CHAPTER 1
RATIONALE FOR THE SCIENCE PLAN

Introduction: The Hydrological Cycle

The Earth's climate is unique among the climates of all known planets by the coexistence of water in three physical states—solid, liquid, and gas. The cycling of water among the three phases is overwhelmingly important for Earth, driving not just the atmospheric general circulation, but also the very existence of life as we know it. The Earth's water cycle can be viewed highly schematically as consisting of five steps. Under suitable conditions, (1) liquid and solid water evaporate from the ocean and land into the atmosphere; (2) water vapor is transported through the atmosphere by winds; (3) water vapor condenses into cloud droplets and crystals; (4) cloud particles aggregate by coalescence and accretion into larger liquid and solid drops that fall as precipitation to the surface; (5) continental rivers, aquifers, and ocean currents transport the water through land and ocean reservoirs. On average, as much water precipitates to Earth's surface as evaporates. On average, as much atmospheric water is transported to continental regions as is discharged by continental rivers and groundwater aquifers back to the oceans.

Water plays essential parts in both surface conditions and the atmospheric circulation. The conversion of liquid and solid water to water vapor results in a local latent cooling; without this cooling, the land surface would warm, much like hot pavement or the sand of subtropical deserts. On average, the latent cooling at the Earth's surface is balanced by the latent heat released in the atmosphere when water vapor is converted to liquid and solid cloud droplets and crystals. This transfer of latent energy can be huge; the flux of latent energy in the atmosphere is a major component of the transport of energy from the equator to the poles. In general, latent heat is the principal source of energy that drives cyclogenesis (the formation of low-pressure systems) and sustains weather systems like the convective cells that generate tornadoes and the tropical storms that evolve into hurricanes.

Water molecules also have a large impact on Earth's radiation budget. They are strong absorbers of infrared radiation, and the resulting greenhouse effect of atmospheric water vapor is by far the strongest determinant of the Earth's surface climate. Atmospheric humidity is highly variable and responds very sensitively to changes in atmospheric temperature. Thus, atmospheric humidity provides a highly effective feedback mechanism to amplify global climate change induced by other factors. Further, while clouds contribute about 50% of Earth's planetary albedo (reflective power), they also absorb terrestrial radiation as much as the combined "greenhouse gases" other than water vapor. Radiative heating and cooling are major contributions to the diabatic (heat transfer) processes that cause air parcels to rise or sink in the atmosphere, thereby powering weather systems. The net radiant energy reaching Earth's surface is critical in determining temperature, evapotranspiration, photosynthesis, and the Earth's primary biological productivity. Thus, measuring and forecasting spatial and temporal patterns in water vapor and clouds are essential to address climate, water resources, and ecosystem problems.

As water cycles through terrestrial regions, it strongly influences other element cycles, notably those of carbon and nitrogen. Water availability regulates the growth of land plants and thereby the rate of nitrogen uptake and carbon assimilation. Moisture and temperature are the primary variables controlling soil respiration. And water, the "universal solvent," carries nitrogen, carbon and a host of other chemicals over and beneath the Earth's surface to the world oceans. There is growing awareness that nonlinear feedback systems exist between vegetation and climate within the coupled Earth system (e.g., Pielke et al. 1999b). Changes in inland water chemistry are probably also linked to other changes in the global water cycle via complex feedback systems (Vorosmarty and Meybeck 1999).

A Global Cycle with Regional and Local Impacts

Adequate freshwater supply is critical in maintaining human populations and ecosystems. Any threat to the reliability and sustainability of this supply clearly deserves focused attention. Unfortunately, such threats are now increasing in direct response to human pressures. The demand for water, for example, is undeniably increasing with human population; the world's population (currently about 6 billion) has more than doubled since 1950, and it is likely to increase by an additional 3 billion by 2050 (United Nations, http://www.popin.org/6billion/b2.htm) . Meanwhile, the supply of usable water is decreasing due to pollution and other stresses. Some projections suggest that rapid increases in demand coupled with limited supplies will lead to the development of a global water crisis in a matter of decades, with the precise timing of this crisis point uncertain due to limited knowledge of the world's water resources (Rodda, 1995). On the other hand, too much water over a brief period of time can be a curse. Flooding exacts tremendous economic costs (Box 1.1), and the outlook is for even higher costs as more people move into floodplains and areas vulnerable to hurricanes.

