A Science and Technology Center for the Sustainability of Water Resources in Semi-Arid Regions

1. Summary

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 be critically dependent 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). 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. Through an aggressive and pragmatic approach to education and outreach, building particularly on extensive programs already established at Columbia University Biosphere 2, the Center will better prepare educators, scientists, and decision-makers to meet the challenges of managing limited water resources in the coming century.

We have assembled a unique, multi-disciplinary team for the proposed Center. The Center 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, San Diego, and Riverside), Columbia University Biosphere 2, the University of New Mexico, Arizona State University, and three Mexican institutions. Equally important will be the participation of governmental researchers from the Los Alamos National Laboratory, the U.S. Geological Survey, the Agricultural Research Service, and the Army Corps of Engineers. 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 expansion and growth.

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2. Project Description

2.1 Focus and Justification

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 1). Each of these activities involves both science and technology--the science being the descriptive understanding acquired and the technology consisting of the physical and computational tools that facilitate, support, and implement this understanding. However, "big science" and "sophisticated technology" are clearly not enough. To achieve the intervention required for resource sustainability, there must be an effective mechanism for synthesis, integration, education, and outreach to support rational and implementable management decisions.

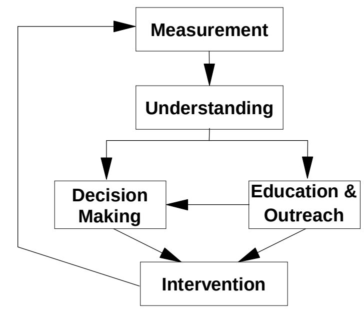

Figure 1. A model of science and sustainability

2.1.1 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 translating, synthesizing, and facilitating the current state of scientific knowledge into usage by the agencies responsible for such management*. The proposed Science and Technology Center 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).

2.1.2 Why Should this Center Focus on Semi-Arid Regions?

A significant fraction of the world (including 25% of the contiguous United States) is under arid or semi-arid climate. Throughout the world, 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., population is projected to grow from 45 million today to nearly 70 million by 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 (including the natural sciences--hydrology, ecology, etc.--as well as the social sciences). 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, thereby facilitating the rapid assimilation of new technologies, analytical tools, and modeling approaches into the understanding and management of water resources in semi-arid regions. Testing of the methods at sites in other geoclimatic regions will extend the consequent impacts beyond semi-arid regions.

2.1.3 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 University of Arizona. A comprehensive range of expertise will be provided by participants from numerous universities and governmental organizations (see Section 2.7). 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.

2.2 Relevance

Economic development in semi-arid regions is being supported by exploiting both surface and groundwater 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 groundwater or through interbasin transfers of water. Readily exploited groundwater reserves become depleted rapidly, which eventually begins to deplete the surface flows as well. Even with groundwater interception and interbasin transfers, nearly all major cities in the western United States, including Albuquerque, Denver, Las Vegas, Los Angeles, and Phoenix, 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 following three case studies. These studies make clear that ecological systems can be disrupted, and water quality can deteriorate dramatically over a relatively short 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.

An effort 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 is very likely to return huge societal benefits in the long term.

2.2.1 Case Study: Interaction of Groundwater 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 arid Southwest. Although riparian systems comprise a relatively small percentage 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 groundwater to satisfy human consumption inevitably affects riparian communities by reducing or eliminating discharge from the groundwater 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. Understanding of groundwater-surface water interaction is fundamental 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 wastewater recharge and other options to sustain San Pedro River flows critical to the riparian habitat (Vionnet and Maddock, 1992).*

2.2.2 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 (Pillsbury, 1981). The salinity of river water normally increases as it flows downstream, but human activities exacerbate this trend in several ways. Consumptive use increases the degree of evaporation and transpiration of the water, 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. Figure 2 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 750mg/L at El Paso, with particularly large increases seen in reaches of the river adjacent to intense agricultural activity. At distances from the headwaters greater than 600 km, 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 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.*

