3. Project Summary

A Science and Technology Center for the
Sustainability of Water Resources in Semi-Arid Regions
Director: Soroosh Sorooshian - University of Arizona

We propose the formation of a Science and Technology (S&T) Center to study and promote the "Sustainability of Water Resources in Semi-Arid Regions". Population growth has resulted in intense demands on the quantity and quality of water resources worldwide. The *sustainability* of these water resources in the 21st Century will depend critically on our ability to correctly manage water resources systems under a more variable (and possibly warmer) future climate. Semi-arid regions are in particular jeopardy – they are experiencing rates of development that exceed those of other climatic regions and are highly sensitive to increasing anthropogenic pressures, variations in climate, and the disruptions associated with long-term climate change. The development of improved management strategies and viable interventions to meet these challenges will entail unprecedented coordination and integration across a broad range of disciplines, including the natural and social sciences. Although the current system of individual- and multiple-investigator research projects is successful in advancing scientific knowledge and developing improved technologies, *there is a critical gap* between this research and the tools used by water resources practitioners.

The problem is that there is currently *no effective mechanism for rapidly moving the state of scientific knowledge into widespread usage by the public and private agencies responsible for managing our water resources*. The proposed S&T Center will provide an effective and efficient bridge across this gap by: i) monitoring the critical hydrologic issues, ii) identifying which issues can be effectively addressed in a timely fashion, iii) coordinating and integrating studies involving many disciplines and institutions, iv) bringing ripening technologies and ideas to an advanced state of development, and v) focusing and committing resources at the appropriate level and in a manner relevant to the development of viable interventions (both technological and educational). This process will bring about much-needed changes in how water resources are both viewed and managed, and the consequent impacts will be felt not only within hydrology and related sciences, but across water resources management in general. While our primary study areas will be in the Southwest, to take advantage of ongoing activities and infrastructure, the Center's impact will be extended by testing successful methods in other geographic regions.

Research activities of the Center are organized into five major thrust areas, the results from which will have a significant influence on water management in the greater Southwest and other semi-arid regions. First, research will lead to improved understanding of the various components of the basin-scale water balance in semi-arid regions, including methods to accurately estimate the spatial distribution of precipitation and how these are partitioned into runoff and recharge (both mountain front and alluvial). We expect that after five years the more-accurate methods of measuring and modeling both rainfall and snowmelt produced by the Center, combined with improved understanding of evapotranspiration and soil moisture, will directly result in more accurate forecasts of runoff and recharge. This new information will feed directly into the making of more-efficient, more-equitable and better-informed water management decisions, which often have billion-dollar implications for regional economies. Working with existing climate research centers, we will combine this improved knowledge of water balance with emerging regional climate forecasts to develop seasonal hydrologic forecasting tools that are of sufficient accuracy to influence water-resources management decisions in the southwestern U.S., northern Mexico and other areas.

Second, after five years the Center will develop improved and much-needed tools for determining components of the basin-scale salinity balance, by combining innovative uses of environmental tracers with advances in modeling. When merged with improved estimates of the water-balance components, these new tools will provide resource managers with a more-scientific basis for salinity management.

Increased salinity in surface and ground waters is an emerging, critical issue threatening sustainability of many arid and semi-arid regions, including the greater Southwest.

Third, after five years the Center will provide sufficient understanding for sustainable uses of ground-water resources that maintain the viability of riparian ecosystems as critical corridors of biological diversity. This understanding will be backed by a variety of innovative measurement and modeling tools, which will continue to be developed over the life of the Center. Social science research will point to the implications of demographic and economic shifts, changing legal structures and economic markets for water, and changing public attitudes for sustainable water management.

The Center will bring researchers together with other stakeholders to jointly evaluate research needs and set research priorities. It will be a significant and visible vehicle for promoting researcher-user partnerships across the broader water resources field. By the end of five years we aim to have a representative cross section of resource managers in the Southwest engaged in some way with the Center, including all of the major agency and private water resources sector stakeholders. Technology transfer will be an ongoing and integral part of the day-to-day operation of the Center, and will rely heavily on research partnerships with the private and public sector end users of the new technology emerging from the Center.

Educational initiatives will have a high profile in the Center, and will constitute about 10% of the budget, not including graduate assistantships for students engaged in research under the Center. The Center's educational efforts will contribute to sustainability by bringing water resources issues into the forefront of science education at all levels. K-12 teachers will be a key target group. They will be afforded opportunities for pre- and in-service training linked with systemic change, science research experience, and linkages with on-going activities such as the international K-12 Global Learning and Observations to Benefit the Environment program, and the Earth system science educational programs at Columbia University's Biosphere 2. It is our aim that after five years nearly 200 K-12 teachers will have been directly trained in Center-sponsored workshops or classes, with nearly 1,000 teachers influenced in some part by the Center. A significant fraction of these teachers will reach minority students, with particular emphasis on Native Americans in Arizona and New Mexico. While the educational program will evolve in time, it is built on a solid commitment to develop significant and transferable programs. The Center will also impact the university education of non-science majors in measurable ways, bringing innovative teaching tools on water into the classroom and various forms of electronic media. Finally, the Center will educate a new generation of water resources professionals, giving them the interdisciplinary perspective and technological skills required for practicing sustainable water resources management.

We have assembled a unique, multi-disciplinary team for the proposed Center. The Director and staff will be located at the University of Arizona's top-ranked Department of Hydrology and Water Resources, with participation of university scientists and engineers from New Mexico Tech, Penn State University, the University of California (UCLA, Scripps, and Riverside), Columbia University Biosphere 2, the University of New Mexico, Arizona State University, Northern Arizona University, and two Mexican institutions, the Instituto Mexicano de Tecnologia del Agua and the Instituto el Medro Ambiente y Desanollo Sustenable del Estado de Sonora. Equally important will be the participation of governmental researchers from the Los Alamos National Laboratory, the U.S. Geological Survey, the Agricultural Research Service, the Army Corps of Engineers, and the International Boundary and Water Commission. By building on the already strong leadership roles of these institutions and the individuals who will participate, the Center will be an influential world leader in the sustainable management of water resources. The funding requested from NSF will be used as seed money to establish an initial infrastructure that can attract additional revenues from other sources for growth and long-term sustainability of the Center.

4. Project Description

4.1 Focus

Arid and semi-arid climatic regions include a significant fraction of the world (including 25% of the contiguous U.S.). Such regions are experiencing rates of development that exceed those of other climatic regions, with rapid development expected to continue. In the southwestern U.S., the population is projected to grow from 45 million today to nearly 70 million by the year 2025. Semi-arid regions are characterized by strong heterogeneities in ecology, topography, and land use. *Because of extreme sensitivity to disruptions brought about by climatic and anthropogenic changes, the sustainability of water resources continues to be placed in further jeopardy.* Development of viable management strategies and interventions will entail unprecedented coordination and integration across a broad range of disciplines. Existing studies are in need of synthesis, and recently developed technologies have yet to be exploited. The proposed Center will link natural and social scientists, educators, practicing engineers (from both public agencies and private companies), economists, legal experts, and decision-makers. With this blend of talent we will facilitate the rapid assimilation of new technologies, analytical tools, and modeling approaches into the understanding and management of water resources.

4.2 Relevance

Economic development in semi-arid regions is currently supported by the exploitation of both surface and ground-water resources at a level that puts a severe strain on the available water supplies. The rate of water extraction typically exceeds the long-term rate of re-supply and, in the short-term, the deficit is often made up by mining ground water or through interbasin transfers of water. Readily exploited ground-water reserves become depleted rapidly, which eventually begins to deplete the surface flows as well. Even with ground-water interception and interbasin transfers, nearly all major cities in the western United States, including Albuquerque, Denver, Las Vegas, Los Angeles, Phoenix, and San Diego, are facing or soon will face water supply shortages.

These shortages will lead to severe conflicts between ecological, economic, and water resources interests as illustrated by the four case studies that follow. These studies make clear that ecological systems can be disrupted, and water quality can deteriorate dramatically over a relatively short period of time. Given the increasing demand for water, the increasingly stringent quality restrictions, and the already marginal water quality in the lower portions of most western drainage basins, even small-to-moderate water-quality transients could have severe economic impacts. Such transients may become irreversible. If the underlying causes of such transients can be understood, it may be possible to alter basin management practices now to minimize future impacts.

Our efforts to quantitatively analyze and understand current and projected future water quality and quantity in drainage basins in the southwestern U.S. and other semi-arid regions are very likely to return huge societal benefits in the long-term. The country of Mexico provides an effective opportunity to evaluate our science, technology and outreach efforts in a developing country context. More than 85% of Mexico’s land area is classified as arid or semiarid, and water resources development has been critical to the sustainability of Mexico’s rapidly expanding agricultural and industrial economy and demographic growth. Although it has a similar physical environment to the southwestern U.S., Mexico has dramatically different social, economic, and institutional conditions. Our research activities and collaborations in northern Mexico provide an important set of comparative case studies for using hydrological and other scientific knowledge for sustainable development. Mexico also shares a number of surface, and ground-water resources with the United States including the San Pedro, Colorado, and Rio Grande rivers, and this proposal is intended to support cooperative, bi-national management of these water resources.

4.2.1 Case Study: Interaction of Ground-water Pumping and Riparian Systems

Riparian systems are composed of stream and stream-dependent plant and animal life. They are critical to continued biological diversity and sustainability of regional ecosystems in the Southwest. Although riparian systems comprise a relatively small fraction of the land area in the Southwest, over 70% of all species inhabiting this region, as well as many transiting migratory species, depend on riparian habitats. Unfortunately, Southwestern riparian systems often become the focus of intense conflicts between development and preservation interests because highly complex interactions among fauna, flora, and the physical hydrologic system can be seriously perturbed by external human and natural stresses. In particular, interception of ground water to satisfy human consumption inevitably affects riparian communities by reducing or eliminating discharge from the ground-water system into the perennial streams that sustain riparian communities. Through application of the Endangered Species Act, the Clean Water Act, and the Federal Reserve Water Rights Act, the federal courts are beginning to exert control to protect riparian habitats in the Southwest. An understanding of ground-water and surface-water interaction is fundamental in order for Congress, state legislatures, and courts to promulgate law and to make proper rulings to protect riparian systems.

Example 1: *Water samples collected within the Sierra Vista basin, an important riparian area in southern Arizona, enabled identification of the origins of perennial stream flows. Chemical and isotopic analyses of samples from the regional and floodplain aquifers, the San Pedro River, and a bedrock spring in the nearby Huachuca Mountains indicate a strong coupling between both aquifers and the San Pedro River. Inflow to the river from the regional aquifer is estimated to be 50-70% of the stream discharge. Earlier modeling studies and current field measurements indicate that pumping of the aquifer systems has reduced flows in the river. Nearby communities are currently considering expensive waste-water recharge and other options to sustain San Pedro River flows critical to the riparian habitat (1).*

4.2.2 Case Study: Natural and Anthropogenic Sources of Water Salinity

The basin-scale problems associated with water quality, while not as well known, are even more significant. Water quality problems that receive the greatest attention, such as contamination by agricultural pesticides or industrial chemicals, are sometimes easily solved compared to the fundamental problem of salt balance in arid drainage basins (2). The salinity of river water normally increases as it flows downstream, but human activities exacerbate this trend in several ways. Consumptive water use increases the degree of evaporation and transpiration, thus concentrating the residual salts. Other human activities add significantly to the salt burden because sources of salts include road salt, sewage, and fertilizers.

Example 2: *Surface-water quality degrades progressively as it moves through the regional-scale drainage basin of the Rio Grande River. Figure 1 shows the mean total dissolved salts (TDS) concentration and chloride concentration for water year 1994-1995 as a function of flow distance downstream from the headwaters of the river. The TDS concentration increases from 84 mg/L in the headwaters to over 750 mg/L at El Paso, with particularly large increases seen in reaches of the river adjacent to intense agricultural activity. At distances greater than 600 km from the headwaters, the average TDS concentration significantly exceeds the threshold value for human consumption, 1000 mg/L. For example, during low-flow periods from 1938 to 1996, the river salinity at El Paso varied from lows around 1000 mg/L to highs exceeding 2000 mg/L. To improve water quality, El Paso will soon*

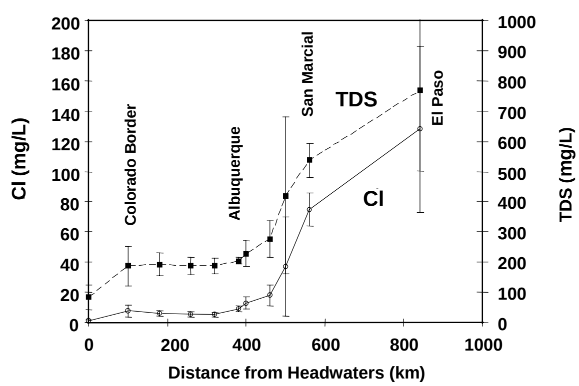

Figure 1. TDS and Cl along the Rio Grande, 1994-1995

spend more than $200 million to build additional water treatment facilities and is investigating improved water conveyance systems and retirement of agricultural lands that overlie salt-bearing geologic strata. The Colorado River and rivers in other semi-arid basins show a similar pattern.

4.2.3 Case Study: Irreversible Water Quality Degradation Caused by Transients

Human activity may increase the rate of flushing of natural solutes from the subsurface. Such natural sources include saline pore water in thick desert vadose zones, discharges of deep sedimentary brines, and pumping of low-quality ground water. Moreover, multiple ill-defined sources of anthropogenic contaminants often occur (3, 4). While response times for surface-water flows are normally short (months to years), response times for subsurface flows are often long (decades to centuries). These subsurface contributions to river salinity can result in unexpected long-term transients in surface-water quality.