Problems of water supply and hydrological extremes tend to manifest themselves at the "local" or "regional" scale. The storm systems that produce damaging floods may be highly concentrated over individual river basins, and a severe drought may span only a few contiguous U.S. states. Nevertheless, addressing such problems scientifically requires a global view of the water cycle—it is the global water cycle that drives local and regional behavior. A region's drought, for example, may be instigated by remote sea surface temperature anomalies. Locally heavy rains may simply be a local manifestation of a complex, continental-scale atmospheric pattern. The local phenomena that affect local water supply and hydrological extremes—phenomena with the greatest impact on society and ecosystems—must be understood in the context of the global system. This scientific understanding can contribute to more effective land and water resource management and hazard mitigation strategies, for example, through improved predictive skill.

To date, assessing variability in water resource availability and predicting and mitigating impacts of hydrologic extremes have all been hampered by large uncertainties in our limited understanding of the global scale water cycle. Uncertainties in estimating water storage and fluxes in the cycle's various reservoirs lead to significant errors in quantifying the overall global water balance (Chahine, 1992; Rodda, 1995), including geographical variations of freshwater availability. Our limited understanding of the many physical processes associated with the water cycle (such as rainfall production) has also impeded our ability to model them accurately, and modeling is fundamental to any prediction strategy. For example, although climate models can accurately reproduce some aspects of atmospheric circulation (e.g., atmospheric pressure distributions), they are poor at reproducing variations in the water cycle (variations in, e.g., relative humidity, precipitation, clouds, runoff, and groundwater). General circulation models (GCMs) have difficulty reproducing certain large-scale aspects of precipitation, as was highlighted by recent simulations of El Niño and La Niña oscillations (Soden, 1999, 2000).

In short, current scientific understanding of the water cycle is significantly limited by measurement uncertainties and deficiencies in models of the physical system. Of course, addressing these two areas will not solve all of society's water-related problems, because many of these problems stem from inefficient management practices and sociopolitical constraints. Nevertheless, improved scientific understanding is absolutely critical for optimal usage of the resource. Only through such understanding can we quantify and predict variations in the water cycle, variations that can have monumental impacts on terrestrial life. The importance of quantifying and predicting these variations is increasing in the face of growing human demand and stress on the environment—with or without global climate change.

If we are to address these socially critical issues in a timely manner, we must go beyond a piecemeal approach to the required research. The relevant multifaceted and interconnected issues require an integrated research program devoted to improving the quantification and scientific understanding of the water cycle at a broad spectrum of scales (global, regional and local). The program must emphasize studies of the feedback mechanisms among processes acting at the different scales, and it must emphasize the explicit integration of information on global water cycles and global cycles of energy, carbon, and nutrients. This integration is needed to reduce uncertainties in estimating water quantity and quality, water movement, and related impacts on ecosystems. Research must also focus on determining how and to what degree human activities influence the water cycle. All such improved understanding is needed to predict water cycle variations and their long-term resource and ecological consequences.

Natural climate variability and human activities have the potential to perturb the fluxes and storages that make up the global water cycle, and these perturbations can have significant societal impacts. For convenience, variability in hydrological processes can be considered through three basic time scales: short-term (weather), seasonal to interannual, and long-term (climate change). The variability associated with each time scale is associated with specific research questions and societal impacts.

Short-term variability, often interpreted as "weather," refers to processes spanning minutes to days. Much of the variability at this time scale is induced by chaotic atmospheric dynamics, which prevent the prediction of a given day's weather weeks in advance. Short-term perturbations in the water cycle that affect society include rainstorms and, in the extreme, flood events. Progress on this front requires analyses of controls on such physical processes as vapor transport, cloud formation, rainfall generation, and runoff production.

