put together our next 5-year proposal by early February, 2003. NSF has asked us to move up our annual report due date this year to allow time for preparation of the next 5-year proposal. Doug James has always set up a site visit to be held after receiving the annual report. This year he has requested that we submit our 3rd Annual Report on July 31, with the site visit in August. We would then receive the NSF site visit report in September, leaving four months to prepare the 5-year proposal, due on February 3, 2003.

Prop 301 was mentioned a number of times during the Annual Meeting. It is a state-funded effort to provide funds for education to high schools and universities. Water was one of the topics chosen for these funds the water initiative has started slowly in the first two years, was a half-million split between four groups, including SAHRA. First five years will receive funds uncertain after that.

Leveraging has been successful NSF gave us more money towards CEA-Crest. Number of other groups have been talked about.

SAHRA offices will be moving into a new building a diagram is on the notebook the top floor will house SAHRA offices. The Board of Regents has recently agreed to a long-term lease. Have fallen behind schedule in building, but should be in by next spring.

Our relationship w/NSF is running more smoothly, and will likely continue to improve, as another STC in hydrology is being considered their focus is on ecological aspects. We are helping guide them through the proposal and start-up process.

Doug James (NSF) is still asking how the various projects integrate while looking at posters.

The main message out of NSF and the Board in the first two years has been, “don’t compartmentalize yourselves into science, but focus on issues.” In our planning we have been moving toward issues rather than specific science questions.
Discussion:

Susan: Was it difficult to arrange around basins rather than TAs?

Soroosh: It was our own idea. As soon as we had it, everyone we talked to agreed that it was the right way to go.

Hoshin: We are planning a number of workshops have not decided on topics yet.

On the last day of last year’s meeting the Thrust Areas got together and came up with questions, and then had workshops based on those issues. There were three workshops: recharge, social science, and modeling.

Deventra: Could have workshops during other conferences, such as AGU could have a focus session on the output of this group. Basic message: Need more planning. For things that have materialized, could have a great impact.

Soroosh: The annual meeting is partly for this purpose. Thursday afternoon and Friday morning will be focused on planning sessions, broken out by basins.

Hoshin: We will be responding to NSF re a strategic plan.

Susan: The Advisory Board can be a great help in developing the strategic plan.

Harold: Regarding the Annual Meeting, was public involvement good?

Hoshin: On Tuesday 50 unregistered people showed up.

Gary: It has been a success in terms of attracting educators, but not a success in attracting the media.

Harold Mooney: Need to do more work on attracting the press, with hooks.

Jim: There is a trade-off with open and focused meeting. Perhaps the next meeting can be much more open.

Hoshin: Jim and Gary had planned an educator’s meeting Tuesday afternoon, but the educators wanted to stay in the main meeting room.

Roger Bales Presentation: Summary of research highlights of the past year (see slides).

Harold Mooney: What about stakeholders - that is part of the mission statement of SAHRA.

Soroosh: Need to balance stakeholder requests. Concern about what we can do, but not able to
provide everything they want.

Harold: There needs to be a dialogue need to respond to stakeholders, but not be expected to do everything they want.

Roger presentation: (See slides)

Development of integrated modeling is a key part of the research.

Stresses on the system to new knowledge & tools to applications
Recharge & riparian health

Scenarios: End-to-end integration

Group identified key areas where research could help.

Can build scenarios, being responsive to stakeholder needs, then design research to answer questions presented by scenarios.

Key knowledge gaps (see slides)

Susan: Regarding response of riparian vegetation structure.... Is timing a part of that?

Dave Q: Yes explanation that’s part of the strategy.

Another angle there’s some burned and unburned areas

Hal: Regarding scenario: riparian ecosystem slide question of percent of effort

70-80 percent of effort goes along the middle blue line Water nutrients
20-30 percent goes for management

Soroosh: In hydrological management, a large problem is the uncertainty issue the more we reduce the uncertainty the better decision making will be available.