Example 3: *The Murray-Darling River in southern Australia (5) is the sole water supply for the major city of Adelaide, as well as much of the surrounding region. The drainage basin is semi-arid, with deep vadose zones, and natural vegetation is highly water-efficient mallee scrub. Clearing of the natural vegetation for agriculture and grazing has greatly increased water fluxes through the vadose zone. Enhanced recharge is rapidly flushing highly saline vadose pore water (which is a natural result of concentration of the precipitation by mallee scrub) into the ground-water system, which discharges into the rivers. As a result, river salinity is already above drinking water limits for much of the year and is predicted to continue rising by ~5 ppm every decade (6). Although the sequence of events was initiated in the last century, the response time of the subsurface system was so long that the salinity trend was not noticed until a few decades ago and the cause identified less than 10 years ago. The damage appears to be irreversible.*

4.2.4 Case Study: Intergovernmental Conflict Over Water Resources

Many countries in arid and semi-arid regions around the world have significant proportions of their surface and subsurface water resources originating outside of their borders. In the Middle East, approximately 21%, 97%, and 66% of the water resources originate outside their borders for Israel, Egypt, and Iraq, respectively. In most cases, the relations between entities sharing water resources are tenuous at best, even if formal use agreements exist.

Example 4: *Use of Jordan River water has been a source of political and military conflict for several generations, with strong hydrologic interdependence between the countries sharing the river basin. A mutually beneficial approach to the socio-political problems has been proposed, but many water management principles remain to be developed (7).*

4.3 Research Plans

The focus of the proposed Center will be primarily on semi-arid regions of the greater Southwest, but the tools and methods that are developed should be applicable to and will be tested in other geoclimatic regions. The scope of the research has been designed to: (i) be comprehensive in covering the key fundamental components of the hydrology of semi-arid regions, (ii) not be too broad (because most breakthroughs come from detailed research on well-defined questions, rather than a superficial approach covering many areas), and (iii) leverage, not duplicate activities supported by other programs. There are several ongoing academic and research programs at the University of Arizona (UA) and the other cooperating institutions that can be coordinated with Center activities, including: (i) four NASA-EOS interdisciplinary science investigations that focus on climate and hydrology (three at Arizona and one at Penn State), (ii) a number of GEWEX/GCIP investigations, (iii) a NOAA pilot project on integrated assessment of climate change in the Southwest, (iv) an NIEHS Superfund Research Center focused on assessment and remediation of hazardous chemicals in the environment, (v) various climate forecasting activities (e.g. Scripps), and (vi) a U.S. Geological Survey initiative to study ground-water and surface-water interactions in the Southwest. For administration, research is organized into broad “Thrust Areas.”

Brief descriptions of each thrust, with examples of promising innovations and emerging technologies and probable applications are given. More specific research plans and investigators are detailed in subtasks.

4.3.1 Thrust Area 1: Spatial and Temporal Properties of Hydrologic Variables

Background: In semi-arid regions, quantitative knowledge of the components of the hydrologic cycle is quite limited, primarily because of the large temporal and spatial variability in precipitation, runoff, recharge, and evapotranspiration (ET) within a basin. Much of the variability is caused by the large degree of natural landscape heterogeneity that is encountered in a typical watershed of 10,000-100,000 km^2: large ranges in elevation (1,000-3,000 m), vegetation (alpine to desert), and surficial geology (granite to alluvial sand). Human activities introduce even more heterogeneity. In the Southwest, much of the annual runoff comes from winter snow in the higher elevations, which remains stored in the snowpack until spring melt, and then runs off over a relatively short period of a few weeks. Most of the remaining precipitation falls during the "summer monsoon", which is characterized by a dramatic directional shift in the lower atmospheric wind field that brings moisture from the Gulf of Mexico and the Gulf of California to the Southwest. Up to 80% of the annual rainfall in parts of northwestern Mexico occurs under these conditions.

Promising Innovations: Space, aircraft, and land-based remote-sensing products. Synthesis of the spatially and temporally distributed water and energy balance, particularly in physically based evaporation, runoff, and snowmelt models. Mobile Raman LIDAR. Improved RADAR and satellite methods for spatially distributed precipitation estimates. Regional climate models nested within General Circulation Models (GCMs). Expanded geographical information system (GIS) capability.

Applications: A major focus of the Center will be to improve the measurement and characterization of precipitation in time and space and to improve estimates of ET, snowmelt, and runoff (8, 9). This will require not only exploitation of emerging remote-sensing products in expanded GIS applications, but also a detailed understanding of soil-atmosphere transfer processes that can be used to translate measured and remotely sensed soil properties into hydraulic parameters like saturated conductivity, infiltration capacity, and moisture-tension relationships (10, 11). Physically based snowmelt models, coupled with improved remote-sensing products, will be used to investigate snow distribution, streamflow, and mountain-front recharge during the melt season (12). Regional climate models nested within GCMs will help characterize the spatial variability and predictability of winter- and summer-monsoon precipitation (13-15). Many of these approaches show promise based on small-scale tests; in the Center, we will develop them for basin-scale application.

Subtask 1.1 – Snow accumulation and melt (Bales, Davis, Leavesley, McConnell): The objective is to develop an advanced set of tools for accurately estimating spatially distributed snow accumulation and melt in seasonally snow-covered catchments, which provide most of the seasonal runoff for semi-arid regions such as the southwestern U.S. Current snowmelt and streamflow forecasting methods are based largely on empirical approaches developed over the past several decades, with steady improvements in data collection and processing occurring up to the present (16). Multi-billion dollar decisions depend on forecasts of water availability and flow. We will integrate newly emerging remotely sensed data on snow, radiation, and land cover with a new generation of models designed to use these data (12, 17, 18) and test the approach at the basin scale (e.g., Salt and Upper Rio Grande rivers). Close coordination with other basin-scale and integrated modeling subtasks (Thrusts 1-2) is critical for both accurate modeling and appropriate evaluation of products. The demand for and impact of this new technology will be continually assessed (Thrust 5).

Subtask 1.2 – Rainfall distribution (Goodrich, Rosengaus, Sanchez-Sesma, Sorooshian): The objective is to develop means to accurately determine the occurrence and spatial distribution of rainfall in semi-arid catchments using satellite data, radar and ground measurements. Satellite techniques pioneered by Hsu et al. (8) have the potential to compensate for sparse ground instrumentation and mountain blockage of radar signals, both of which seriously compromise precipitation measurement in semi-arid regions. Data from heavily instrumented sites and good radar coverage (e.g. Walnut Gulch Experimental Watershed) will be used to develop relationships linking satellite, radar and ground truth rainfall (19), which will then be extended to mountain regions not covered by radar. The work will be especially important to the World Bank funded deployment of Doppler radars in Mexico (20).

This subtask will provide critical input to Thrusts 2-4 and will be conducted in close coordination with climate modeling in Thrust 4.

Subtask 1.3 – Evapotranspiration (ET) and soil moisture (Leij, Marsh, Mohanty, Shuttleworth, Sorooshian): The objective is to map the spatial distribution of ET at the catchment scale. Research will focus on the development of a distributed hydrological model that is capable of describing the evolution of surface energy and water exchanges and the evolution of soil moisture. The model will use: (i) near-surface meteorological forcing derived by downscaling and assimilating remotely sensed and in-situ data into the National Center for Environmental Prediction diagnostic fields; (ii) remotely sensed measures of vegetation type and vigor, and (iii) relevant soil data derived from pedofunctions for the modeled catchment. It will operate in near real time, thus allowing potential application to flood hazard warning. In so doing, the model will document surface fluxes, thereby validating coupled hydrologic-atmospheric models operating in the predictive mode. Surface water and ET are critical for both climate modeling and ground-water recharge (Thrusts 2-4).

Subtask 1.4 – Soil hydraulic properties (Goodrich, Leij, Mohanty, van Genuchten, Warrick): The objective is to develop methods for modeling water flow in catchment soils with sparse data. Vadose zone soil hydraulic properties from directly measured values will be compared with values from indirect methods (e.g., pedotransfer functions), which are derived from simpler soil information such as particle size, bulk density, and organic matter. These pedotransfer functions will be extended to establish pedo-topo-vegetation transfer functions by including landscape (e.g., slope, aspect, elevation, depth to water table) and land use/cover (e.g., vegetation type, density, rooting depth) features for large land areas. This information is crucial for Subtask 1.3 and Thrust 3.

Subtask 1.5 - Runoff and re-infiltration (Goodrich, Nimmo, van Genuchten, Valdés, Warrick): Our objective is to closely couple field experimentation and modeling to understand the failure in scaling runoff/infiltration relationships and achieve uniform runoff model performance over a wide range of catchment scales. Physically based runoff models coupled with interactive infiltration work relatively well in semi-arid regions up to scales of approximately 10 km^2 (21, 22), but model performance significantly degrades at larger scales (> 100 km^2) (23). Proper representation of microtopography and flow convergence is a critical key in breaking the runoff model scaling barrier. We will use rainfall simulator experiments, newly available high-resolution digital elevation data (2.5 m over large areas) from interferometric synthetic aperature radar (IFSAR) radar systems, along with indirect methods of determining soil parameters (Subtask 1.4). This work will interact closely with Thrusts 2 and 4.

4.3.2 Thrust Area 2: Processes Controlling Water and Chemical Balances in Catchments

Background: Although the quantity of water available for use is usually considered to be the primary constraint on sustainable development, often the quality of the water is even more important. As illustrated by the case of the Rio Grande (**4.2.2**), there is a general tendency for severe degradation of the water quality by increases in total dissolved solids with flow distance through the drainage basin. The relative contribution to this degradation by various sources and processes is usually poorly understood and difficult to quantify. The example of the Murray/Darling Basin (**4.2.3**) shows how even apparently benign human activities, such as clearing land for grazing, can result in damaging long-term fluctuations in water quality that may ultimately threaten sustainable use. Quantification of both the sources of salinity and the processes affecting salinity increase must be a priority if adequate water quality is to be sustained. There are three major sources of salinity. "Natural" sources include: (i) "cyclic" salts originating from natural atmospheric deposition and from weathering of rocks ("uncontrollable" source), and (ii) "subsurface" source salts, from dissolution of evaporites, deep basin brines, and geothermal discharges (interception may be feasible). Second are anthropogenic sources such as road salt, fertilizers, and "household" salt that is added to waste water (controllable to some extent). The third source is evapotranspirative concentration. In the lower reaches most arid-region rivers are reduced to a fraction of their upstream discharge. Salt additions that might be inconsequential upstream become major problems after evapotranspiration concentrates river water by a factor of 10 or more (controllable to some extent). Factors influencing salinity increases are inextricably linked and require an improved knowledge of the water balance. They are difficult to quantify because salt addition and evapotranspirative concentration operate simultaneously.

Promising Innovations: Advances in accelerator mass spectrometry, conventional mass spectrometry, and other analytical methods allow a suite of environmental tracers to be applied to fingerprint causes of salinization, water balance, and related issues. Integration of new modeling approaches with remote-sensing data to treat water and salt balance at the basin scale.

Applications: A relatively new suite of conservative environmental tracers can now be applied to quantifying sources of salt and processes that increase ground-water salinity. The most important of these are ^{36}Cl, Br, $^{3}H/^{3}He$, chlorofluorocarbons, ^{14}C, B, and As. Although these have been applied separately in local-scale studies (24-27), we will apply them for the first time to a comprehensive understanding of salinization at the basin scale for distinguishing the various salt sources and for separating evapotranspirative concentration from salt addition. Remote-sensing data will be combined with new approaches to quantifying the spatial distribution of recharge and discharge in order to assess the effects of human-induced or climate-induced changes in the water balance. We will also explore the use of microgravity to monitor mountain-front recharge (28) and tools such as tracking of seasonally driven thermal pulses in ground water to estimate percolation beneath arroyos (29) at both the large basin scale and in smaller basins that are not significantly influenced by human activities (Thrust 5).

Subtask 2.1 – Ground-water flow paths and residence times (Bassett, Long, Phillips, Zreda): Our objective is to develop tools for determining recharge areas, flow paths of ground water, and residence times along those flow paths at the scale of a regional aquifer (e.g., Middle Rio Grande, Tucson, Phoenix basins) using a combination of emerging and routine environmental tracers. The $^{3}H/^{3}He$ pair (30) and concentrations of atmospherically derived CFCs (26) will be used to estimate residence times of ground water recharged during the historical period. $\delta^{18}O$ and $\delta^{2}H$ in water will be used to determine the ground-water source (e.g., river underflow vs. mountain-front recharge), work that will be closely linked with Thrust 1. This approach will enable reconstructing residence times, flow paths, and salinity distributions (Subtask 2.2) in the interconnected aquifer-river systems, which will then be used to calibrate the regional ground-water flow model (Thrust 4). The model can then be used to predict transients in water quality, effectively addressing what is perhaps the most critical water resources management issue in semi-arid basins (Thrust 5). Traditional approaches, which focus on physical methods to estimate water balance, fail in part because small fluxes of saline water, whose estimates have large uncertainty, can profoundly affect the salt balance.

Subtask 2.2 – Sources of salinity (Aparicio, Bales, Conklin, Phillips, Tecle): The objective is to develop the use of $^{36}Cl/Cl$ and Cl^{-} and Br^{-} concentrations, together with other environmental tracers, to quantitatively evaluate the causes for increases in salinity along flow paths at the basin scale. Sampling will be done from the headwaters, where solutes derive primarily from atmospheric deposition and mineral weathering by precipitation, through the system to the lower reaches, where solutes derive from both natural (geothermal, deep brines, sedimentary deposits) and anthropogenic (sewage, roads, agriculture) sources (31, 32).

Subtask 2.3 – Mountain-front and alluvial recharge (Duffy, Goodrich, Lal, Long, Nimmo, Williams, Wilson): Our objective is to merge advanced modeling tools with the innovative use of environmental tracers to estimate mountain-front and alluvial recharge and discharge over seasonal to interdecadal time scales (33-35). In addition to the tracers noted in 2.1, we will explore use of the cosmogenic isotope ^{32}Si in soil as an indicator of recharge. The characteristic time scale for storage varies with altitude and the geologic characteristics and structure of the mountain-basin system. Flow-path information (Subtask 2.1) will be used to calibrate a dynamical systems model that is fit to runoff and ground-water data and distributed according to the dominant hydrogeologic features across the mountain front (upland hillslopes, transitional flows through the fault zone, alluvial basin). Stream-channel recharge is covered under Subtask 3.1. The resulting systems approach is suited for water management over time scales from seasons to decades (Thrust 5) and can be integrated with the modeling under Subtask 4.1 and 1.1.