Seasonal to interannual variability occurs over time scales of months to years and, like all variability in the water cycle, is determined in significant part by ocean and land processes and their impacts on the atmosphere. Although the time scale of “memory” in the atmosphere is generally short, random variability or persistent general circulation anomalies (such as blocking) can produce significant seasonal variations. The atmosphere's connection to the land and ocean, each of which is characterized by a much longer memory, can induce droughts and pluvial periods extending over seasons to years, with potentially severe consequences for agriculture and water resources (Box 1.2). The El Niño–La Niña cycle is the most obvious example of a coupled phenomenon that produces significant seasonal to interannual variability. It is known to influence the global and regional water cycle far from the tropical Pacific where it originates. Research in this area must encompass such land issues as soil moisture physics, groundwater transport, snow processes, organic matter retention, and nutrient fluxes.

Variability on longer time scales reflects shifts in long-term climate that may or may not be human-induced. Much evidence of natural long-term variability is found in paleoclimatic records; paleolimnological records, for example, indicate prolonged drought conditions in the tropics lasting 100 years or more, and equally prolonged periods of very wet conditions (e.g., Street-Perrott, 1995). Historical data suggest that present-day U.S. precipitation is characterized by more higher volume events relative to earlier decades of the 20th century (e.g., Karl and Knight, 1998). Changes in land cover and land use have been extensive in the United States and the rest of the world, and these changes have local, regional, and even global impacts on the hydrological cycle (e.g., Pielke et al., 1999a; Toon, 2000). Some of these changes can be considered permanent, for all practical purposes (Box 1.3). According to climate model predictions (IPCC, 1996), the most significant manifestation of CO_2-induced global warming would be an intensification of the global water cycle (an increase in global water fluxes), leading to greater global precipitation, faster evaporation, and general exacerbation of extreme weather and hydrological regimes, including floods and droughts. In fact, an increase in atmospheric water vapor would heighten CO_2-induced warming because water vapor is itself a strong greenhouse gas.

What scientific advances are needed to determine whether the global water cycle is intensifying, and if so, how human activities may be causal factors in this trend?

Clearly, regardless of origin, long-term changes in the quantity and quality of water available for municipalities, agriculture, and industry can have far-reaching societal impacts. The possibility of such changes clearly has strong implications for water resource planning (e.g., Lettenmaier and Sheer, 1991). Long-term changes in the water cycle will also be strongly coupled to changes in biogeochemical processes in terrestrial and freshwater ecosystems: water is the main transporting medium for organic carbon and major nutrients (Box 1.4); and nutrients influence terrestrial vegetation processes (e.g., Aber, 1999). Important biogeochemical transformations of C and N species occur within terrestrial and aquatic ecosystems. The rates of critical transformations depend on seasonal patterns of the water cycle. Mechanisms underlying changes in the coupled water, C, and N cycles involve interactions among many components of the Earth system, and they must be characterized in greater quantitative detail to be used for evaluating potential societal impacts.

The impacts of water cycle variability on human society are very real and are well recognized. The National Drought Policy Commission, for example, charged by Congress to "provide advice and recommendations on the creation of an integrated, coordinated Federal policy designed to prepare for and respond to serious drought emergencies," recently submitted their report. The Commission recognized that droughts will occur and that they will cause hardship. To minimize the adverse impacts, the Commission recommended that scientists work with managers to understand which monitoring, research, data collection, modeling, and other scientific efforts are needed. Society has a vested interest in understanding water cycle variability and in predicting specific variations when possible, so as to minimize supply shortfalls and infrastructure damage.

In the face of increasing water demand and other stresses, traditional strategies for managing water supply, and related agricultural and natural ecosystem issues, are becoming inadequate, and improvements in prediction are becoming critical. Water management in the United States and other nations has traditionally focused on manipulating and safeguarding freshwater supplies to meet users' needs. However, water managers are now faced with increasing demands, increasing development costs, capital shortages, government fiscal restraints, less favorable storage reservoir sites, and increasing environmental concerns. For all these reasons, they are beginning to rethink traditional approaches and to experiment (see USGS web site http://water.usgs.gov/watuse/wutrends.html). Environmental Science&Technology (1999) has reported that global water use efficiency will need to double over the next 25 years if the world's food supply is to

What scientific advances are needed to better predict the effects of land use, vegetation, and cryospheric changes on the cycling of water and important biogeochemical constituents?

keep pace with population. As water resources are more fully exploited throughout the world, precise, reliable, and nontraditional management tools become increasingly necessary.