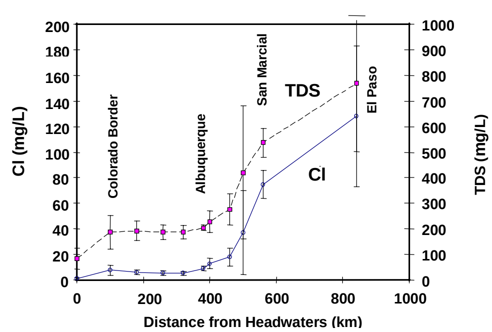

Figure 2. TDS and Cl along the Rio Grande, 1994-1995

2.2.3 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 groundwater. Moreover, multiple ill-defined sources of anthropogenic contaminants often occur (Bassett et al., 1995, Leenhouts et al., 1998). 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 (Wolley, 1994) 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 groundwater 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 (Allison et al., 1990). 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.*

2.3 Research Plans

The focus of the proposed Center will be primarily on semi-arid regions of the Southwestern U.S., but the tools and methods that we develop should be applicable to and will be tested in other bioregions. 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 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 center for 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) an International Research Institute (IRI) for climate forecasting (Scripps and Columbia), and vi) a U.S. Geological Survey initiative to study groundwater and surface water interactions in the Southwest.

Research is organized into "Thrust Areas" that cover the broad subject areas which need immediate attention. A brief description of each thrust, along with examples of promising innovations and emerging technologies and some probable applications, are given below.

2.3.1 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 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 Global Circulation Models. Expanded Geographical Information System 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 (Hsu et al., 1997, Hsu et al., 1998).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 (Tietje and Tapkenhinrichs, 1993; Unland et al., 1996). Physically based snowmelt models, coupled with improved remote-sensing products, will be used to investigate snow distribution, stream flow, and mountain front recharge during the melt season (Cline et al., 1998**)**. Regional climate models nested within General Circulation Models (GCMs) will help characterize the spatial variability and predictability of winter- and summer-monsoon precipitation (Anderson et al., 1997; Chen et al., 1998; Roads et al., 1996). Many of these approaches show promise based on small-scale tests; in the Center, we will develop them for basin-scale application.

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

Background: As the example of Murray Basin makes clear, anthropogenic and natural fluctuations in the salt balance of arid-region river basins pose a long-term threat to sustainable water use. Assessing and mitigating salt-balance problems requires a thorough understanding of the distribution of subsurface salinity, residence times of water in various parts of the system, an understanding of the interconnections between the surface water and groundwater systems, and locations and amounts of runoff versus groundwater recharge. These are typically difficult to evaluate, and are poorly known in most arid-region river basins. We propose to address them using a combination of environmental tracers, remote sensing, and modeling. This framework was identified as a priority research area in the recent "Opportunities in the Hydrologic Sciences" study (National Research Council, 1991).

Promising Innovations: Application of cosmogenic nuclides measured by accelerator mass spectrometry, and combinations of other isotopic and chemical tracers, to issues in environmental hydrogeology such as salinity and water recharge. Integration with space and aircraft remote-sensing data to analyze hydrologic systems using high-performance modeling. Steady-state centrifuge method for estimating unsaturated hydraulic conductivity.

Applications: Research activities will focus on developing new methods for using high-precision isotopic and chemical measurements and other non-traditional approaches as tools for estimating water fluxes, residence times, and flow paths in the heterogeneous environments typical of semi-arid regions. A combination of isotopic and chemical tracers ($^{36}Cl/Cl$, ^{14}C, $^{3}H/^{3}He$, chlorofluorocarbons, Cl, Br, B, As) will be applied for the first time at the basin scale to determine the sources of salinity in surface and groundwater systems and to quantify the contributions of natural salinity sources, anthropogenic ones, and enhancement due to evapotranspirative concentration (Phillips et al., 1988; Carlson et al., 1990; Solomon et al., 1993; Busenberg and Plummer, 1992). The tracer results will be integrated with the basin-scale surface/subsurface modeling effort (described below) to analyze the causes of salinization, predict future trends, and explore alternatives for water quality enhancement. Eastoe et al. (1997) used radioactive tracers from nuclear bomb testing to provide information about the origins of water and flow paths at the basin scale. Pool and Schmidt (1997) demonstrated the use of microgravity to monitor mountain front recharge, and Constantz and Thomas (1996) used tracking of seasonally driven thermal pulses in groundwater estimate percolation beneath arroyos. We will explore these and other innovative techniques and demonstrate the methods at both the large basin scale and in smaller basins that are not significantly influenced by human activities.