Subtask 2.4 – Diffuse recharge processes (Hendricks, Phillips, van Genuchten, Warrick): The objective is to develop innovative tools for estimating the spatial distribution of ground-water recharge over large areas using a combination of chemical, geophysical, and mathematical tools. Vadose zones in semi-arid regions are significant sites of salt storage and, over decadal to century time scales, perhaps water flux. The approach will build on subtasks in Thrust 1.

4.3.3 Thrust Area 3: Functioning of Riparian Systems

Background: In many semi-arid basins, ground-water resources constitute the primary water source that sustains human habitation, agriculture, and riparian ecosystems. Riparian systems in the Southwest are under great stress, yet they harbor a large majority of the regional biodiversity (36, 37). At present, reliable tools for managing riparian communities do not exist for a number of reasons. These reasons include uncertainties in (i) riparian plant-water relations, (ii) basin boundary conditions, (iii) physical hydrological processes over large areas, such as riparian ET, which is a significant factor in the basin water balance in semi-arid regions (38, 39), and (iv) hydrologic flow paths and residence times. Conflicts between development and preservation typically arise in an atmosphere of ignorance and are exacerbated by institutional disputes and laws or regulations lacking sound scientific foundation (40).

Promising Innovations: Precision isotope/chemical analyses. Scanning Raman LIDAR. Sapflow, stomatal conductance, nutrient flux, and plant architecture measurements to estimate cottonwood/willow/tamarisk and subcanopy ET and plant function. Improved land, aircraft, and satellite remote-sensing products. Passive and active vadose zone and aquifer test procedures to estimate saturated and vadose zone properties and spatially averaged streambed conductance.

Applications: Our detailed studies of hydrologic fluxes that transfer water and solutes among streams, ground water, and plant communities will provide a scientific basis for management decisions affecting riparian systems (41-43). We will focus on two primary management actions: (i) pumping aquifers connected to riparian systems, and (ii) perturbations to nutrient fluxes in sensitive riparian systems. Principal among the resulting scientific management tools will be a well-documented measurement methodology, modeling software, and a decision process that will allow managers to simulate the effects of different levels of ground water and nutrient stress and to chose management actions. We will leverage research efforts from the Semi-Arid Land Surface-Atmosphere (SALSA) Program and Long-Term Ecological Research (LTER) sites in southern New Mexico and Arizona. The goal of SALSA is to determine the consequences of natural and human-induced change on the water balance and ecological diversity of arid and semi-arid basins at event through decadal time scales (44, 45).

Subtask 3.1 - Water exchange in riparian systems (Arias, Cooper, Goodrich, Leake, Maddock, Mohanty, Moran, Stromberg, van Genuchten, Warrick, Watts, Webb, Williams): The objective is to develop a holistic approach for assessing the effects of ground-water development and conjunctive surface-water management on riparian ecosystems. The goal is to provide sufficient understanding coupled with innovative measurement and modeling tools to sustain both the availability of ground-water resources and the viability of riparian ecosystems as crucial corridors of ecological diversity in arid and semi-arid regions. An integrated treatment of ground, vadose, surface, and plant water movement (ET), closely coupled with riparian ecology, is critical given the different time scales of interaction: (i) ET varies over both daily and seasonal cycles, (ii) ground water generally changes over months to years, (iii) vadose zone moisture varies from hourly to multi-year scales depending on location, (iv) surface flow has both a baseflow (ground water) and quick response component, and (v) ecological plant succession from water stressors varies from annual to decadel time scales. Our approach is conceptually novel in that hydrologic and ecological interactions will be studied over all these time scales. This will be accomplished using intensive short-term experimental campaigns coupled with long-term studies and monitoring. Intensive multi-disciplinary experimental campaigns will be carried out with simultaneous hydrologic, plant, and remotely sensed measurements from the regional ground-water aquifer through all water pathways to the lower atmospheric boundary layer in riparian regions experiencing varying degrees of hydrologic stress (gaining, intermittent, and ephemeral reaches) (see (44) for an experimental model to build upon). Coupled long-term studies in these reaches will result in tools to predict ecological succession with changing hydrologic stress. A Center is the only realistic mechanism to enable ground-water, vadose zone, and surface-water hydrologists to work closely with plant physiologists, ecologists, and micrometeorologists over a period of sufficient length to acquire the necessary data, conduct analyses, and develop detailed models of riparian function. This subtask will interact closely with Thrusts 1, 2, and 4.

Subtask 3.2 – Nutrient cycling (Bales, Conklin, Grimm, Harvey): The central objective is to understand the role of biogeochemical cycling in the hyporheic zones of streams as a pathway for removal of natural and anthropogenic solutes in riparian ecosystems. Riparian zones can be highly variable, depending on channel type, perturbations (such as beaver dams), and local vegetation. The interaction of nutrients and biota affects redox conditions in shallow ground water (46), which influences the movement of anthropogenic inputs in the system (e.g., metals) (47, 48). The efficiency of this biogeochemical cycling depends on availability of nutrients, characteristics of the riparian ecotone, and hydrologic characteristics of hyporheic flow paths. In streams of the semi arid Southwest, the common limiting nutrient is nitrogen (49). Large N 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 similar seasonal patterns (50). Given the central importance of this element, we will focus our investigation on determining the role of the riparian ecotone in retaining nitrogen inputs, although other materials will also be studied. We will build on Subtask 3.1 efforts and use natural and introduced tracers to determine the extent of the hyporheic zone (Br^-, radon, short-lived radium isotopes, and temperature gradients). Innovative use of these tracers will help to identify subsurface (hyporheic) flow paths in both the active channel and riparian zone. ^{15}N will be used to determine N transport and retention in the ecosystem. Studies will be extended using our modified versions of OTIS (51,52), a numerical code used to estimate hyporheic zone parameters. Using our results, modeling under Subtask 3.1 will incorporate the hyporheic zone in describing ground-water/surface-water interactions. Identification of sources and fates of nitrogen inputs will be coordinated with Subtasks 2.1 and 2.3.

4.3.4 Thrust Area 4: Integrated Modeling of Catchment-Scale Processes

Background: Planning and operation of large-scale water systems must deal with year-to-year variability of inflow. Water-resources decisions are based on hydrologic forecasts made days, weeks, or months in advance (53). Often, the decisions carry significant economic impact, and uncertainty dictates that operations of reservoir systems be very conservative. Good predictions can lead to significant benefits, however. In Fall 1997, predictions of a strong El Niño led the Salt River Project to modify releases to take advantage of predictions of higher-than-average precipitation during the late winter season. By supplying users directly with surface water rather than ground water, they vacated reservoir capacity for future inflows, saving over a million dollars in pumping costs and avoiding further drawdown of the regional aquifer. Similar potential exists on the El Fuerte and Culiacán river systems in Mexico (54). Long-term operations in the range of a year and longer could also benefit from improved hydrologic forecasts (55-61).

Computational models of hydrologic systems provide a conceptual framework for integrating theory with data analyses and experiments (Figure 2). Integrated system models typically couple atmospheric, land-surface, stream, and ground-water subsystems. When properly identified and calibrated, such models provide simulations (and associated uncertainty estimates) that are indispensable for guiding decision-making related to integrated management of hydrologic resources (Thrust 5). Hydrologic systems are inherently nonlinear because they involve feedback among subsystems that are themselves nonlinear. Additional complexity arises due to interacting subsystems that operate at different spatial and temporal resolutions (e.g., runoff may operate on a scale of meters per second, while the ground-water processes to which runoff is linked through infiltration may operate on a scale of meters per day). In the past, limited computer resources and lack of spatially distributed 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.

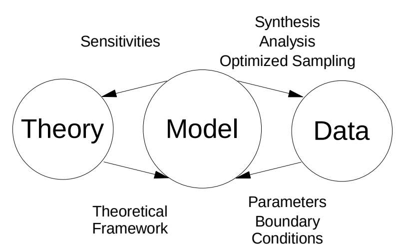

Figure 2. Integrating data with theory

Promising Innovations: Faster computers (10^{12}-10^{14} flops). Integrated models. Improved model parameter calibration and uncertainty estimation procedures. Spatially distributed field and remotely sensed data at finer temporal and spatial scales. Advanced computational and visualization environments.

Applications: The model integrates theory with data (Figure 2). The challenge is to develop methods of coupling subsystems that do not ignore or distort nonlinear feedbacks. Perhaps the most straightforward approach is to simulate each pair of coupled processes at the scale of the member whose physics require the highest resolution. Parameter calibration and model testing will require multi-criteria procedures firmly rooted in Bayesian uncertainty estimation theory (62-64). The high-resolution models will support an experimental environment in which scenarios based on different inputs (boundary and initial conditions, forcing functions, management alternatives, etc.) and their uncertainties can be assessed (65-69). High-performance computing such as that being developed at the Los Alamos National Laboratory will be required for such computations, especially if uncertainty is evaluated through Monte Carlo simulation or numerical analysis of statistical moment equations.

Subtask 4.1 – Integrated climate and hydrologic modeling (Barron, Breshears, Sorooshian, Springer, Winter): The objective is to develop integrated regional modeling from forecasts of climate variability (NCEP, IRI, EPCP) and climate change (IPCC WG1 simulations) through ground-water flow and transport as a tool to support research and decision-making in water resources. One emerging priority issue is the use of seasonal forecasts (e.g., El Niño) in water resources decision-making (Thrust 5), both in the southwestern U.S. and Mexico. The modular Los Alamos modeling system will provide a basis for accommodating results from subtasks in Thrusts 1-3.

Subtask 4.2 – Calibration and evaluation of hydrologic models (Gupta, Sorooshian): The objective is to extend the theory and methods of model calibration to complex, interacting, multiple-time scale, coupled systems models with large numbers of parameters. Such systems must be constrained by a variety of spatially and temporally distributed data sources. The multi-criteria theory developed by Gupta et al. (63) enables handling of such data and will provide the framework for developments based on Bayesian analysis that facilitate recursive (step-wise) data handling, estimation of model uncertainties, and evaluation of model deficiencies.

Subtask 4.3 – Climate modeling (Bossert, Dickinson, Roads): The objective is to adapt a regional climate modeling system to develop short-term (synoptic) and long-term (climatological) characteristics of the hydrologic cycle for the Southwest (adaptable to other regions) for better understanding of the existing climate and for downscaling seasonal to interannual weather predictions and projections of long-term climate change. Control simulations will be evaluated with available data, and modifications will be made in order to gain confidence in the ability of the global and regional modeling system to predict regional climate change. GCM simulations will be used as boundary conditions. Regional high-resolution model data (such as the precipitation, near-surface wind speed, temperature, humidity, and radiation fluxes) will be integrated with a hydrologic model (Subtask 4.1) and a resource input/output flow model to produce monthly to seasonal climatologies of soil moisture, runoff, and local and regional water supply.

Subtask 4.4 – Variably saturated water, heat, and solute movement (Mohanty, Simunek, Suarez, van Genuchten, Warrick, Winter): The objective is to develop predictive tools for simulating one-and multi-dimensional water, heat, and major-ion multi-component solute transport in the subsurface. Applications will be linked to subtasks on salinity sources and diffuse recharge processes (2.2 and 2.4). Models will be complementary to other Thrust 4 subtasks, and techniques will be pursued to determine and use effective hydraulic properties in flow and transport models at larger scales, including the effect of heterogeneity on progressively larger scales. Currently, most soil hydraulic properties and transport modeling are derived on the pedon scale or smaller.

4.3.5 Thrust Area 5: Sustainable Water Resources Management

Background: Water policy in semi-arid regions such as the Southwest is increasingly driven by the need to secure reliable long-term water supplies of adequate quality in the face of dwindling ground-water reserves, over-committed surface-water supplies, and rapidly expanding demand from population growth and increasing impacts of climate variability. Therefore, the end users of much of the research completed within this Center will be policy makers, managers of water utilities, operators of reservoir systems, farmers, recreational activity providers, and other major water users. In managing water resources, both quantity and quality are critical for long-term sustainable development. For example, under the Arizona Groundwater Management Act, new development can proceed only if there is a 100-year assured supply, which is especially critical where ground water is the main supply (e.g., Tucson). Unfortunately, these regulations do not address the issue of adequate water quality. Conjunctive use of surface water and ground water can increase the efficiency, reliability, and cost-effectiveness of water use, particularly where spatial and temporal imbalances exist between water demands and natural supplies. Conflicts also exist between competing users. For example, 80% of water use in the Southwest is for agriculture; however, a shift toward greater municipal and industrial use is a current trend that is expected to continue on both sides of the U.S.-Mexico border because urban users are willing to pay more for water. Inter-regional transport of surface water is another important component of water supply for the greater Southwest and could increase in the future. The Northwestern Interconnected Hydraulic System (Mexico) plans the transfer of about 2,000 million m^3/yr of water over a distance of 1,000 km. Some parts of the system are already operational, while others are under construction, and some others remain as plans (70). In addition, consequences of ground-water pumping, artificial recharge, and water banking must be addressed in the context of long-term planning as they affect water availability, subsidence, and critical environmental habitat.

Promising Innovations: Stakeholder involvement in defining research to meet the needs of decision makers and use of established social science methods to identify user perceptions, vulnerabilities, needs and priorities. Because competing demands are an increasing challenge for sustainable water resources management we would also use innovative methods to integrate hydrologic and social information including integrated assessment, conflict resolution, geographic information systems, optimization and other decision support systems.

Applications: Improved seasonal to interannual forecasts, long-term climate projections, and better procedures for scaling of the hydrology and climate, including estimates of uncertainty, will provide the foundation for improved management of water resources. A combination of regulatory control, supply enhancement, improved decision-making, and market forces will be needed to maintain the balance between supply and demand. Solutions require a combination of policy, economic analysis, planning, and management of resources using advances in technology of optimization theory, integrated assessment, and conflict resolution. The Center will provide a stable central resource for transfer of decision-making information to users. Water suppliers such as the Salt River Project, Elephant Butte Irrigation District, and El Fuerte River system in Mexico will be the primary collaborators on problems associated with large-scale water supply. The process for developing operating policies for the El Fuerte River system will include conflict resolution. This range of collaborators will allow comparisons between different policy options and institutional settings.