Hal: Do some people think we are giving them one thing, and we are actually giving them something else.

Roger: Most of this refers to supply. Could have expanded on demand issues.

The social science is maybe another dimension of this.

Dave Q: We as scientists can do work on the issues stakeholders need need to maintain ongoing dialogue scientists and the public can be looking at not appropriate issues need to keep dialogue going.

Soroosh: Stakeholders include more than just the public also includes organizations involved in weather issues, etc., not only the public or politicians, but also water-related organizations.
Roger Presentation: Benefits for decision makers (see slides)

Groundwater recharge issues  global as well as local

Knowledge gap: recharge rate? Vegetation change, how does it affect recharge.

Benefits for decision makers: better estimates of recharge at basin scale

Trying to strike a balance between individual researcher’s work vs. focus on larger issues.

Harold: The question is, how are you going to take all the excitement for the individual projects and turn it into an integrated thing. (Lots of pretty flowers, turn them into a beautiful bouquet).

Soroosh: That’s the challenge  also looking at the gap of resources to needs.

Dave G: Continuing the analogy we have to decide which flowers we want to fertilize.

Susan: Agree that integration is a difficult problem. Over the last two years, have we seen an evolution in how we think and how we pose the research questions? Relates to the filtration issue. It was by Thrust Area, but now needs to move towards how one research issue feeds into someone else’s research. Need to think about those lines.

Larry: We have started thinking towards the basin drives the sharing of the projects moving towards looking at basins rather than Thrust Areas.

Roger: One aspect would be co-authored papers.

Soroosh: We hope moving toward the basin-centered research will help with this.

At the NSF STC meeting we learned from long-term STC leaders that their focus had totally changed during the project, and that 10-20 percent of the people who started with the project were no longer involved in the center. STC Centers in general are built around rapidly changing technology. Other Centers are more trying to foster the science, while we are looking at information dissemination.

Dave G: We can center research on one topic, as long as it contributes to a larger issue.

Susan: Can look at the whole basin, and look at the issues that you have answers for, and what parts are missing. It looks to the observer that our work is more fragmented.

Constance: In contrast, we see the various areas coming together over time.

Susan: This center is in the perfect place to find out where the gaps are, and how they can be filled.
Devendra: Also need to look at time scales. Short and long to millennium. All length of time scales. Need to find out how to do this to look at the different issues.

John Bernal: Excited about the general thrust of sustainability. In own work, spend a lot of time debating even locally, population growth Sonora conservation plan trying to tie the science to policy makers decision makers and public policy makers need to be aware of the science that is going on.

Dave G: Maybe someone in SAHRA should be going to those meetings.

Hoshin Gupta Presentation:

Structural issues: Staff is in place; post-docs are in place organization is moving along smoothly, so can focus on other issues.

Budgets: NSF funding issues have some carry-over. Large portions of that is for filling positions, which will be filled later. Field work is costing more than we anticipated, so that’s a drain on operations.

NSF is not all of the budget. Handed out budget pages, identified by funding source.

We are running a huge deficit this year, which will make an impact on future planning.

Need to look at where other work is going on, or find other resources.

Carrying 36-40 students, had budgeted for 24 students. Nat is excited about this that is where he wants our money to go. And said for us to go see him about that.

Need to actively look for additional funding.

Review of past year:
- Time working with post-docs, getting them integrated into our activities.
- Still not completely comfortable with the Thrust Area structure. Thrust Areas are emerging into something else and melding.
- Proposed: Thrust areas with matrix (see handout).
  Four interdisciplinary groups
  Rio Grande
  Colorado River Group (San Pedro, Salt Verde)
  Regional scale studies
    Precip (rain/snow)
    Mesoscale modeling
  Cross-Border (US/Mexico) & International
Plans for coming year:
- 5-year proposal
- Review of projects
- Leveraging
- Strategic Plan (rolling)
- International issues including workshop
- Diversity (Hispanic/Native American)
- Education

Based on the four groups and rolling Executive Committee Proposal to fill these positions

Harold: Should integrate social science with basin group leader.