This report does not focus on water management. However, it does focus on the development and use of new scientific methods and results that may greatly improve the efficiency of water management. Such achievements can be particularly high if scientific advances are well coordinated to meet the needs of water, land use, and natural resource management. There will always be a multitude of political and regulatory issues in implementing water management strategies, but they can be much more soundly based. To address issues of wetlands, fisheries, invasive species, and other aquatic biota, good water resource management will depend on better integration of flow regimes and better knowledge of carbon and nutrient cycling and of biotic responses at a range of time scales. Better techniques to assess water quality and quantity are critically needed. Management strategies can have major impacts on both the environment and society, and they need to be adequately assessed. Uncertainties about the water cycle and its connections to carbon and nitrogen cycles limit our ability to make these assessments.

One of the most promising scientific approaches for water management is predictive modeling. By capturing the physical mechanisms that control water cycle variability, along with current state of the system, models can predict water cycle variations over a range of time scales, including those variations that affect freshwater supply (e.g., precipitation, runoff, and groundwater levels). Although water managers have recognized the usefulness of predictive modeling for decades, the accuracy of predictions even today is strongly limited. Fundamental limits to predictability (as determined, e.g., by atmospheric chaos) have yet to be ascertained, but they are presumably far from being reached. To attain the predictability possible, enhanced observational databases are needed, both to improve existing model formulations and to initialize model states. Current model resolutions are also generally too coarse due to inadequate computer resources; as the United States develops the next generation of supercomputing resources, the requirements of water cycle simulation and prediction must be included in the planning.

Better prediction has clear implications for managing rapidly changing human and ecosystem vulnerabilities to hydrological extremes. The Mississippi floods of 1993, which resulted in large economic losses throughout Midwestern urban and agricultural areas, and the devastation to coastal areas caused by hurricanes Andrew and Floyd are but a few of the recent examples of this vulnerability. Planning for and mitigating the impacts of these hydrologic extremes requires significant improvements in predictive capabilities at all three time scales described above. Our limited understanding of the linkages among the water cycle and other components of the global climate system is a major impediment to improving predictions.

New technologies for measuring, modeling, and organizing data on the Earth's water cycle offer the promise of deeper understanding of water- cycle processes and of how management decisions may affect them. It is clearly time to take advantage of these

opportunities. Remotely sensed observations of land, ocean, and atmosphere from satellites and suborbital platforms (e.g., aircraft and balloons) provide synoptic, high-resolution coverage that is unprecedented in the geophysical sciences. The new information from these observations may initiate important shifts in the conceptual basis of these sciences, as indicated by Entekhabi et al. (1999) for hydrology. Examples of the burgeoning use of remotely sensed data abound. Improved rainfall estimates are being derived from ground-based radar and from satellite. Satellite estimates of sea surface temperature, height, and winds can help initialize of coupled ocean-atmosphere seasonal forecast models; and satellite estimates of soil moisture may someday initialize the land component of these models. Satellite-based water vapor measurements are assimilated into weather prediction models. Remotely sensed data have been the basis for many of the advances in snow hydrology, allowing the prediction of basin responses to inputs of water, energy, and chemicals (e.g., Bales and Harrington, 1995). Biotic parameters, including land cover (vegetation), extent of riparian wetlands, and in-stream algal and plant growth can all be detected through remote sensing. These examples are not at all comprehensive, of course; the list goes on and on.