Subtask 5.1 -- Water resources decision making (Buras, Dracup, Lansey, Sorooshian, Valdés, Varady, Yeh): The main research objective is to develop innovative approaches to water resources decision making under uncertainty. This includes developing decision support systems that incorporate recent advances in optimization under uncertainty and simulation. These systems can be used by water resources managers in the evaluation of alternatives and for showing the impact of policies when different interest groups are searching for compromise solutions. For example as new forecast tools become available (e.g. seasonal forecasts of El Niño), decision makers need improved tools to make use of the uncertainty in these estimates in their decision making processes. This task will employ the findings of Thrusts 1 and 4 to forecasts of water supply and demand in providing an avenue for dissemination to decision-makers.

Subtask 5.2 -- Surveys of user perceptions and needs for hydrologic information) (Bales, Hutchinson, Liverman, Sorooshian, Varady): Surveys and interviews with water resources decision makers (water utilities, irrigation districts, management institutions) will be conducted to identify information gaps, needs, valuation and barriers to effective use of scientific information in the areas of surface-water/ground-water interactions, water quality, seasonal forecasts, and geographic resolution of data. A variety of techniques will be compared so as to identify the most effective methodologies for continued and interactive stakeholder input into scientific research in both the Southwestern U.S. and northern Mexico. This task expands upon an ongoing NOAA supported pilot project to work with the stakeholder community on climate information needs (www.ispe.arizona.edu/).

Subtask 5.3 – Development and assessment of policy options information (Brookshire, Emerson, Glennon, Little, Liverman, Varady): This task will examine the implications of changing water demand and policies in arid regions such as the southwestern U.S. and northern Mexico. Qualitative (interviews, legal and historical analysis) and quantitative (statistical models, simulations, cost-benefit analysis) methods will be developed and combined to assess the implications of demographic and economic shifts (e.g. population growth, urbanization, agricultural intensification), changing legal structures and economic markets for water (e.g. ground-water law, Indian rights, water marketing and banking), and changing public attitudes (e.g. to ecosystem protection, property rights) for sustainable water management. Research will focus on how these changing policy environments generate needs for new and improved scientific information.

Subtask 5.4 – Integrated assessment (Bales, Hutchinson, Liverman, Sorooshian, Varady): . This task sets out to build fully integrated models for sustainable water management using improved scientific information and modeling techniques including both quantitative simulation models and qualitative conflict resolution scenarios as well as combined approaches. Initial work will focus on the San Pedro River in Arizona (where studies in conflict resolution and integrated modeling have already begun) and on a similar river basin such as the Rio Fuerte in Mexico. The models will be used to evaluate the use and benefits of improved scientific information such as seasonal forecasts, water quality and surface-water/ground-water interactions.

5. Education Initiatives

Education Highlights – Plans Include:

- Three new or revised courses for undergraduate non-science majors.
- A new one-year masters of engineering degree for water resource professionals at UA, ASU, and NAU.
- Over 30 post-doc, graduate, and undergraduate RA and TA positions.
- Student exchanges with University of Mexico and other foreign institutions.
- Earth system science summer research opportunities for teachers at Columbia's Biosphere 2 Center.
- Pre- and in-service science teaching courses developed in collaboration with UA College of Education.
- An information clearinghouse linked with water resource centers and agricultural extension offices.
- Participation with MEP, MESA, MORE, and AISES minority outreach and support programs.
- Public and school-based educational activities and signage at Biosphere 2 Center.
- Teacher/classroom mentoring by university students to facilitate TUSD Systemic Change Initiative.

We propose an ambitious, multifaceted approach to educational outreach, proposing projects where there is a mutual advantage to succeed between the current and outside collaborators. This approach is grounded in the excellent educational outreach infrastructure that exists at the UA (see Table 1). Many of our collaborators have long-standing commitments for public and student-based outreach activities (see letters of support from USGS and USDA-ARS), and our academic colleagues have decades of experience teaching science to students at all levels.

Table 1: Major education and outreach collaborators

Organization	**Function**	**Link**
American Indian Environmental Health Science Com. Outreach Pro.	Minority outreach	
AZ Water Resources Research Center (WRRC)	Public/teacher outreach & support	ag.arizona.edu/AZWATER/
AZ Agricultural Extension Service	Public education	ag.arizona.edu/extension/
American Indian Science and Engineering Society (AISES)	Minority support	www.colorado.edu/AISES/
Columbia University's Biosphere 2 Center (B2C)	Teacher research experiences; workshops	www.bio2.edu/
Global Learning and Observations Benefit the Environment (GLOBE)	Teacher training; student science opportunities	www.globe.gov/
Institute for the Study of Planet Earth (ISPE)	Undergraduate education; public education	www.ispe.arizona.edu/
Instituto Mexicano de Tecnologia del Agua (IMTA)	Public education and outreach	www.imta.mx
NAU Science and Mathematics Learning Center (SMLC)	Minority outreach	www.nau.edu/smlc/
Science and Mathematics Education Center (SAMEC)	K-12 education	samec.lpl.arizona.edu/
Tucson Unified School District	Teacher mentoring	www.tusd.k12.az.us/
U.S. Forest Service SW Minority Programs (MORE, MESA)	Minority outreach	
Udall Center	Public education	vpr2.admin.arizona.edu/udall_center/

5.1 Undergraduate Education

Effective undergraduate education that provides non-science students with an opportunity to build inquiry, a sense of wonder, critical thinking skills, and life-long learning skills is essential if we are going to prepare tomorrow's teachers, business people and voters to make decisions in a technological yet sustainable society (1). Students at the UA must complete a series of general education courses in the natural sciences. The Center will have the critical mass needed to introduce a significant fraction of the undergraduate student body to water resources and hydrology – first at the UA and later at educational institutions in the semi-arid world.

General Education Course Development (Luft, HWR Faculty): We will nurture development and evaluation of: HWR 101, a level one overview of hydrologic science; HWR 203, a level two class on Arizona water issues from a community-focused and problem-based perspective; and HWR 205, a level two class that focuses on pressing issues of water sustainability in semi-arid regions. As general education courses, all three must cover certain basic scientific principles, and are expected to engage students in active learning. Pre-service science teachers will be recruited as teaching assistants, and will gain valuable science teaching experience through their participation in these courses.

Virtual Classroom Course Development (Bales, Gupta, Luft, Sorooshian, Washburne): The above three courses and portions of HWR 250, the cornerstone in the UA undergraduate program in hydrology, will be made available over the web and by CDs for university credit to any citizen or high school student. For example, the HWR 101 and HWR 250 laboratories will be converted into web/CD accessible, interactive exercises, simulations and animations. We already have experience in this area through an NSF grant for our Introduction to Global Change Lab (see: www.hwr.arizona.edu/Alpine/IGCL/home.html). We expect to collaborate with the developers of a new type of CD-based, asynchronous learning environment (ag.arizona.edu/NSC/courses/104nsc/104cont.htm (72)). To encourage effective dissemination of these courses, the Center will host an annual workshop for teachers or supervisors of students to introduce and promote these resources.

Minority Outreach (Tellez): Two scholarships will be made available through AISES every year for full tuition support while the student is enrolled in an undergraduate hydrology program at a collaborating institution within this Center. We will take an active role in the Minority Engineering Program (MEP) at the UA, which is an academically based support community reporting to the Dean of Academic Affairs, College of Engineering and Mines. MEP starts working with pre-college under-represented student groups and women in Arizona throughout grades 6-12, provides financial support and mentoring to retain students upon entering college, and promotes career opportunities through industry exchanges and information.

5.2 Graduate Education

Research Assistantships (Senior personnel): Graduate students are the life of most research efforts and serve as seeds of innovation and invigoration to the agencies and offices in which they are employed after graduation. The Center will provide support and industry internships to over 30 graduate students each year (see sections 12 and 15). The UA has a demonstrated ability to attract top students to hydrology; and both the UA and partner institutions attract top students in many disciplines related to water resources. Through the proposed Center we will expose those students to an impressive breadth of cutting-edge research, offer a truly interdisciplinary education, and enable them to complete their degrees in a timely manner. Table 2 gives a profile of M.S. and Ph.D. degrees completed over the past three years under senior personnel.

International Collaboration (Liverman, Valdés): Four three-month living stipends will be made available to graduate students and professionals from collaborating institutions in Mexico to visit members of the Center for cooperative research and training. These short visits are intended to stimulate further long-term collaboration. In addition, the ICSC-World Laboratory has allocated a post-graduate fellowship at the UA to a qualified candidate from a developing country in a semi-arid region (see appended letter).

Masters of Engineering Program (Bales, Sorooshian, Valdés): A one-year Masters of Engineering degree has recently been established by the Arizona Board of Regents. Course work can be completed through affiliated programs at any one of Arizona's land-grant universities (UA, ASU, NAU). The Center will develop a water resources engineering option targeted specifically at water resources professionals. After a two-year start-up period of classes designed to attract students, the program is expected to become self-sustaining. Association with the Center will give this degree option the visibility, uniqueness, and resources needed to attract both a regional and an international student body.

Table 2. Graduate students supervised by senior personnel (completed during the past 3 years).

			M.S.					*Ph.D.*				
	Citizenship		Minority**, Y/N					Minority**, Y/N				
			Male		Female			Male		Female		
Name*	US	Other	N	Y	N	Y	Yrs	N	Y	N	Y	Yrs
Aparicio	0	4	0	2	0	2	2.2	0	0	0	0	0
Bales	6	1	4	0	0	0	2.5	2	1	0	0	5
Brookshire	1	1	0	0	0	0	0	2	0	0	0	4
Conklin	11	4	7	3	3	0	3.3	0	1	0	1	5
Davis	2	1	1	0	0	0	2	1	0	0	1	3
Dickinson	5	3	2	2	3	1	3	0	2	1	2	5
Duffy	3	3	1	0	1	0	2	1	2	0	1	3.5
Goodrich	0	1	0	0	0	0	0	0	1	0	0	5
Graumlich	4	0	0	0	1	1	2	1	0	1	0	4
Grimm	0	1	0	0	0	1	2	0	0	0	0	0
Hutchinson	3	1	0	0	0	0	0	3	1	0	0	5.2
Liverman	7	1	1	0	4	0	2	1	0	2	0	3.5
Long	2	1	0	0	2	0	2	1	0	0	0	5
Luft	3	0	0	0	2	0	4	0	0	1	0	5
Maddock	12	3	5	4	3	1	2.5	1	0	1	0	5
Phillips	7	0	2	0	4	1	2.5	0	0	1	0	6
Shuttleworth	5	6	2	0	1	0	3	3	5	0	0	3.5
Sorooshian	2	6	2	1	0	0	2	0	5	0	0	2.5
Valdes	0	7	0	2	0	0	2	0	4	0	1	4
Warrick	0	3	0	1	0	0	2	0	2	0	0	5
Wilson	4	4	2	2	1	0	2.5	0	2	1	0	4.5
Yeh	9	4	5	2	1	1	1	1	1	1	1	3.5
Total	86	55	34	19	26	8	2 ave	17	27	9	7	4 ave

* Leake, van Genuchten, Varady, Williams, Winter, Woodard have graduated no students during this period.
** includes Alaskan Native, American Indian, African American, Hispanic, etc.

Biosphere 2 Center Field Course*: Monitoring the Metabolism of the Earth* (Bales, Dickinson, Goodrich, Graumlich, Shuttleworth, Sorooshian): Earth scientists increasingly recognize that quantifying land-surface processes as mediated by vegetation processes is critical to improving our understanding and ability to forecast climate and hydrology. Promising new field and laboratory techniques include monitoring interactions between processes of carbon exchange (e.g., photosynthesis, respiration) and water use (e.g., evapotranspiration, isotopic measures of water use efficiencies). An obstacle to progress in this field is the lack of training in these emerging techniques among graduate students. In response, the Center will work with B2C to develop a two- to four-week long course for graduate students (both U.S. and international) in state-of-the-art techniques for monitoring land-surface interactions and hydrologic response. A result of this course will be the dissemination of a new generation of technically skilled scholars who can combine field-based measurements of Earth system processes measured at regional and larger scales with hydrologic models of similar scale and scope. The Center will provide some of the resources needed for course startup, with the course expected to become self-sustaining after the first two years.

Professional Development of Teaching Assistants and Faculty (Luft, Sorooshian): In order to enact effective instruction in undergraduate courses (see above), a program will be developed for teaching assistants and professors interested in current science education research. Through the UA College of Education we will offer workshops to prepare academics to instruct effectively in the sciences. The program will cover video and audio analysis, development of curriculum that is developmentally appropriate, questioning of strategies, and meaningful assessment. Within the College of Education, this program will be integrated into a 12-unit sequence that gives a teaching endorsement for Ph.D. students in science and engineering.

5.2 K-12 Education and Teacher Preparation

Science education is particularly at risk from the growing national trend towards alternatives to traditional public schools, such as charter schools, private schools, vouchers, and home schooling. Arizona leads the nation in these trends with 225 school districts, 944 public schools, 289 charter schools, 353 private schools, and some 13,500 home-schooled children. Many of these districts and schools are small and are located in rural areas. Alternative schools are characterized by small numbers of students, stretched resources, and few science departments. Through the Center we have an opportunity to greatly amplify ongoing efforts and facilitate the delivery of better resources to each of these groups. Both content and instruction will align with the recommendations for science teachers in the National Science Education Standards (73), Professional Standards for the Teaching of Mathematics (74) and the Benchmarks for Science Literacy (75). One pioneering effort in this regard is the international GLOBE program, in which over 2700 schools in 70 countries collect and report scientific observations on meteorology, hydrology, soils, and land cover. The GLOBE hydrology (Bales, Conklin) and soil-moisture (Washburne) science teams are based at the UA, and the UA investigators are active in training teachers to be GLOBE participants. This GLOBE connection provides the Center with an excellent avenue to reach schools across the world.

Courses for Pre- and In-service Science Teachers (Bales, Conklin, Luft): An undergraduate course built around the Center's theme will be developed and offered for pre-service elementary teachers. This course will use water issues as a unifying theme to integrate key concepts in mathematics and science. The course content will not only educate teachers, but provide them with material that is applicable to K-8 settings. The same integrated mathematics and science course with hydrology as the focus will be offered in evenings, weekends, or summer for in-service elementary and secondary science teachers to assist their learning of hydrology, issues surrounding water, and inquiry-based instruction. A broader Earth system science course was offered at night to this audience in 1996 (Bales, McConnell) and it was very well received, but was discontinued for lack of funds. As an extension to the proposed university course, teachers will have the opportunity to participate in full GLOBE training. This will prepare them to begin a regular program of environmental observations and investigations once they return to their classrooms.