Hoshin: Working with balance within the Executive Committee. We need to come up with a structure that will be acceptable to the Advisory Board and current Executive Committee.

Advisory Board: How do we want them to proceed?

Soroosh: Meet with each other to discuss and make a report to us. Suggestions were given on what to consider in discussing issues.

Need to do a self-evaluation on all our projects.

Also consider advice for NSF.

Susan: SAHRA needs to advise NSF of the amount of time we spend on writing reports for NSF.

END OF MEETING

Advisory Board met for discussion will send a report with suggestions to Soroosh.

rf

-7-
April 17, 2002

Soroosh Sorooshian
Director, SAHRA
J. W. Harshbarger Bldg., Room 318
The University of Arizona
Tucson, Arizona 85721

Re: SAHRA Second Annual Meeting

Dear Soroosh:

Following is the Advisory Committee report on the SAHRA program.

The program has made great strides in a relatively short amount of time. It has engaged a large number of hydrologic investigators in the southwest, and has brought a lot of new student talent into this project. A solid management team is in place and the program is thus poised to make substantial contributions to the hydrology of semi-arid regions, both in the US and elsewhere. The team has concentrated on the advancement of the science and on hydrologic education, and has a lot to show for these efforts. The team is now beginning to concentrate more on the integration of the many studies in progress. The decision to use some of the major water basins in the southwest as a framework is a good one, and will certainly focus the integration efforts. Integration of these studies is the strength of the program and should be foremost in future planning.

The scientific papers presented at the meeting were of a reasonably high standard. Substantial work has now begun to address issues pertinent to Thrust Areas 1 through 4.

Following are our specific recommendations:

1. A draft road map for future activities of SAHRA should be provided to our Committee for review comments before our next meeting. This would go hand-in-hand with the strategic plan.

2. The mission statement for the program should be revisited. Although the team is making good progress on science integration, they may not really be addressing the mission statement of stakeholder driven research. Nor is the team giving much focused attention to the management of water resources, except from an educational perspective. This may be acceptable, as long as the local community does not think that the team is doing something that they are not, and
develops a sense of frustration in the coming years. This region may not become sustainable in water resources, given the present level of development, population pressures, and the current water use patterns, no matter what kinds of results this program brings forth. It certainly would be good if more attention was paid to water use, demand, and management, rather than primarily on the natural supply. There is a need for a continuing dialog with the users of water to make them fully appreciate the dynamics and fragility of the water balance in semi-arid regions.

3. Specific time should be allotted in the committee review schedule for the advisory committee to discuss progress and plans, both independently and with the SAHRA management team. In this way more thoughtful advice can be provided.

4. A strategic plan is being developed for the SAHRA program. The new plan and organizational structure are critical for the eventual success of this very ambitious and important program. Hard choices are going to be made on where to put resources in the coming year or two, and these will be driven by the plan. The advisory committee could be of value in critiquing the plan before the next annual meeting.

5. The basic technical problems have apparently been identified, and it now seems necessary to get on with reducing the number of options, finalizing the action items, and implementing them in a systematic manner.

6. Because many of the research problems undertaken by SAHRA have time scales of more than 10 years, it is necessary to plan on such time scales, and to think about building a scientific group with high expertise in all aspects of experimental and theoretical hydrology. It is also important to have a strong research base in atmospheric sciences, including a reasonable capability in the area of forecasting precipitation.

7. In future advisory committee activities, we request allocating about half a day, solely for the advisory committee to meet, and then to meet with the SAHRA Director.

8. Information for advisory committee review should be provided at least several weeks before each annual meeting.

We on the advisory committee look forward to continued interaction with the SAHRA program. Again, we are highly impressed by the efforts and results so far.

Please contact me if you have any questions.