Remote sensing from satellites can radically improve the usefulness of conventional observation networks, but it cannot replace them. A base of spatially and temporally consistent "ground-truth" data (i.e., data collected by direct measurement to verify that remote sensing data are accurate) is essential for work on the water cycle. Data from networks operated over the long term are essential. Determining variability necessarily involves comparisons of data collected at different times and places, and consistency is essential to ensure that any apparent variability comes from the underlying hydrological variables rather than data collection techniques. The archiving of current observations must be continued; and it must be enhanced where necessary (e.g., certain aspects of archiving of radar rainfall data may need to be improved) to ensure that valuable data are not lost. Existing networks and systems must continue operating to obtain current data that can be compared meaningfully with past records. In addition, existing networks and systems must be expanded spatially to ensure that ground-truth data will be available for calibration and verification of new observational systems, especially remote-sensing systems. Finally, the importance of preserving, maintaining, and expanding the existing base of the auxiliary scientific data and information needed for modeling, process, and budget studies[1] must be recognized. Examples of such auxiliary data include digital elevation models (DEM), hydrologic derivative DEM products like stream-channel networks and drainage-basin boundaries, land use and land cover data, digital orthophotoquads, and satellite imagery .

Remote sensing is not the only new technology worthy of mention. Surface and borehole geophysical methods, for example, have led to much improved characterizations of subsurface flow regimes, which had previously been hard to quantify (NRC, 2000). New developments in ground-based instruments, possibly using nanotechnology, might well allow automated measurements in remote locations that could be used to “ground truth” remote-sensing observations. New approaches are being developed and applied to

[1] The term "budget study" refers to analysis of the balance among inflows, outflows and changes of storage of water, energy, and other quantities important to water cycle research as described in this document.

interpret stable water isotopes in terms of water cycle processes (e.g., Kendall and McDonnell, 1998). It is important that this work be integrated with water cycle research. Development must continue on data assimilation methods for weather and climate prediction. They have led to remarkable progress in estimating global water and energy fluxes. Applying the same techniques to hydrology (e.g., McLaughlin, 1995) or biogeochemistry can yield quantitative data for variables that have heretofore been unavailable. Significant progress has been made in validating physical models and in analyzing how calibration can improve their performance (e.g., Wood et al., 1998). Improvements in modeling have also been directed to problems of water management (e.g., Wagner, 1995).

Overall, continuing advances in global observation and modeling of the Earth system promise exciting developments in estimating and predicting water fluxes among ocean, atmosphere, land, and cryosphere over a variety of time and space scales. Such achievements can yield large benefits for water, land, and biological resource management, and thus regional economies—if the information (including related uncertainties) is communicated effectively to decision makers and the public. Various recent predictability studies (e.g., Shukla, 1998) and successful forecasts regarding the 1997–98 El Niño (Barnston et al., 1999; Mason et al., 1999) indicate that scientific advances can certainly have a positive impact on important societal problems.

What scientific advances are required to substantially reduce the losses and costs of water cycle calamities such as droughts, floods, and coastal eutrophication?

Critical Elements of an Integrated Water Cycle Science Program

Recognizing that a new investment in water cycle science is needed, the USGCRP appointed a Water Cycle Study Group (Appendix A) to develop a national research plan for fiscal year 2002 and beyond. Understanding the global water cycle is critical in assessing human, economic, and ecological consequences of global environmental change and/or increasing water demand. "Water is at the heart of both the causes and the effects of climate change. It is essential to establish rates of and possible changes in precipitation, evapotranspiration, and cloud water content. Better time series measurements are needed for water runoff, river flow and the quantities of water involved in various human uses" (NRC, 1998). The pressing needs of water resource sustainability (for both human society and ecosystems) and hydrologic hazard mitigation motivate the research plan presented here.

Such a water cycle science program must go beyond simply accelerating research that is now underway. The water-related problems facing society today are too complex for any handful of individual scientists or agencies to manage alone. An unsystematic approach to these problems, carried out with the vague hope that somebody somewhere will fit all the puzzle pieces together, will not be effective. An *integrated* research plan is essential.

The present plan aims at providing an integrated framework to address the numerous, multifaceted aspects of the problem in a coordinated and efficacious way.