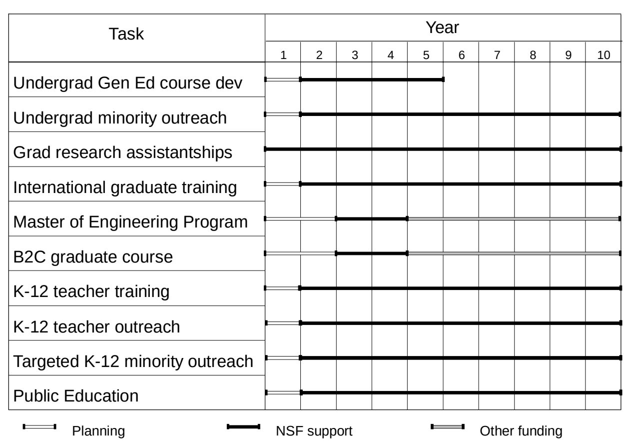

Figure 3. Schedule for education initiatives

Summer Field-based Research Opportunities for K-12 Science Teachers (Colodner, Goodrich, Graumlich, Luft): Teachers will have the opportunity to participate in research projects with Center scientists. Consistent with new standards for professional development (76), teachers will be expected to take their experience and transform one idea into a research project that informs their colleagues about the practice of hydrology or inquiry-based instruction. Each teacher will receive 3-6 units of graduate credit and will be supervised by both a scientist and an education faculty member. Many of our agency collaborators already have or will have field or lab-based internship programs for teachers, which place a teacher alongside a practicing scientist/mentor for 2-8 weeks. A keystone in this effort will be a new summer Earth system science investigation for teachers at the Biosphere 2 Center. For two weeks, a select group of teachers will work with scientists to investigate the water budget within three environmentally distinct B2C habitats. In order to extend the impact of this experience and provide a framework for transferring this knowledge to students, teachers will be offered full GLOBE training.

Dissemination of Curriculum Material (Washburne, Woodard): We propose to join forces with water resource research centers and county extension offices throughout the Southwest to deliver more focused water resources materials and to assist teachers and students. This will be accomplished in part through a water resources clearinghouse that will: (i) produce and update a resource catalog on the many existing, relevant curriculum materials (audience is K-12 teachers and librarians); (ii) establish teacher resource centers in cooperation with local cooperative extension offices throughout the Southwest; (iii) train teachers to use available water resource curriculum materials using master teachers plus GLOBE; and (iv) translate selected curriculum materials into Spanish for use in Mexico and in bilingual programs. The Center will also hold a water workshop for teachers and faculty in conjunction with the SAMEC, which attracts over 100 Arizona science teachers to UA in February of each year for professional development. Broader dissemination of information will be through web pages, presentations at national and local conferences, and GLOBE. Locally, we will work with the Tucson Unified School District (TUSD), using it as a convenient test bed for curricular materials. TUSD, which has just been awarded $5 million over five years by NSF under the Local Systemic Change Initiative (LSCI) Program, is the leading K-12 educational organization in Tucson with over 62,000 students (95-96 data: 45% Anglo, 40% Hispanic, 15% other minorities). Through connections to TUSD, the Center will have an ideal opportunity to dramatically influence water resource-related curricula through seminars for master teachers and by promoting mentoring relationships between teachers and university students (see, e.g. student.biology.arizona.edu/sciconn/).

Minority Outreach (Lindner, Medville, Washburne): Science teacher education on Native American lands is a priority because of Native Americans' vulnerability to water shortages and a growing need to manage Indian water rights. Collaborations with minority-serving organizations will be coordinated by the Science and Mathematics Learning Center (SMLC) at Northern Arizona University. SMLC personnel will support workshops, teacher training, and student-based activities. One opportunity to reach 30 Native American and Hispanic students interested in natural resource careers is the Minority Outreach, Recruitment, and Employment (MORE) Eagle Peak Summer camp; the coordinating agency is the U.S. Forest Service (USFS). Another program, the American Indian Environmental Health Science Community Outreach Program (AIEHS-COP) at ASU reaches Native American communities throughout the Southwest with community-orientated science education outreach. The Center will collaborate with them to deliver a wide range of hydrology-orientated K-14 training and support.

6. Knowledge Transfer

The Center aims to be a significant, visible vehicle for promoting research-user partnerships across the broader water resources field. We will do this by engaging the agencies and companies who have both a direct and indirect stake in water resources decisions. Knowledge transfer will be multi-directional. Center researchers will use a structured approach to get stakeholder impact, bringing researchers and other stakeholders together to jointly evaluate research needs and set research priorities. Technology transfer will be an ongoing and integral part of the day-to-day operation of the Center, and will rely heavily on research partnerships with private and public sector end users of new technology emerging from the Center. Participating institutions include the U.S and international academic, governmental and private sector organizations listed in Section 9. Collaborating institutions are initially those public and private sector stakeholders that have indicated an interest in and commitment to the proposed STC as indicated by the appended letters of support (see also Section 9).

6.1 Participating Institutions

Formal communication between investigators from the ten U.S. educational institutions, two Mexican institutions and five governmental agencies (see Section 9) will be at the annual meeting of the Center (see Section 8.3). At all times, Thrust area leaders will have responsibility for ensuring coordination of subtasks within and between thrust areas.

A critical aspect of knowledge transfer will be data sharing. The Center will have a database manager who will archive data, including metadata, as soon as possible after the data are developed. Data will be available for sharing among Center participants immediately, and available to the larger water resources community shortly thereafter, pending quality checks on data.

Short-term visits of personnel between participating institutions, paid out of Center funds, will be used for more in-depth transfer of information. Knowledge transfer to the broader scientific community will rely on traditional journal and meeting papers, in addition to the Internet.

Examples of ways in which the Center expects to interact with participating institutions follows (not exhaustive). Some of these interactions are committed (see appended letters) and others are projected (see also Section 13).

- *Scripps, UC, San Diego*: Experimental forecasts from Scripps will be used by researchers at UA and other institutions.
- *USGS*: Common scheduling of intensive field campaigns on riparian study areas in the Southwest and sharing of data will lower costs and increase data availability for USGS and the Center alike.
- *Penn State University*: Successful development of tools to investigate water balance components in the Salt River basin and Rio Grande basin during the first five years of the STC will lead to testing of methods in Eastern U.S. catchments in the later years of the Center.
- *Northern Arizona University*: Successful use of isotope and chemical tracers to delineate salinity sources in the Rio Grande basin will lead to incorporation of similar methods by NAU researchers into their studies of salinity on the Hopi Reservation in northern Arizona.
- *ARS, U.S. Salinity Laboratory*: New techniques developed at USSL will be tested for watershed-scale application through collaboration with the STC.
- *USACE/CRREL*: Techniques for modeling snow accumulation and melt in the Boreal forest will adapted and included in watershed-scale research for forecasting snowmelt runoff. The resulting watershed-scale modeling will then be applied to catchments/reservoirs operated by USACE regional offices.
- *International Boundary and Water Commission*: Knowledge transfer with Mexican colleagues will be strengthened through direct contacts set up through the IBWC.

- *Instituto Mexicano de Tecnologia del Agua*: Colleagues from IMTA make short (few days to weeks) visits to UA in order to adapt measurement techniques or decision tools developed at UA to local problems in northern Mexico.

6.2. Collaborating Institutions

Growth of the Center will be largely through greater participation of collaborating institutions in Center research and knowledge transfer activities. It is in part through collaboration with public and private sector partners that the Center will become self-sustaining. All collaborating institutions will be invited to participate in the Center's annual meeting (Section 8.3), and will have access to selected results from research carried out under the Center. Active collaborators (see Section 9) will have earlier access to selected results of research under the Center by actively participating in or supporting the research. The appended letters provide an excellent beginning and good cross-section of the collaborators that the Center needs in order to succeed. Some example means of collaboration follow.

- *Bureau of Reclamation*: Sharing of Bureau of Reclamation data and field sites will be valuable for testing models, with Center-supported personnel working on questions of common interest.
- *Campbell Scientific*: Center field campaigns can be a test bed for Campbell equipment, with Center research providing expanded applications or opportunities for Campbell.
- *Riverside Technologies*: Results of Center research can be further tailored for end users and marketed through Riverside.
- *California Department of Water Resources*: Technologies or approaches developed by the Center can be independently tested by California DWR.
- *NASA Hydrological Sciences Branch*: Exchanges of data and visits of Center personnel to NASA will be valuable for training and collaborative research.
- *Burr-Brown Corp*: Use of Center forecasting tools as indicators of water availability, will provide data for corporate planning.
- *Salt River Project*: Sharing of data and field sites will be valuable for testing models, with Center-supported and SRP-supported personnel working on common projects.
- *Elephant Butte Irrigation District*: This district is a possible site for testing the application of decision-making tools developed through the Center.
- *Tucson Water:* New isotopic tools developed for water balance studies on the middle Rio Grande will be applied to the Tucson basin.
- *Northern Arizona University-Science and Mathematics Learning Center:* K-12 curriculum materials developed and tested at UA will be delivered to reservation schools/teachers through summer workshops offered by SMLC.

6.3 Decision Makers

To effectively transfer knowledge and scientific information generated by the research components to the wide range of decision makers, the Center will work with the UA Udall Center for Studies in Public Policy to undertake a series of activities aimed at the interested members of the public, key stakeholders, and public policymakers. The Arizona Water Resources Research Center and the Arizona Cooperative Extension will collaborate in these activities.

Interested Members of the Public (Bales, Brookshire, Hutchinson, Liverman, Maddock, Varady, Woodard). The Udall Center will organize a large (300-person), tri-annual symposium on *Sustainable Water Use and Management in Semi-arid Regions*, a conference for an array of participants: teachers, private-sector persons, non-governmental organization representatives, individuals in the media, and other interested members of the public-at-large. The event will compliment the schedule of and build upon discussions from the stakeholder dialogues and policy briefings described below. In general, the topics of the presentations and panels will parallel those of the Center's thrust areas and case studies. These presentations will be tailored for a general audience. The symposium will be proceeded by preparation of white papers aimed at a general audience, and will include formal proceedings.

Stakeholders (Aparicio, Arias, Bales, Collado, Dracup, Little, Liverman, Maddock, Sorooshian, Valdés Varady). The Center will convene a series of semi-annual regional *Dialogues on Sustainability of Water Resources Use and Management in Semi-arid Regions*. These events will be small meetings of scientists, local officials (elected and appointed), and other stakeholders (ranchers, developers, water managers) — with about 20 to 30 persons for each meeting and held periodically in different venues in the Southwest (e.g., Tucson, Phoenix, Albuquerque, Las Cruces), including locations convenient for Native American stakeholders. The forums will offer opportunities for detailed discussions about how the Center's research findings will facilitate sustainable water use and management, and about the unmet needs of stakeholders that will help determine new Center research efforts. These forums will build on meetings that we have already instituted under a NOAA-supported pilot project on impacts of climate variability and change in the Southwest (R. Bales, PI). Stakeholders on both sides of the U.S.-Mexican border will be engaged in the meetings.

Policy Makers (Glennon, Liverman, Maddock, Sorooshian, Varady). The Udall Center will organize half-day briefings for policymakers -- specifically state legislative, administrative, or judicial officials in Arizona, New Mexico, and California. These briefings will examine ongoing or emerging, and often scientifically complex, water-resources issues in the region and will include tutorials that focus on the transfer of new knowledge generated from the Center research projects, as well as facilitated discussions to solicit recommendations from the policymakers about what new areas of research might prove most useful. Separate briefings will be organized for the legal community, making use of existing meetings where possible.

6.4 Public Education and Outreach

Outreach (Sorooshian, Woodard): The Arizona WRRC will help coordinate, disseminate and produce public outreach efforts for both the pre- and post-college populations. Many of the Center's activities will be publicly available on the web. This includes educational opportunities, classroom activities, newsletters, research findings, and white papers on topics of significant public interest or impact. Several interns will be hired to maintain the web site and help research public inquires and policy announcements. Each state has a Water Resources Research Center, and the Arizona WRRC is a leader in the network of WRRCs in the Southwest. Through these connections, the Center's outreach will extend throughout the region.

Biosphere 2 Center (Graumlich, Faust): B2C annually attracts almost 200,000 visitors from every state in the nation and from around the world. We propose to develop interpretive signage within the publicly accessible Demonstration Laboratory greenhouses and around the Biosphere that highlights the critical role that water plays in climate and ecology. Each artificially created biome can be linked to similar climates around the world and tied to issues of water quantity and quality.

Extension Agent Training (Woodard): The rural public has a close relationship with the local extension agents and has come to depend upon them for a wide range of information and technology transfer. The Center will ensure that these agents get the latest information on water sustainability issues in their locations.

7. Rationale for the Center concept

The formation of a Science and Technology Center for *Sustainability of Water Resources in Semi-Arid Regions* constitutes a major commitment of scarce resources and can only be justified if the Center serves a unique and compelling function – one that is not being accomplished by individual-investigator projects, governmental research organizations, or industry. In the context of water resources and regional sustainability, the particular function that is *currently lacking is an effective closure of the loop of activities linking measurement, understanding (through synthesis and modeling), education/outreach, decision-making, and intervention* (see Figure 4).

Why do we need a Science and Technology Center for water resources? Population growth has resulted in intense demands on the quantity and quality of water resources worldwide. The *sustainability* of these water resources (over the medium- to long-term) is critically dependent on the ability to correctly manage (plan and operate) our water resources systems under a more variable (and warmer) future climate. Several factors complicate this problem, including: (i) intense competition among many beneficial uses (e.g., municipal, industrial, agricultural), (ii) laws governing such usage, (iii) major gaps in the understanding of mechanisms that influence water availability and quality at various space-time scales, and (iv) *lack of an effective mechanism for rapidly synthesizing and translating the current state of scientific knowledge into usage by the agencies responsible for water management*. The proposed STC will provide an effective and efficient bridge across this gap by: (i) monitoring the critical hydrologic issues that need attention, (ii) identifying which issues can be effectively addressed in a timely fashion by the current state of the science, (iii) coordinating and integrating studies involving many disciplines and institutions, (iv) bringing ripening technologies and ideas to an advanced state of development, and (v) focusing and committing resources at the appropriate level and in a manner relevant to the development of viable interventions (both technological and educational).