Sincerely yours,

Kenneth D. Schmidt
Chairman, SAHRA
Advisory Committee

KDS:ld
Appendix D: Media Publicity Materials

Transcript of KVOA Eye Witness News broadcast, 6 PM, July 22, 2002:

<table>
<thead>
<tr>
<th>Region</th>
<th>Summary</th>
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<td><strong>W-DROUGHT</strong></td>
<td>Despite a rainy forecast, local experts say Arizona's drought continues. Everywhere I go people are talking about the rain. And how the drought is over. The fact is it isn't. And it probably won't be no matter how hard it rains.</td>
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<tr>
<td><strong>P-DROUGHT</strong></td>
<td>Ah rain. We prayed for it. And give thanks for it. Once again it's safe for us to build campfires because of it. And we can cut back on outdoor watering. But will the monsoon end our drought? Most of the time the monsoon does not help us out of a severe drought. Andrew Comrey is a University of Arizona climatologist. He's studied southeastern Arizona's weather over the past 107 years. We've had 17 severe droughts since 1895. This year would make the 18th. And during all those years Comrey says the monsoon ended the drought. Just 4 times. How hard would it have to rain to rescue us this summer? It would take something between 9 and 12 inches in this zone in southern Arizona where it's blue to get us out of the current drought in the next three months. The odds of that are about 2 to 3 percent. Comrey's advice. Get used to droughts. And floods. His research shows in southeastern Arizona there's no such thing as normal weather. On the contrary he says it's as volatile as the current stock market. It's the wild west. And we can expect crazy climate and crazy weather. By eastern standards.</td>
</tr>
<tr>
<td><strong>T-DROUGHT</strong></td>
<td>Of course here in Tucson we get the summer monsoon. And winter rains. This winter forecasters say we could get more storms because of El Nino. But they question whether even the winter storms will rescue us from the drought. Comrey believes there's a lesson in all this. Whether we're firefighters, farmers, ranchers or water workers. We all need to do a better job of planning for the extremes.</td>
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Break out the blades...

By Mithri Tobin

Peck and Properly, we're still in a drought, and unless this monsoon moves it's likely to continue for most of the summer.

This monsoon will not be able to break the drought, it will only help to bring some relief.

Monsoon rainfall unlikely to end it

By Mithri Tobin

The monsoon has ended and it has not brought the much needed relief to the region.

Drought expected to bring slightly above normal rain

By Mithri Tobin

The monsoon rainfall is expected to bring slightly above normal rain.

If there's anything that defines our climate, it's that it's hardly ever average.

Andrew Cassie

University of Arizona climatologist

The monsoon rainfall is expected to bring slightly above normal rain.
Ruff-water rafting

Drenching nice, but drought's long way from over

By David J. Chisum, Tucson Citizen

The desert monsoon season has gotten off to a slow start this year, with only 1.5 inches of rain in May and June, according to the National Weather Service. This is the second year in a row that the monsoon season has been delayed due to high pressure systems over the region.

The delayed monsoon season is unusual and is caused by a combination of factors, including the timing of the jet stream and the position of the Bermuda High. This year, the jet stream was weaker than normal, which allowed high pressure systems to move across the region, preventing the monsoon from developing.

In the past, the monsoon season usually begins in late July or early August, but this year it did not start until mid-August. This lack of rainfall has led to a drought that is still ongoing, with many areas experiencing severe water shortages.

The drought has had a significant impact on agriculture and wildlife in the region. Many farmers have had to reduce their crop production, and wildlife populations have declined due to a lack of water.

The monsoon season is crucial for replenishing water supplies in the region, and it is hoped that the season will pick up in the near future.
ALTERNATIVE FUTURES FOR CHANGING LANDSCAPES
The Upper San Pedro River Basin in Arizona and Sonora
Carl Steinitz, Hector Arias, Scott Busselt, Michael Flaxman, Timus Gourie, Thomas Maddock III,
Dave Mount, Richard Peiser, and Allan Shearer

Leading landscape architect and planner Carl Steinitz has developed an innovative GIS-based simulation modeling strategy that considers the demographic, economic, physical, and environmental processes of an area and projects the consequences to that area of various land use planning and management decisions. The results of such projections, and the approach itself, are known as “alternative futures.”