2.3.3 Thrust Area 3: Functioning of Riparian Systems

Background: In many semi-arid basins, groundwater resources constitute the primary water source that sustains human habitation, agriculture, and riparian systems. Riparian systems in the Southwest are under great stress, yet they harbor a large majority of the regional biodiversity (Grantham, 1996; Stromberg, 1994). At present, reliable tools for managing riparian communities do not exist for a number of reasons. These 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 (Unland et al., 1998; Maddock et al., 1998), 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 (Glennon and Maddock, 1994).

Promising Innovations: Precision isotope/chemical analyses. Scanning Raman LIDAR. Sap flow measurements to estimate cottonwood/willow ET. Improved land, aircraft, and satellite remote-sensing products. Aquifer-test procedure to estimate spatial average streambed conductance.

Applications: To provide a scientific basis for management decisions affecting riparian systems, we propose a detailed study of hydrologic fluxes that transfer water and solutes among streams, groundwater, and plant communities (Snyder et al., 1998; Williams and Ehleringer, 1996; Schaeffer and Williams, 1998). We will focus on two primary management actions: i) pumping aquifers connected to riparian systems, and ii) perturbation to nutrient fluxes in sensitive riparian systems. The research will lead to prototypes of scientific tools that can be used in a variety of management situations. Principal among these is a well-documented measurement methodology, modeling software, and a decision process. Such a model will allow managers to simulate the effects of different levels of groundwater and nutrient stress and to determine what mix of management actions will achieve desirable conditions in the riparian zone. To accomplish our objectives, we will leverage research efforts from the Semi-Arid Land Surface-Atmosphere (SALSA) Program and three Long Term Ecological Research (LTER) sites in southern Arizona and New Mexico. SALSA's goal is to investigate 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 (Goodrich et al., 1998; Cooper et al., 1996; Moran et al., 1994).

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

Background: Computational models of hydrologic systems provide a conceptual framework for integrating theory with data analyses and experiments (Figure 3). Furthermore, model simulations can be used to guide decision-making. Hydrologic systems are inherently nonlinear because they involve feedback among subsystems that are themselves nonlinear. System models typically couple atmospheric, land surface, stream, and groundwater subsystems. Interactions between subsystems are additionally complicated by the fact that each subsystem operates at a different resolution of space and time. For instance, runoff may operate on a scale of meters per second, while the groundwater processes to which runoff is linked through infiltration may operate on a scale of meters per day. Because of limited computer resources and lack of spatially distributed data at sufficient spatial and temporal scales, it has not been possible in the past to simulate coupled hydrologic systems at scales fine enough to

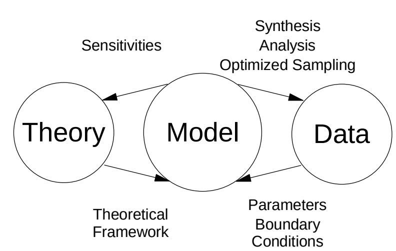

Figure 3. Integrating data with theory

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.

Promising Innovations: Faster Computers (10^{12}-10^{14} flops). Integrated models. 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 3). 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. Once they have been calibrated and tested (Sorooshian et al., 1993; Gupta et al., 1998; Yapo et al., 1998), high-resolution models can support an experimental environment in which scenarios based on different input (boundary and initial conditions, forcing functions, management alternatives, etc.) can be assessed (Wolford et al., 1996). 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.

2.3.5 Thrust Area 5: Implementation in Water Resources Management

Background: Water resources in semi-arid regions such as the Southwest are sensitive to: i) a shift in average precipitation, ii) changes in the year-to-year variance in precipitation, iii) the magnitude and persistence of seasonal fluctuations in precipitation amount and timing, and iv) the frequency and intensity of extreme storms. Because much of the annual runoff and groundwater recharge in the Southwest are from winter precipitation, fluctuations in seasonal snow accumulation translate directly into water availability for municipal and agricultural use. The intensity of rain in summer storms has a direct impact through flooding and erosion, while fluctuations in the net seasonal input of precipitation as rain impacts agriculture and ecosystems. Because more than 80% of water use in the Southwest is for agriculture, transfer from agricultural to municipal and industrial use is a current trend that is expected to continue because urban users are willing to pay more for water. Inter-regional transport of surface water is an important component of water supply for the Southwest and could increase in the future.

Promising Innovations: Integrated observations and modeling as planning and management tools, from climate dynamics to groundwater chemistry.