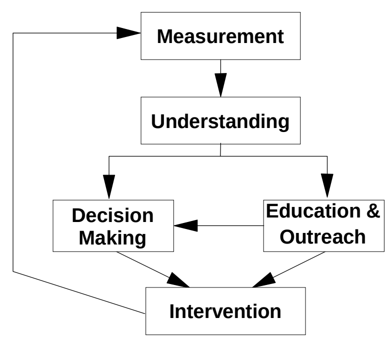

Figure 4. A model of science and sustainability

Why do we constitute the best team to form this Center? We have assembled a unique, multi-disciplinary team. The Director and staff of the Center will be located in the top-ranked Department of Hydrology and Water Resources, at the UA. A comprehensive range of expertise will be provided by participants from numerous universities and governmental organizations (see Section 9). By building on the already strong leadership provided by these institutions and individuals, the Center will be an influential world leader in the sustainable management and development of water resources.

What will the Center provide? The proposed Center will help to bring about much-needed change in how water resources are managed in the greater Southwest and other semi-arid regions. The means to determine basin-scale water balance and salinity balance will be developed, including methods to accurately estimate the spatial distribution of precipitation and snowmelt and how these are partitioned into runoff and recharge (both mountain front and alluvial). These tools will enable climate forecasts to be translated into accurate spatially distributed hydrologic resource (quantity and quality) forecasts. Improved scientific understanding and innovative measurement and modeling tools will form the basis for rational strategies for sustaining the ground-water resources while maintaining the biological diversity and usability of riparian systems. Implementation of these strategies will be facilitated by moving water resources into the forefront of K-16 science education, by providing training for water resources professionals and public officials, and by providing a source of accurate and unbiased information to the general public.

8. Management Plan

Management of a large, distributed, Center involving senior personnel from more than a dozen institutions is clearly a formidable task, and our approach builds on that used for other successful research centers at the UA and partner institutions. Using the management structure and leadership illustrated on Figure 5 and described below, the Center will achieve its mission to: (i) create an environment conducive to creativity, cross-discipline synergy, innovation, and excellence in science, education, and technology, thereby bringing about these qualities to their fullest in the Center's participants; (ii) provide a responsive, effective, yet simple forum for making decisions, prioritizing tasks, distributing responsibilities, and monitoring progress across disciplines as well as participating institutional units, and (iii) foster an environment of continuous development and growth of the Center participants, partners, anticipated faculty members, students, and staff.

8.1. Center Organization

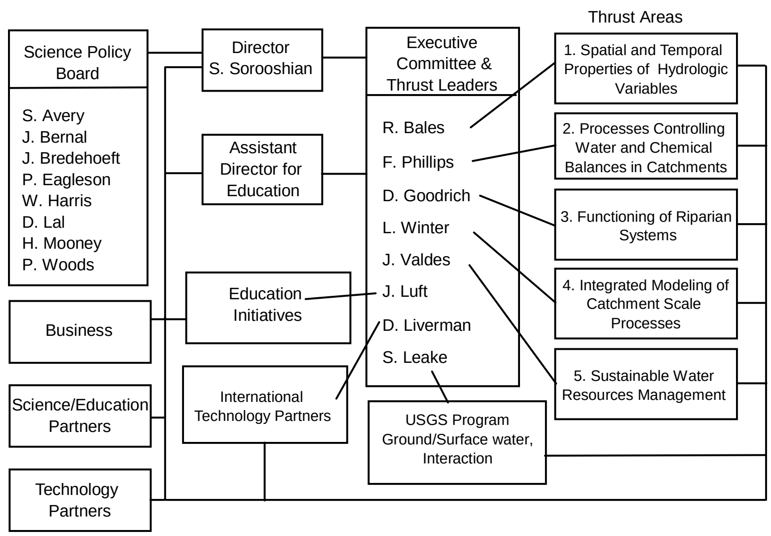

Figure 5. Organization of the proposed Center

***Center Director*:** The Center Director, S. Sorooshian, will oversee the activities of the Center to ensure implementation of NSF policies and guidelines as well as policies established by the Science Policy Board. He will devote 50-75% of his time to the research, educational, outreach, and administrative aspects of the Center. Dr. Sorooshian served as head of the UA Department of Hydrology and Water Resources from 1989-1996, during a time when extramural research in the department grew to nearly $4 million per year. With 14 full-time faculty, 130 graduate students and 30-40 undergraduates it is both the largest and the top-ranked hydrology program in the U.S. Dr. Sorooshian is a fellow in several societies, is currently president of the American Geophysical Union’s 6,000-member hydrology section and has chaired many interdisciplinary national and international scientific panels. Dr. Sorooshian is clearly a leader in the field and one who commands the respect of Center participants, the scientific community and our technology partners.

***Assistant Director for Education and Outreach*:** The Assistant Director will devote 100% of his/her time to the smooth and timely functioning of the Center’s educational activities, including knowledge transfer (see sections 5-6). We will recruit nationally for this position, and will seek a person who has strong qualifications in both science and education.

***Science Policy Board*:** The Board will help guide the scientific and educational direction of the Center. Through annual meetings to review the direction and progress of the Center, the Board will make definite recommendations to the Director and Executive Committee. In this way, each research initiative and educational program will be reviewed by an outside panel. The Board will be asked to evaluate both continuing projects and proposed new initiatives, and recommend how resources should be allocated. Members will be senior scientists from the fields of hydrology, climatology, ecology, geochemistry, and interdisciplinary education. Most Board members will be from institutions not directly involved with the research.

Executive Committee: The Executive Committee, comprised of the thrust-area leaders, the Center Director and one outside representative, will oversee all aspects of Center activities including research, education, and outreach. Research undertaken by the Center will be divided into five thrust areas, with a sixth thrust area being education. Individual projects will be placed under a single thrust area for administrative purposes, although we recognize that a project may involve aspects of multiple thrust areas (e.g., modeling and observations). Thrust area leaders will exert both scientific and technical leadership in their areas. Initially, the outside representative will be S. Leake, who is program manager on the USGS five-year surface-water/ground-water research program in the Southwest. We aim to achieve a high degree of coordination and sharing of facilities with the USGS. We also aim to achieve a high level of collaboration with the USDA-ARS, and D. Goodrich is on the executive committee. The Executive Committee will monitor the progress of all thrust areas, plan future activity, work with the Science Policy Board to set priorities, and make final decisions on allocation of Center resources. Executive Committee positions will be for a nominal 3-year period, with reappointment possible. The balance of representation from the UA versus other institutions shown on Figure 5 will be maintained. One member of the Executive Committee will be also serve as Deputy Director of the Center, empowered to act in the Director's absence and represent the Center when the Director is not available.

8.2. Selection of Research Activities and Allocation of Resources

Selection of research directions and allocation of resources in this Center will be fundamentally different in at least two ways from the single-investigator or small-research-team approach that most university researchers who receive grants from NSF are accustomed. Intellectual merit and scientific impact are necessary, but not sufficient conditions for allocating resources to a specific subtask. First, research and education within a Center should be strongly driven by the expressed needs of the stakeholders that the center is set up to serve. A more formal approach for getting stakeholder involvement in setting research agendas has been developed for the U.S. Global Change Research Program (USGCRP) Southwest regional assessment process (through the Udall Center). Focused workshops and collaboratively prepared reports document: (i) how stakeholders use available information, (ii) what additional information is needed and its value, and (iii) research that can provide new tools or information that stakeholders (77). Under an ongoing pilot project at UA on integrated assessment of climate change in the Southwest, a workshop was held that involved the key individuals responsible for water supply forecasts in the lower Colorado River basin. At this workshop, a research agenda was developed to assess and improve forecast accuracy. The Center will adopt a similar stakeholder-centered approach. Second, the research carried out under different subtasks and by different individuals will be highly integrated, through shared scientific aims, field sites and measurements, and modeling. Both the Executive Committee and Science Policy Board will be charged with ensuring that this integration is ubiquitous in all Center activities. As an extension of this, our research and educational activities will also be highly integrated with complimentary efforts by the USGS, ARS and other agencies (see Section 13).

Effort on individual subtasks will be sequenced over the ten-year life of NSF support for the Center. The order and level will be based on the scientific readiness of the work, the priority set by stakeholders, and the importance to other subtasks. Our policy will be to begin with a small number of key activities, enable planning on others, and then introduce new areas as existing studies are completed and/or Center funding levels increase. Decisions about project selection will be made by the Center's Executive Committee, with the advice and concurrence of the Center's Science Policy Board. We envision a time schedule like that in Figure 6. Note that the level of resource allocation for each subtask may vary from year to year. For subtasks in which research begins after year 1, we will allocate some planning funds in prior years, as indicated by the middle column.

As indicated on Figure 6, some research under the Center will be initiated with funds from NSF but, after a few years, are expected to continue with funds from other sources (i.e., public agencies and the private sector). Many research activities will have significant support from other sources from the outset. One important responsibility of the Center director (and other senior personnel) will be to seek out additional funds to enable growth in the Center and to make it self sustaining. Because water issues are so pervasive across so many sectors of the economies of semi-arid regions, membership in and support for the Center will come from many sectors. In the greater Southwest, water issues, including effects of climate change, are crucial for urban development, irrigated agriculture, recreation, mining, natural resource management, ranching, and electricity production (76). As indicated by the appended letters of support for the proposed Center, we expect to develop support from both public and private sources. The UA commitment to developing a sustainable research center and regional response is illustrated by the very successful Engineering Research Center for Environmentally Benign Semiconductor Manufacture, headed by Prof. F. Shadman in our Department of Chemical and Environmental Engineering. After only two years in operation, the Center now derives over half of its revenue from non-NSF sources, mainly the private sector. The letters from UA President Likens, public agencies and the private sector suggest that the commitment to our proposed Center on water resources is also very strong.

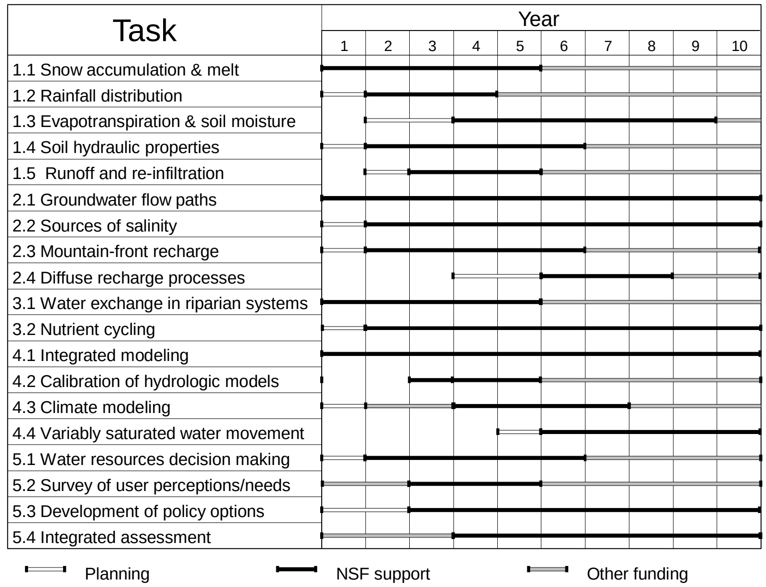

Figure 6. Sequencing of research subtasks

8.3. Annual Meeting.

The Center will hold an annual meeting to further knowledge transfer, assess progress in each of the thrust areas and coordinate activities between investigators from different organizations.

Annual Meeting Agenda

- *Day 1 morning*: briefing by Center director and thrust area leaders, aimed at policy makers, water resources managers and other stakeholders not directly involved in the research of the Center.
- *Day 1 afternoon*: science talks providing highlights of work under the various subtasks, including discussion.
- *Day 1 evening*: group dinner and informal discussion.
- *Day 2 morning*: continuation of science talks.
- *Day 2 afternoon*: meeting of executive committee and science policy board to review progress, evaluate subtask proposals and consider changes in Center activities.
- *Day 2 evening*: continuation of executive committee and science policy board meeting.
- *Day 3 morning*: meeting of Center participants to plan and coordinate the subsequent year's activities.

Participation of Center collaborators from the public and private sectors and participation of Mexican colleagues will be very important for this meeting (see Sections 10-12).

9. List of Academic Participants, Industrial and other Partners

Nearly 70 participants from 12 universities and 5 governmental organizations have contributed to this proposal and expressed a strong interest in being part of the proposed Center. Each will bring a strong record of past accomplishment and unique resources to the Center. With this many potential investigators, it is obvious that not everyone can be active in research supported by the Center, at least when it is first formed. Some will be principal investigators or co-investigators on projects within the five thrust areas, while others may be unfunded (by the Center) collaborators who share resources with projects supported by the Center.