This program must stress ways of developing scientific knowledge of water and its movement in the Earth system in a manner unconstrained by the traditional disciplines—atmospheric science, physical oceanography, hydrology, and terrestrial and aquatic ecology—that have structured our study of water problems to date. The future opportunities and challenges exist across the disciplines, and it is at the boundaries of the traditional disciplines where the new frontiers lie. For instance, hydrologists have extensively studied mechanisms through which precipitation leads to the generation of runoff; but the integrated effects that lead to the dynamics of freshwater delivery to the oceans and the delivery's space-time variability are largely ignored by the oceanographic community. Likewise, hydrologists have not interacted much with the atmospheric sciences community, which has as a central interest in precipitation formation, but generally is much less interested in the space-time variability that controls surface hydrological processes. A more balanced understanding of the fluxes, storage, and dynamics that control water movement and its quality in the land, atmosphere, and oceans will be a critical challenge to water cycle science in the 21st century. In addition, water science must interface properly with the social sciences and users to ensure the translation of scientific progress into societal benefit.

In designing the plan, interdisciplinary aspects of the water cycle and its impacts were therefore given notable consideration. Still, given the complexity of the Earth system and the intricate connections among the various components, the plan could not hope to be fully comprehensive (i.e., involve every relevant discipline) and still be economically and logistically feasible. For purely practical reasons, we were forced to draw the line at certain disciplinary boundaries. The research plan proposed here focuses primarily on atmospheric and land surface components of the water cycle and their interactions with carbon and nitrogen biogeochemistry. It includes studies of the fluxes between the ocean and atmosphere, but it does not include studies of the ocean circulation itself, even though ocean circulation is recognized as relevant and important. Similarly, water vapor transport and distributions are considered explicitly, but many of the associated impacts on atmospheric chemistry are not. Fortunately, research in these and related areas will proceed in parallel with the research proposed here. For a comprehensive view of the global water cycle, we will rely on ample communication with the scientists performing this parallel research.

In preparing this plan, the Water Cycle Study Group had the benefit of consultation with many scientists (Appendix B). The Group was informed about current programs, both within the United States and internationally (Appendix C). In our deliberations, we decided the plan should focus on the science needed to achieve three goals: (1) determining whether the global water cycle is intensifying, (2) enhancing our ability to make useful predictions, and (3) developing information that would mitigate the effects of hydrological calamities (e.g., those described in boxes 1.1 through 1.4 above).

We concluded that three key science questions could be used to structure the science planning process:

1. What are the underlying causes of variation in the water cycle on both global and regional scales, and to what extent is this variation induced by human activity?

2. To what extent are variations in the global and regional water cycle predictable?

3. How will variability and changes in the cycling of water through terrestrial and freshwater ecosystems be linked to variability and changes in cycling of carbon, nitrogen, and other nutrients at regional and global scales?

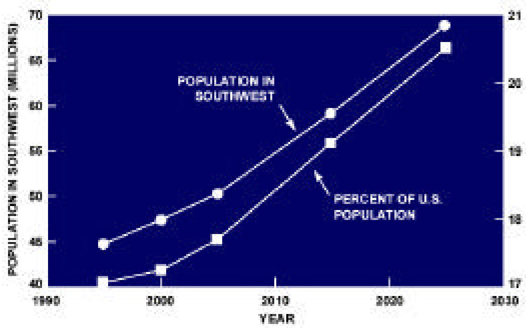
The next three chapters discuss these science questions individually and present a suite of initiatives aimed at addressing them. These questions are not independent of one another (e.g., observations of hydrological and meteorological variables are essential for all three science questions). But they do provide a useful framework for outlining science needs. Initial priorities for research, selected from the initiatives outlined in Chapters 2 through 4, are presented in Chapter 5.

Box 1.1. Damage survey in St. Genevieve, Missouri, during the 1993 Midwest floods [courtesy of FEMA]. Floods cause extensive damage: "during 1991-1995, flood related damage totaled more than US$200 billion (not inflation adjusted) globally, representing close to 40% of all economic damage attributed to natural disasters in the period" (Pielke Jr. and Downton, 2000, citing IFRCRCS, 1997). In the United States, annual flood damage runs in the billions of dollars (Pielke Jr. and Downton, 2000). Improved prediction of floods could reduce these costs substantially, in addition to reducing flood-induced loss of life.