Alternative Futures for Changing Landscapes presents for the first time in book form a detailed case study of one alternative futures project—an analysis of development and conservation options for the Upper San Pedro River Basin in Arizona and Sonora, Mexico. The book gives a comprehensive overview of how the study was conducted along with descriptions and analysis of the alternative futures that resulted.

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Send e-mail orders to orders@islandpress.org
Send inquiries to service@islandpress.org

Carl Steinitz is the Alexander and Victoria Wiley Professor of Landscape Architecture and Planning at the Harvard University Graduate School of Design.
Hector Manuel Arias Rojo is assistant director and land use planner for the World Wildlife Fund’s California Program.
Scott Busselt is post-doctoral fellow at the Desert Research Institute.
Michael Flaxman is lecturer at the Harvard University Graduate School of Design.
Timus Gourie is a consulting hydrologist with HydroSystems Inc., Tempe, Arizona.
Thomas Maddock III is professor of hydrology and water resources at the University of Arizona and co-director of the Research Laboratory for Riparian Studies.
David Mount is associate research professor at the Desert Research Institute.
Richard Peiser is the Michael D. Spier Professor of Real Estate Development at the Harvard University Graduate School of Design.
Allan Shearer is research fellow at Harvard University.

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World, All Languages
Landscape Architecture/Planning
Desperately seeking a sustainable vacation: Phoenix begins to meet the challenge

By Victor Lessig

A desert oasis, as is an overdeveloped metropolis that is incorporating the water systems of the local ecosystem. Phoenix has traditionally been polluting to the water market and...
Soil Protocols: Getting Started
by Dr. Jim Washburne

Ever wonder why soils come in so many beautiful colors, why dirt roads become impassable in morn over after a little rain, or why farmers spend so much effort tilling their fields? The GLOBE soil protocols can seem challenging but many schools are finding the measurements simple to perform and helpful in answering these and other questions.

A good starting point is for students to gather soil samples following the suggestions in "Soils In My Backyard" from the GLOBE Teacher's Guide. Using this Learning Activity, students qualitatively compare and classify the wide range of soils from their own communities. Dig a pit or use an auger and just explore what's happening in the soil. The students may find things they did not expect.

When you are ready to begin the GLOBE soil protocols, the first step is to determine the soil structure. Scientists use the term "ped" to describe a unit of natural soil. Some soils vary greatly, a ped does not have a uniform weight, shape or volume. Some of the more typical structures are: granular, platy, blocky, prismatic, and columnar.

Sometimes, soil may be structureless, which means that the soil peds do not have a defined shape. In this case, the soil structure is either single-grained or massive. Single-grained soil is like sand, a beach or in a playground where there are individual sand particles that do not stick together. Massive soil structure sticks together in a large mass that does not break in any pattern.

It is common to see more than one type of structure in a soil sample, but GLOBE scientists need reports on the most common type in your study site.

Soil temperature is also an easy but important measurement that can be conducted by students of all ages. Soil temperature is important for understanding the length of the growing season, the amount of water that plants need, the decomposition of waste and other organic material, and many other important processes within the environment. Little preparation or equipment is required for this weekly measurement, but the data GLOBE students can provide is critical for scientists. For additional background information on these and other GLOBE soil protocols, see the GLOBE Teacher's Guide online at www.globe.gov.

Dr. Washburne is the GLOBE Principal Investigator for the soil temperature and moisture protocols. He works at the University of Arizona in Tucson.
Drought to Stay With Us

Monday, 16 July 2002

Jeff Alexander

There doesn’t seem to be anything average about weather and climate in the
Great Plains. You can look at the weather page in the newspaper or on the Internet
and find “average temperature” and “average rainfall,” but that’s just picking
numbers around on a piece of paper, and U.S. drought doesn’t follow the mean
deviation.