Applications: Research in the other thrust areas can be translated directly into actions by water resources management agencies. Water policy in semi-arid regions such as the Southwest is increasingly driven by the need to secure reliable long-term water supplies in the face of dwindling groundwater reserves, over-committed surface water supplies, and rapidly expanding demand from population growth. For example, under the Arizona Groundwater Management Act, new development in some areas can proceed only if there is a 100-year assured supply of water based on projected demands and supply. This is especially critical in cities like Tucson, where groundwater is the main source of supply. In the Phoenix area, water for agriculture and urban use comes from surface water reservoirs on the Salt and Verde rivers, with groundwater providing supplies during seasons and years when surface water flows are below demand. Climate change is expected to lead to less runoff and thus greater demands on groundwater supplies, which would lead to further overdraft of aquifers. The likely response would be a costly restructuring and expansion of pumping and conveyance facilities and further pressure to reduce agricultural production. Our premise is that better knowledge 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, and market forces will be needed to maintain the balance between supply and demand. Using market forces to help determine water allocations and pricing would be a major shift in policy.

2.4 Education and Outreach

The integration of research and education will be a central driver of all aspects of the Center. Although many interconnections already exist in our respective research and education programs, the Science and Technology Center Program represents both an opportunity and a responsibility to integrate research and education more effectively. Overall, our general objectives are to foster effective communication with the public, to encourage greater awareness of educational opportunities for water resources studies at all levels, to improve teacher and student preparation, and to foster two-way collaborations between academia and industry. While the Center's plan will evolve in time, it will be built on a solid commitment to developing significant and transferable programs, especially at the K-12 and university levels. Such programs will help rekindle interest in science and mathematics by connecting education to problems that are not only fundamental, but understandably important to our country given the essential nature of water to human life and to the health of planet Earth.

The new Earth Learning Center that Columbia University has established at the Biosphere 2 Center (B2C) will act as a principal vehicle to disseminate information, scientific results, and new technologies to students, educators, water resource professionals, and to the general public. The B2C attracts almost 200,000 visitors a year from every state and from around the world. It is leading the establishment of partner institutions that will enable the Center to attract and retain university students from under-represented groups. Existing undergraduate partners include Barnard College, Morehouse College, Pomona College, and Pima Community College, among others. These institutions are recognized for their commitment to new opportunities for women and minorities and will help guide and design programs to achieve the Center's educational and outreach objectives. Linkage between the University of Arizona and Columbia's western campus already is strong. A University of Arizona faculty member, Lisa Graumlich, now leads the Columbia research and education programs. The close proximity of B2C to the University of Arizona has proven beneficial for both institutions. For example, B2C has a relatively small faculty, but can tap into the rich faculty expertise at the University of Arizona to expand its educational offerings. Further, B2C has set up an excellent outreach program that University of Arizona educators can make use of to extend their impact on the field. This linkage also engages Teacher's College of New York, further magnifying the Center's impact at the national level.

Pre-college educational initiatives will include efforts to develop and support effective teacher in-service seminars, workshops, and summer symposia to promote and extend the Center's mission. Considerable hands-on science opportunities for K-12 students already exist within the region. For example, the Global Learning and Observations to Benefit the Environment (GLOBE) program's hydrology and soil-moisture investigations are based within the University of Arizona's Department of Hydrology and Water Resources. GLOBE is a hands-on science and education program that unites students (particularly K-12), educators, and scientists around the world in studying the global environment. Connections already established through GLOBE within the U.S. and the around the world will be exploited to extend the reach of the Center's activities.

Outreach to under-represented groups is particularly strong in the Southwestern U.S. because the majority of students throughout the region are classified as minorities, primarily Hispanic, Native American and African American. The B2C resources will also be used as a site for student and teacher institutes, and we will develop summer day programs for K-12 students to reinforce fundamental science skills and to introduce them to global change and water resource issues.

2.5 Administration and Management

Our policy will be to begin with a small number of key projects and then introduce new projects as existing studies are completed. 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. Using the management and leadership structure 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.

Center Director: The Center Director 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. The Director will devote 50-75% of his/her time to the research, educational, outreach, and administrative aspects of the Center.

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. 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 and the Center Director, will oversee all aspects of Center activities including research, education, and outreach. It 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. Board positions will rotate every three years.