U.S. University Participants (senior participants in bold face)

1. University of Arizona:
    - Dept. of Hydrology & Water Resources: **Roger Bales**, Professor; Randy Bassett, Professor; Nathan Buras, Professor; **Martha Conklin**, Associate Professor; Hoshin Gupta, Adjunct Professor; **Thomas Maddock III**, Professor; Joseph McConnell, Research Assistant Professor; **James Shuttleworth**, Professor; **Soroosh Sorooshian**, Professor; James Washburne, Adjunct Assistant Professor; Marek Zreda, Assistant Professor.
    - Dept. of Atmospheric Sciences: **Robert Dickinson**, Regents Professor.
    - Dept. of Civil Engineering & Engineering Mechanics: **Juan Valdés**, Professor and Head; Kevin Lansey, Associate Professor.
    - College of Education: **Julie Luft**, Assistant Professor.
    - College of Engineering and Mines: Edmund Tellez, Director of Minority Engineering Program.
    - College of Law: Robert Glennon, Professor.
    - Dept. of Geography and Regional Development: **Diana Liverman**, Associate Professor and Director, Latin American Area Center.
    - Dept. of Geosciences: **Austin Long**, Professor.
    - Dept. of Soil, Water & Environmental Sciences: **Arthur Warrick**, Professor.
    - School of Renewable Natural Resources: **David Williams**, Assistant Professor.
    - Udall Center for Studies in Public Policy: **Robert Varady**, Associate Research Professor, Deputy Director, and Director of Environmental Programs; Kirk Emerson, Coordinator, Environmental Conflict Resolution Program.
    - Office of Arid Lands: **Charles Hutchinson**, Professor and Associate Director; Stuart Marsh, Associate Professor.
    - Water Resource Research Center: **Gary Woodard**, Acting Director.
2. New Mexico Institute of Mining and Technology, Hydrology Program: **Fred Phillips**, Professor; Jan Hendricks, Associate Professor; **John Wilson**, Professor.
3. Pennsylvania State University: Earth System Science Center: Eric Barron, Professor & Director; Dept. of Civil & Environmental Engineering: **Christopher Duffy**, Associate Professor.
4. University of California at San Diego, Scripps Institute of Oceanography, Experimental Climate Prediction Center: John Roads, Director; Devandra Lal, Professor.
5. Columbia University Biosphere 2: **Lisa Graumlich**, Deputy Director; Debra Colodner, Director of Educational & Academic Affairs; Alexis Faust, Educational Coordinator.
6. University of California at Los Angeles, Dept. of Civil & Environmental Engineering: John Dracup, Professor; **William Yeh**, Professor.
7. University of California at Riverside, Dept. of Soil and Environmental Sciences: F. Leij, Associate Research Soil Physicist.
8. Arizona State University, Dept. of Biology: **Nancy Grimm**, Associate Professor and Co-Director of the Central Arizona-Phoenix Long-Term Ecological Research Project; Juliet Stromberg, Associate Professor; Life Sciences: Karen Medville, Director, American Indian Environmental Health Sciences Commission Outreach Program.
9. Northern Arizona University: Gloria Lindner, Program Director, Science and Mathematics Learning Center (SMLC); School of Forestry: Aregai Tecle, Associate Professor.
10. University of New Mexico, Dept. of Economics: **David Brookshire**, Professor and Head.

Mexican Institutions

1. Instituto Mexicano de Tecnologia del Agua (IMTA), Mexico: Alvaro Aldana, Director**; Javier Aparicio**, Head, Hydrologic Technology Coordination; Jaime Collado, Head, Water Resources Dept., Micheal Rosengaus,

Group Leader; Jorge Sanchez-Sesma, Hydraulics Specialist.
2. Instituto del Medio Ambiente y Desarrollo Sustentable del Estado de Sonora (IMADES), Mexico: Hector Arias, Director; Christopher Watts, Professor.

Governmental Research Organizations

1. Los Alamos National Laboratory
   - Geoanalysis Group: **Larry Winter**, Group Leader.
   - Atmospheric and Climate Sciences Group: James Bossert, Research Scientist; Daniel Cooper, Research Scientist.
   - Environmental Science Group: Everett Springer, Group Leader; David Breshears, Research Scientist.
2. U.S. Geological Survey
   - Reston: Judson Harvey, Research Hydrologist.
   - Menlo Park: John Nimmo, Physicist and Project Chief, Unsaturated-Zone Flow Project.
   - Denver: George Leavesley, Research Hydrologist.
   - Tucson: **Stan Leake**, Research Hydrologist, Robert Webb, Hydrologist.
3. Agricultural Research Service
   - Tucson: **David Goodrich**, Research Hydraulic Engineer and SALSA Program Co-leader; Susan Moran, Physical Scientist, U.S. Water Conservation Lab.
   - U.S. Salinity Laboratory, Riverside: **Rien van Genuchten**, Research Leader; Binayak Mohanty, Assistant Research Scientist; Don Suarez, Research Leader, Soil & Water Chemistry Unit; Jirka Simunek, Soil Physicist..
4. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory: **Robert Davis**, Research Scientist .
5. International Boundary and Water Commission: Debra Little, Head, Environmental Management and Design Division.

Science Policy Board

- Susan Avery, Director, Cooperative Institute for Research in Environmental Sciences (CIRES)
- John Bernal, Commissioner, International Boundary and Water Commission (water resources eng.)
- John Bredehoeft, Chief Hydrologist of USGS (retired)
- Peter Eagleson, Professor Emeritus, Water Resources Program, Massachusetts Institute of Technology
- William Harris, President, Columbia University Biosphere 2
- Devandra Lal, Professor of Oceanography, Scripps Institute of Oceanography (geochemist)
- Harold Mooney, Professor of Ecology, Stanford University
- Peggy Woods, Head of Science Dept., Amphitheater High School and Adjunct Professor, Northern Arizona University.

Stakeholders and Other Organizations

The proposed Center's outreach program will aggressively pursue partnerships with the private sector and with public agencies at the federal, regional, state, and local level. In this proposal, we list a few as examples of organizations who would supply technologies, use products of the Center's research, or both. We have contacted the individuals listed, and others not listed, regarding their interest in being affiliated with the Center and have secured firm commitments from these and other organizations (see appended letters of support).

- Burr-Brown Corp: S. Madavi
- Campbell Scientific: B. Tanner
- Riverside Technologies: L. Brazil
- Salt River Project: J. Sullivan
- Elephant Butte Irrigation District: G. Arnold
- City of Santa Fe, NM: Mayor L. Delgado
- National Weather Service: D. Fread
- State Engineer, NM: T. Morrison
- NASA-Hydrological Science Branch: E. Engman
- ICSC – World Laboratory: A. Zichichi
- U.S. Bureau of Reclamation: N. Stessman,
- White Mountain Apache Tribe: L. Lacher
- State of Arizona: Governor J. Hull
- Tucson Water: B. Johnson
- California Dept. of Water Resources: M. Roos
- Metropolitan Water District of S. Cal.: W. Horne

10. Intellectual Property Rights

The proposed Center will develop new tools for use in water resources management that will find application in both the public and private sectors. These tools will include measurement methods, field equipment, computer models, and new ways of applying emerging technology. Project teams who develop these new tools will be from multiple academic institutions, from governmental research organizations, and from the private sector.

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

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

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

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

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

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

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

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

11. Projected Funding by Source

The cost sharing and matching funds committed to the proposed Center are nearly $20 million for five years (Table 3). Combined with our requested contribution from NSF, the total projected revenue for the Center is $36 million for five years, or over $7 million per year.

Table 3: Cost sharing and matching funds.

	Thousands of dollars											
	Year 1		**Year 2**		**Year 3**		**Year 4**		**Year 5**		**Total**	
Projected funding	Actual	In kind	Actual	In kind	Actual	In kind	Actual	In kind	Actual	In kind	**Actual**	**In kind**
NSF	2,641	-	2,949	-	2,985	-	3,042	-	2,875	-	14,491	-
Industry(a)												
Committed	50	-	50	-	50	-	50	-	50	-	250	-
Projected	25	25	50	50	75	75	100	100	125	125	375	375
University												
UA	266	1,103	266	1,103	266	1,103	266	1,103	266	1,103	1,330	5,515
UCLA	-	43	-	44	-	45	-	47	-	48	-	226
UCSD	-	90	-	92	-	94	-	96	-	97	-	468
UNM	-	11	-	11	-	11	-	12	-	12	-	57
NMT	-	71	-	71	-	71	-	71	-	71	-	355
Other (b)	-	100	-	120	-	140	-	160	-	180	-	700
Govt.												0
LANL	250	1,500	250	1,500	250	1,500	250	627	250	500	1,250	5,627
ARS	-	377	-	388	-	400	-	412	-	424	-	2,000
USACE	-	500	-	500	-	500	-	500	-	500	-	2,500
Other (c)	-	100	-	200	-	300	-	400	-	500	-	1,500
TOTAL	3,232	3,919	3,565	4,079	3,626	4,239	3,708	3,526	3,566	3,561	17,697	19,324

(a) Includes non-profit organizations; (b) Projected amounts for UCR, PSU, B2C, ASU, NAU, TUSD;
(c) Projected for USGS, NWS and other agency partners

Given the very strong interest expressed by lawmakers, university administration, public agencies and the private sector for the proposed STC, it has an excellent chance of becoming a long-term, sustainable part of the University of Arizona and collaborating institutions. The Center Director, senior personnel and other individuals who will be part of the STC are committed to making the Center sustainable and are committed to doing research under the Center type of operation. Some of the plans that we have for expansion of the Center's funding base are listed below.

1. The UA administration will give high priority to developing a decision package on water resources for consideration by the Board of Regents and Arizona legislature (see appended letter from UA president Peter Likens). A decision package represents a permanent increase to the university's budget, and will provide the base funding needed for the Center to build on in attracting funds from other sources.
2. Agency partnerships will be a significant source of cost sharing, and in some cases matching funds for the Center. We will further engage key water resources agencies in collaborative research, building on the strengths of our existing relationships (e.g. see appended letter from USGS).
3. Cooperation with quasi-public and private entities, including those whose mission involves not only water but also power will be significant to the Center, and offers the possibility for long-term student support, internships and joint research support (e.g. see appended letter from Salt River Project).
4. Active collaboration with private industry has potential for direct support, and for marketing of Center technology. For example, the University of Arizona has a very successful Engineering Research Center for Environmentally Benign Semiconductor Manufacture, which after two years has industrial support at the same level as NSF support, and has a very active industrial research collaboration. As another example, the UA's Department of Soil, Water and Environmental Science has over $100,000 per year of private funds pledged to a planned water quality center.

12. Institutional and other Sector Support

University of Arizona. Resource commitments will involve new faculty hires, space for the Center, graduate student fellowships, release time for the Center director, and staff support. A breakdown of these commitments follows (C is cost share, M is matching).

Item	**C/M**	**Annual**	**5-yr total**
Faculty position, surface water hydrology (joint position, Hydrology and Civil Engineering Depts.)			
Salary	C	$76,000	$380,000
Startup (averaged over 5 years)	M	20,000	100,000
Faculty position, water resources (Hydrology Dept.)			
Salary	C	66,000	330,000
Startup (averaged over 5 years)	M	8,000	40,000
Faculty position, microbiology (Soil, Water, and Environmental Science Dept.)			
Salary ½ A.Y.	C	29,000	145,000
Startup (averaged over 5 years)	M	8,000	40,000
Center director release from teaching, ½ time	C	70,000	350,000
Business manager (accountant), $^3/_4$ time	M	30,000	150,000
Computer system manager, ½ time	M	30,000	150,000
Graduate fellowships (8 each)	M	120,000	600,000
Graduate tuition waivers (8 each)	C	40,000	200,000
Visiting fellow(s)	M	50,000	250,000
Senior Personnal, 10% AY	C	120,240	601,200
ERE on salaries	C	94,430	472,150
Indirect on all costs	C	371,660	1,858,300
Subtotal Cost Sharing		$1,103,330	$5,516,650
Subtotal Matching		$266,000	$1,330,000
TOTAL		$1,369,330	$6,846,650

The faculty positions will involve recruitment of new faculty to the university and include state-supported salary and one-time startup funds for each position. The university's space commitment will be 3000 ft^2 of new research space for the faculty, students, and staff associated with the Center. This space will include office and laboratory space for the two new faculty positions, a computer laboratory for the Center, and offices for the Director, Assistant Director, staff, students, and visitors. Costs for this space are not included in the above list.

Los Alamos National Laboratory. LANL is supporting development of an integrated modeling capability that will be applied to the research proposed under this Center. The current commitment to this modeling is $1 million per year for the next three years. LANL will also contribute to the modeling to be carried out under this Center by making supercomputer time available. DOE's Accelerated Strategic Computing Initiative is a major commitment and, as announced by President Clinton in early February, includes environmental applications (e.g., see www.llnl.gov/usci-pathforward/pf-news.html). In addition, LANL is developing the LIDAR, which is one of the promising technologies that may be used in research sponsored by the Center. The LANL commitment to the LIDAR effort is $125,000 (for riparian campaigns). LANL is also committing one person to the Center's research.

Other Institutions. Other institutions that receive research support through the Center are expected to provide a comparable resource commitment, including in-kind contributions, state or institutional funds, and return of overhead funds to Center investigators and projects.

13. Shared Experimental Facilities

The proposed STC will make maximum use of existing and planned experimental facilities, making incremental additions where needed to accommodate research associated with the Center. These will include computing facilities at Los Alamos National Laboratory and a new, dedicated, cluster of shared workstation computing facilities at the University of Arizona, as well as experimental facilities at the Agricultural Research Service's Walnut Gulch Experimental Watershed, the Arizona District of the United States Geological Survey, and the University of Arizona's Laboratory of Isotope Geochemistry.

13.1. Los Alamos National Laboratory

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

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

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

13.2. USDA-ARS Walnut Gulch Experimental Watershed

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

The Walnut Gulch facility consists of 29 nested watersheds that range in drainage area from 0.002 to 150 square kilometers. Rainfall and runoff instrumentation (including 85 recording raingages) has been in place since 1964. Eleven of the nested watersheds are gauged for runoff with concrete supercritical flumes that are specially designed to give very accurate estimates of runoff (notoriously difficult to obtain in semiarid regions). Extensive monitoring of erosion and sediment transport is conducted on 8 of the smaller sub-watersheds. Hydro-meteorological instrumentation at two locations, one grass dominated and the other brush dominated, provide measurements of the energy balance, soil temperature, soil moisture and CO_2 fluxes. Biotic characterization has been ongoing. A very high resolution Geographic Information System database for the watershed has been created. All of the recording instrumentation is currently undergoing conversion to digital systems with telemetry for remote data transfer. The NEXRAD radar system installed by the National Weather Service at Tucson provides excellent radar coverage. The ARS Walnut Gulch headquarters facilities outside Tombstone include soils and sediment laboratories, and workshops for electronics, machine and welding/fabrication. The facilities and instrumentation are maintained by four full-time support staff, and on-site lodging is available for up to six visiting scientists.

The Walnut Gulch watershed and the containing San Pedro basin are currently the venue for a highly instrumented large-scale multi disciplinary research campaign conducted by the earth science community to understand global change and watershed function in semi-arid regions over a large range of scales. Ground, aircraft and satellite data are being collected and the area will serve as the semiarid validation site for NASA's Earth Observing System ASTER instrument to be launched in 1999. SPOT and LANDSAT images are being routinely archived.