Most meteorologists at the University of Arizona say there are many, many factors
that influence periods of drought and periods of rain. Each of these has a
effect on the other and for the largest, overall pattern.

Monsoonal rains are already having an adverse impact on Arizona’s dry-weather
conditions, says Arizona’s Professor Andrew Czaja, who teaches hydrology and
directs the Center for Sustainable Hydrology and Resources (CSHR) at the University of
Arizona.

Research in the 16,000-50-year-ago era has revealed three kinds of drought: agricultural,
ecological and hydrological. Agricultural forest fires have altered the
hydrological cycle, largely because rain is now distributed in a less predictable
manner. More rain and more severe dry spells in an unusual biome landscape, which is to say reliance on
large surface runoff and lakes.

“The weather influence is extreme in the region and small increase will affect the
flood,” he says, “I have observed point of view in the west that drought could be
a new trend. You may not want a quick recovery.”

The southern half of Arizona is, to most scientists, a large rainshadow, which climatologists have
described as “arid” “North of the Mogollon Rim it is more like desert, or savanna,” says Czaja.

Gregg Ralston, a co-founder with the U.S. Institute for the Study of Planet Earth (ISP) and the Climate-Assessment

On Thursday (16th), high winds reaching the Mauna Kea Observatory near the summit
of the Big Island in Hawaii, which measures average rainfall, caused科学家们 to
improve the accuracy of climate information.

With the variability of drought that is expected to last, researchers are focusing on finding
strategies to deal with the drought. Andrew Czaja, a
climatologist and assistant professor of geography and regional development at the U of A, says Arizona’s
average climate is dry and rain is scarce. “This past century had no major
and better drought during the first decade of the twentieth century and during the 1940s.

"What’s missing? A long, moderate drought, or a short, intense one that ended quickly," Czaja
says, adding, “I believe the next time the monsoon season will be from drought, at least continues it. In order to
end the current drought, it would help to have some rain. It’s a typical monsoon, lasting 5 to 7 months. Czaja
says the odds of the long-term trend ending before August is only about 2 to 3 percent.

On Thursday, the National Weather Service received a report of extreme drought, which
will affect the monsoon. The report will be held in the east to the north, and while Monsoon promises of
rain will remain normal to this coming winter, it doesn’t mean they will necessarily
rainwater patterns.

And looking at the background is the phenomenon called the Pacific Decadal Oscillation (PDO), a
long-term cycle based on average temperatures in the Gulf of Alaska and off the North American
Coast. Wet or dry temperatures there affect drought and wetter conditions further
north, including the Big Island and western Hawaii, making for warmer
climates, says Czaja.

From a policy position, Czaja says, the monsoon will affect the monsoon. The
drought is a problem in the desert. However, the monsoon season is
beginning to show signs of drought.

Woodard says you can join about 10 and coffee can be from a newspaper column in Chicago in 1997.

"The most news is that if the drought improves, within a few years we’ll all be drinking
combined water, and the good news is that there won’t be enough to go around."
March 11, 2002

Gary Woodard  
University of Arizona  
SAHRA  
Harshbarger Building  
Tucson, AZ 85721

Dear Gary,

Here is a copy of the Science Update ("Low-Flush Toilets") based on our interview from last November. The official air date of the show is 3/18/02. In addition, the show will be posted on our webpage, <http://www.scienceupdate.com>.

Thank you so much for speaking with me. Although the program's strict time limit permits just a couple brief clips of your voice, the interview was essential to the program. And while there's never enough time to cover all the interesting issues, I hope you'll find the segment accurate, entertaining, and accessible to a lay audience.

Again, thank you for your time and cooperation. We'll be producing other programs from my visit to SAHRA, so I'll let you know as soon as they are completed.

Sincerely,

Corinna Wu  
Producer, Science Update  
(202) 326 7011  
cwu@aaas.org

Enclosure: Science Update tape