Thrust Area Leaders: Studies undertaken by the Center will be divided into five thrust areas. 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.

Assistant Director: The Assistant Director will devote 100% of his/her time to the smooth and timely functioning of the research, educational, outreach, and administrative aspects of the Center.

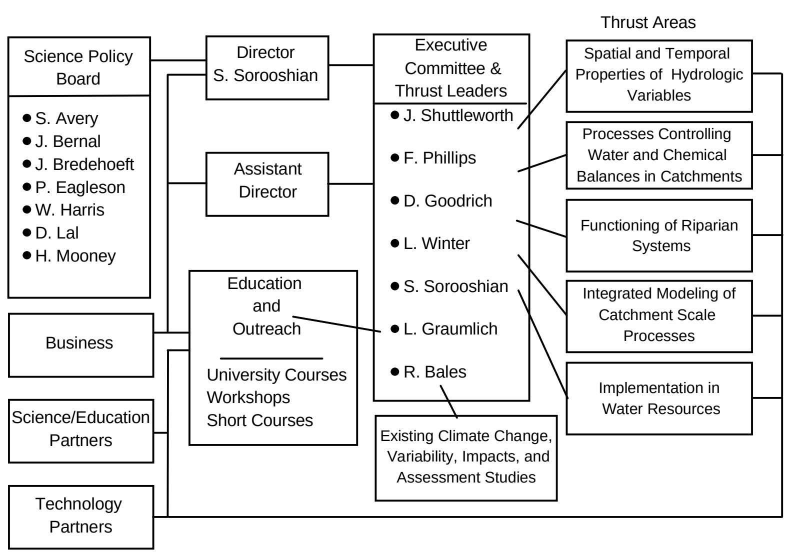

Figure 4. Organization of the proposed Center

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

Nearly 50 participants from 17 universities and governmental organizations have contributed to this pre-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. In order to better develop and define the role of each participant, a series of two meetings will be held in the interim between the time of acceptance of our pre-proposal and submittal of the final proposal. The purpose of these meetings will be to determine each participant's responsibilities in the Center and to decide on the level and form of interactions among the various institutions and individuals. The more-specific research plans required for a full proposal will also be discussed at these meetings.

U.S. University Participants

1. University of Arizona:
   - Dept. of Hydrology & Water Resources: Roger Bales, Professor; Randy Bassett, Professor; Martha Conklin, Associate Professor; Hoshin Gupta, Adjunct Professor; Thomas Maddock III, Professor; James Shuttleworth, Professor; Soroosh Sorooshian, Professor; T.C. Jim Yeh, Associate Professor; Marek Zreda, Assistant Professor
   - Dept. of Atmospheric Sciences: Robert Dickinson, Regents Professor
   - Dept. of Civil Engineering & Engineering Mechanics: Kevin Lansey, Associate Professor; Juan Valdes, Professor and Head
   - 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 and Associate Director
2. New Mexico Institute of Mining and Technology, Hydrology Program: Fred Phillips, Professor; Jan Hendricks, Associate 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
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
9. 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
2. Instituto del Medio Ambiente y Desarrollo Sustentable del Estado de Sonora (IMADES), Mexico: Hector Arias, Director; Christopher Watts, Professor
3. Universidad Autonoma de Chihuahua, Mexico: Abundio Osuna Vizcarra, 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: J. 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
   - U.S. Salinity Laboratory, Riverside: Rien van Genuchten, Research Leader
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

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 pre-proposal, we list only 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 regarding their interest in being affiliated with the Center, and will follow up to secure firm commitments from these and other organizations during preparation of the full proposal.

1. Campbell Scientific: Bert Tanner
2. Riverside Technologies: Larry Brazil
3. Soilmoisture Equipment Corporation: Whitney Skaling
4. Salt River Project: Dallas Riegle
5. Elephant Butte Irrigation District: Gary Esslinger

2.7 Institutional and Other Resource Commitments

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
TOTAL		$800,000	$4,000,000

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.

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. While LANL is not in a position to make firm commitments for the full life of the Center, 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 current LANL commitment to the LIDAR effort is $250,000 for another three years.

Other Institutions. Other institutions that receive research support through the Center will be expected to provide a resource commitment comparable to that provided by the University of Arizona. This will include in-kind contributions, state or institutional funds, and return of overhead funds to Center investigators and projects.