13.3. University of Arizona, Laboratory of Isotope Geochemistry

The Laboratory of Isotope Geochemistry conducts research to develop quantitative understanding of the aquifer hydrodynamics using isotopic tools in concert with conceptual and computer flow models. The research focus is in low-temperature isotope studies and hydrogeochemical research on ground water. Experimental instrumentation includes six low-level beta counters for radiocarbon and tritium measurements, three isotope ratio mass spectrometers for measurements of the stable isotopes of carbon, hydrogen, oxygen, sulfur and chlorine, and an automated device for detecting O and H isotopes in water. Current projects include identification of the sources of active ground-water recharge in the Tucson basin by identifying the bomb-pulse tritium in ground water and by radiocarbon measurements, study of the origin of sulfate in ground water, study of artificial recharge, study of influence of variations in solar energy on ^{14}C production (and thereby the Earth's climate) using high-precision radiocarbon measurements in tree rings, study of the relationships among climate, tree growth and the stable isotopes of carbon and oxygen in tree cellulose, and stable chlorine isotope analysis to assess the contribution of human-contributed chloride and the origin of chloride in basin brines. The lab, led by Professor Austin Long, has five permanent personnel and receives funding through sample analysis in conjunction with numerous projects.

13.4 Arizona District of the United States Geological Survey

The U.S. Geological Survey currently is conducting extensive research on the ground-water resources of the southwestern United States. Many of the projects conducted by District programs in each state have great relevance to this proposal. In addition, scientists in the USGS National Research Program provide research tools and models that are standard to ground-water analysis and research in the United States.

The Arizona District of the USGS located in Tucson is leading a multidisciplinary ground-water project called the Southwestern Groundwater Project that is highly relevant to the proposed center. The project, which is in its beginning stages of work plan development, involves research and evaluation of the spatial and temporal variability of ground-water recharge and outflow in shallow aquifer systems. The project consists of five parts: (i) a regional synthesis and review of existing ground-water models, particularly those related to surface-water/ground-water interactions; (ii) an evaluation of the effects of climatic variability on ground-water recharge and outflow; (iii) development of new geophysical and geochemical techniques for identifying and quantifying the spatial and temporal variability of ground-water recharge; (iv) development of techniques for using riparian vegetation as a tool for assessing the long term stability of shallow ground-water systems; and (v) development of new tools to more realistically model the temporal and spatial variability of ground-water recharge and outflow. This five-year project begins October 1, 1998 and is funded at $1-2 million per year, in addition to existing USGS projects with state and local cooperators. The project will provide several opportunities for collaboration with the proposed STC. In particular, it is planned to conduct studies of ephemeral wash recharge and ground-water outflow in the Middle Rio Grande basin near Albuquerque, New Mexico, and the San Pedro River National Conservation Area in southern Arizona. These investigations will include important research opportunities for students in the hydrology and ecology programs.

In addition, the USGS has other resources that will be useful to the science and technology center. USGS operates the most extensive set of streamflow gaging stations in the United States, thereby providing an essential long-term database from which to evaluate outflow from shallow ground-water systems such as the San Pedro River. The USGS also has extensive analytical facilities for isotopic and other geochemical measurements, as well as geophysical tools for assessing the characteristics of aquifer systems. A drill rig is maintained in Menlo Park, California, and is available to the Arizona District for drilling high-quality monitoring wells. A national database system maintains information regarding wells and ground-water geochemistry.

13.5 University of Arizona Workstation Computing Facilities

A Sun multiple-CPU high-performance compute (HPC) server with 2GB RAM, 200GB of disk space, and high capacity tape drives will be purchased to provide a parallel processing resource for data analysis and numerical modeling. The HPC server will act as a file server until a dedicated file server is purchased. Several desktop workstations will serve as client machines in accessing the server. In addition, the Department of Hydrology and Water Resources has several multiprocessor Sun Sparc 10s and 20s, a multiprocessor Sun Ultra 2200, an IBM RS6000 591, and a number of lower performance Sun workstations, including a computer lab with 10 Sun Sparc 10 computers that will be accessible to students. The HPC server and desktop PCs will be connected locally with 100 megabit ethernet and most likely the entire lab will have a 100 megabit connection to the campus ATM backbone. The University of Arizona is a vBNS site and the entire lab and or server would be made vBNS accessible. As part of the University Sun Pak Scholar Program, FORTRAN 77/90, C and C++ compilers are available to all university users. ESRI's ARCINFO, Erdas Imagine and Matlab will be available through an existing University site license.

13.6 Jornada and Sevilleta LTERs

These two Long Term Ecological Research Sites (LTER) in New Mexico are candidate locations for watershed-scale and riparian research. Given the already active biological and other research on site, these represent excellent resources for the Center. There are major advantages to conducting research on the LTERs, including: (i) security since both LTERs are fenced and patrolled, (ii) existing instrumentation networks for measuring rainfall, solar radiation, soil temperature and moisture, wind speed and direction, and other climate variables, (iii) ongoing hydrologic studies, and (iv) available satellite data.

14. Facilities, Equipment, and Other Resources

FACILITIES

Laboratory:

- UA Laboratory of Isotope Geochemistry, 10% access, UA campus,
- Low level Beta (radiocarbon, tritium), Isotopic ratio mass spectrometer (C, O_2, S, Cl), Ion chromatograph, automatic detection of ^{x}O and ^{x}H.
- UA-HWR Hydrochemistry Labs, 100% access, 250 m^2, walk-in cold room, 10 ion/liquid/gas chromatographs, atomic absorption, UV/VIS spectrometers, microcomputers.
- USGS Analytical Labs (Isotope and Geochemistry), access for joint projects.
- Biosphere 2 Center Biomes, access for students and teachers participating in summer field courses, 1.2 ha of heavily instrumented and environmentally controlled biomes.
- NMT Labs: ^{36}Cl isotope lab (45 m^2); Vadose zone lab; Hydraulics lab/shop

Computer:

- UA campus optical fiber telecommunication network (100 Mb internet, ATM backbone, vBNS access).
- UA-HWR Surface Water Research/Computer Lab, 100% access, 80 m^2.
- LANL computer network backbone

Office:

- UA: 270 m^2 NEW dedicated space for Center; existing space for participating faculty.
- ARS: shared office space for two students working on this project.
- NMT: participating faculty and staff occupy 80 m^2

Field:

- ARS Walnut Gulch Experimental Watershed, Tombstone, AZ, 100 km SE Tucson, 150 km^2, raingages, flumes and archive data access, machine shops and motor pool.
- USGS SW Ground-water Project ($1-2 million in USGS funding)
- USGS operational streamflow network, telemetry and archive data access.
- SRP operational watershed monitoring network, telemetry and archive data access.

MAJOR EQUIPMENT

- LANL: computer resources, 10% access to 100 teraflop, 2048 x 250 MHz super computer; Mobile LIDAR, field time for riparian campaigns.
- UA-HWR: NEW Parallel high-performance computer system, 2 GB RAM.
- UA-HWR: Research workstation cluster, 24 SUN Sparc 10’s and 20’s, Software: Matlab, ArcInfo, Imagine.
- UA-HWR: Student workstation cluster, 10 SUN Sparc 10’s
- NMT: Hydrology/Geophysics computer lab, current NSF upgrade to 7 Sparc Ultras
- ARS: NEW Roving monitoring equipment: sap-flux, soil moisture, meteorology, eddy correlation, Bowen ratio.

OTHER RESOURCES

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

15. Budget

Budget Justification

Senior Personnel: Summer salary is included for senior personnel (see section 9): full professor (Bales, Long, Maddock, Sorooshian, Valdes, Warrick), associate professor (Conklin, Liverman, Varady, & 1.5 mo TBD), assistant professor (Luft, McConnell, Williams & 1.5 mo TBD). Assistant director for education and outreach will be a professional appointment, recruited through a national search.

Other Personnel:
- Five post-doctoral associates will work on projects within the five thrust areas; recruitment will be through a national search. In addition, the U of A will provide partial support for 2 visiting fellows each year (see section 12), including international scholars.
- Twelve graduate students will be supported through NSF funding, with an additional six supported through U of A funds (see section 12) and at least two supported by industrial partners (see section 11).
- Ten undergraduate students will be supported to work both on research and on the educational activities of the center. We will run this undergraduate program like NSFs REU (Research Experience for Undergraduates) program, and suggest that NSF establish this aspect of the Center as a formal REU program. In that case, recruitment will be national.
- One full time programmer will support computational activities, support development of educational materials and assist in technology transfer. One half-time system manager will be supported (by U of A funds, see section 12) at the programmer level to administer computer systems and to perform regular software and hardware maintenance.
- A database administrator will have responsibility for archiving and managing the multi-layered data archive associated with the Center. Experience in HDF and web programming will be essential to manage the distributed archive of the center as well as the archives resulting from various campaigns and research activities. Our aim is to make these data readily available to the broader scientific community via the web.
- One full-time staff technician will be supported by the Center to conduct various chemical, isotope, soil, and water quality analysis. Another position will be divided based on need to support computer aided design of educational material and data collection campaigns.
- The two secretarial/clerical personnel will assist the director, assistant director and business manager. Note that the ¾-time business manager will be supported by U of A funds. At least one secretary will devote 30% time to assist in coordinating the various workshops and educational activities.

All salaries are assumed to increase at a 3% annual rate.

Employee Related Expenses: ERE rates are 18.5% for senior personnel and post-doctoral researchers, 21.2% for staff, and 3.1% for students.

Capital Items:
- Computer equipment by year: (i) server, 5 Unix workstation, 5 PCs, 1 laser printer; (ii) 2 Unix workstation, 5 PCs, 1 color printer; (iii) 2 Unix workstation, 5 PCs, server upgrade; (iv) 2 Unix workstations, 4 PCs, 1 laser printer, server upgrade; (v) 2 Unix workstation, 5 PCs, Server will become core of workstation cluster, for computation, files and web.
- Laptop computers are for data collection in the field.
- Ion chromatograph with autosampler and computer control for analysis of major anions and cations; unit will be equipped to analyze a wide range of concentrations, including low-level tracer work under subtasks 2.2 and 3.2. Will include electrochemical detectors, both conductivity and amperometry; also equipped for gradient isochratic operation.
- Data loggers with pressure transducers are for deep wells (5), shallow wells (24), longitudinal wells (22) and streams (6) for recording water levels (subtask 3.1).
- Sap-flux instrumentation is for riparian campaigns (subtask 3.1), planned for years 4 and 7.
- Dye-injection equipment will be used for various riparian studies (thrust 3.).
- 30-m meteorological towers are for various riparian studies (thrust 3.), and process studies (thrust 1).
- 3-dimensional sonic anenometors are for riparian campaigns (subtask 3.1), planned for years 4 and 7.
- Energy-balance towers and instrumentation are for riparian campaigns (subtask 3.1).

Travel:

- Scientific meeting travel is for U of A senior personal, postdocs and graduate students to present the results of their research in scientific conferences (20 domestic and 6 foreign).
- Annual meeting travel is for senior personnel from other institutions and science policy board members to travel to the Center's annual meeting.
- Administrative travel support is provided for the principal investigatorand co-investigators to participate in NSF meetings, meet with potential industrial/agency partners and coordinate Center activities with other agencies and research programs.
- Domestic field work and collaborative research involves vehicle rental ($40/dy, 25 dy/yr), airfare for collaborators (5 trips/yr @ $1,000/trip), food/lodging for personnel in the field (200 person-dy/yr @ $50/dy). First year is ½ of subsequent years. Year 4 is 3 times this amount, for riparian campaign (subtask 3.1).
- Foreign field work and collaborative research (foreign) involves vehicle rental in northern Mexico ($50/dy, 20 dy/yr), airfare for U of A personnel and collaborators (4 trips/yr @ $1,000/trip), food/lodging for personnel in the field in northern Mexico (100 person-dy/yr @ $40/dy). First year is ½ of subsequent years.

Participant costs: Each year the Center will host a number of workshops, for which some participant expenses will be paid.

- Two focused workshops that address thrust-specific issues will be held each year.
- Virtual classroom workshop is for an intensive introduction to materials for high school or community college teachers. Amounts are for 20 persons at $125 each. First year is for smaller prototype workshop.
- International workshop is for technology transfer with Mexican colleagues. Amounts are for 20 participants at $500 each.
- Biosphere 2 summer course is a graduate Earth system science field course, to be supported for 2 years (one domestic and one international). Amounts are for 20 students at $500/wk for 2 weeks and 10 students for one additional week.

Other Direct Costs:

- Materials and supplies include photocopier costs, paper, printing supplies (laser-jet inks), transparencies, poster materials, CD-ROMs (average of $140/mo per each of 20 senior personnel). Also included are $1000/mo for isotope laboratory and $500/mo for chemical analytical laboratory and $7,000/yr for installation of data loggers (yr 1-4).
- Operations includes communication such as phone and fax, postage, and office supplies, estimated at $100/mo for each of 20 senior personnel (and associated students and post-docs). In year 4, there is an additional $40,000 associated with field deployment of the Los Alamos LIDAR unit, mainly rental of vehicles, generators, shipping and related expenses.
- Minority outreach (university) is for 8 in-state scholarships for undergraduate students in an area related to the theme of the Center. Also includes $2,000 recruitment cost for U of A minority engineering program. First year is recruitment only.
- Minority outreach (K-12) includes: (i) 5 scholarships at $1,000 for MORE program, run by USDA Forest Service; (ii) course delivery by Science and Math Learning Center (SMLC-NAU) to reservation schools ($3,300 for 3 workshops/yr); and (iii) course delivery by AIEHS co-op program (ASU) to reservation schools ($3,300 for 3 workshops). In all 3 cases Center personnel and educational resources will be used to improve water-education component of these courses. First year is for planning and trial course offerings.
- Landsat scenes include 36 in year 1 and 8 per year thereafter. The largest use will be on subtask 1.1.
- Overflights are for visible and near-infrared scenes from aircraft, 5 flights at $8,000 each.

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17. Biographical Sketches

18. Current and Pending Support

19. Letters of Interest and Support from Center Partners