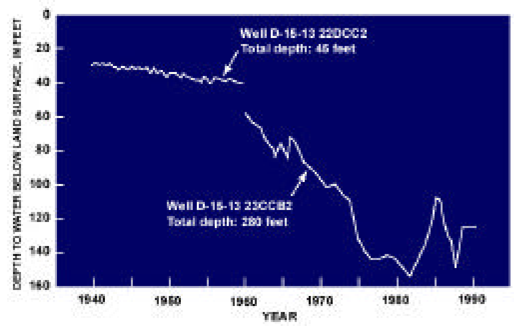
(See http://www.fema.gov/library/photo/midw33.jpg for figure; http://www.fema.gov/library/mw3.htm for description)

Box 1.2. Drought near Bracketville, Texas, in 1980 ravaged the landscape, almost drying up this livestock watering pond [from Preparing for Drought in the 21st Century, Report of the National Drought Policy Commission, 2000]. Droughts are expensive -- the 1998 drought from Texas/Oklahoma eastward to the Carolinas resulted in $6.0-$9.0 billion in damages to agriculture and ranching, and damage from the 1988 midwest drought amounted to about $40 billion. Droughts can also have tremendous environmental impacts, such as a loss of biodiversity through degradation of habitats already stressed from human activities, and social impacts, including diminished food availability, compromised water quality, and conflicts around water rights. Paleoclimatic data [Woodhouse and Overpeck, 1998] show that the climate system has generated massive droughts during the last 2000 years that overshadow the great Dust Bowl drought of the 1930's in both duration and spatial extent. Were such a "megadrought" to occur today -- and we have no way of knowing that it couldn't – the U.S. would be ill-equipped to respond.

(See
http://www.fsa.usda.gov/drought/finalreport/fullreport/ndpcfullreport/ndpcreportpg2.htm
for figure [near top of page].)



Projected population growth in the Southwest, 1995-2025, including Arizona, California, Colorado, Nevada, New Mexico, and Utah



Depth to water in two wells adjacent to the Santa Cruz River in the Tucson Basin near Martinez Hill, Arizona

Box 1.3. WATER IS LIFE. Will there be enough water for the populace, agriculture, and the environment? In the arid and semiarid Southwest, riparian areas associated with streams, rivers, and wetlands occupy a very limited portion of the landscape yet harbor a disproportionately large percentage of the region's biological diversity. Development of groundwater resources for a growing population and increased irrigated agriculture in the last 50 years has resulted in outright elimination or alteration of many perennial streams and associated riparian ecosystems. The Tucson Basin in southern Arizona provides a vivid example of the impacts of ground-water development on these riparian ecosystems. The repeat photographs of a section of the river south of Tucson near Martinez Hill in 1940 and 1989 illustrate the dramatic impact of lower ground-water levels from pumping on the Santa Cruz riparian system. In the 1940's a vibrant cottonwood/willow forest and mesquite bosque was present. By 1989 the riparian vegetation was virtually eliminated. The changes to the stream are profound and nearly impossible to reverse. Data from two wells near Martinez Hill indicate ground-water level declines of more than 30 meters (100 feet) in the area. The future promises even greater pressure on the region's water supply, not only for riparian preservation, but also for agriculture and support of burgeoning population growth. (Courtesy of Stan Leake [USGS, WRD, Tucson, AZ] and Dave Goodrich [USDA-ARS, Tucson, AZ].)

Box 1.4. The global water cycle plays a pivotal role in the transport of sediment and nutrients through the earth system, as exemplified in this Landsat 7 image of the North Carolina coast. The image was taken on September 23, 1999, one week after Hurricane Floyd hit the continent. Along with soil swept away by the flood waters, the estuaries were filled with human and animal waste, fertilizers, and pesticides. The slow degradation of the deposited organic waste and soil is expected to worsen greatly the eutrophic conditions in the estuaries as oxygen is depleted and as increased nutrient concentrations stimulate algal blooms. The pulse of organic rich sediments from the flood represents a persistent ecological impact threatening the sport and commercial fisheries in this large productive estuary. (Image by Brian Montgomery, NASA GSFC).

(See http://earthobservatory.nasa.gov/Study/FloydIntro for figure)