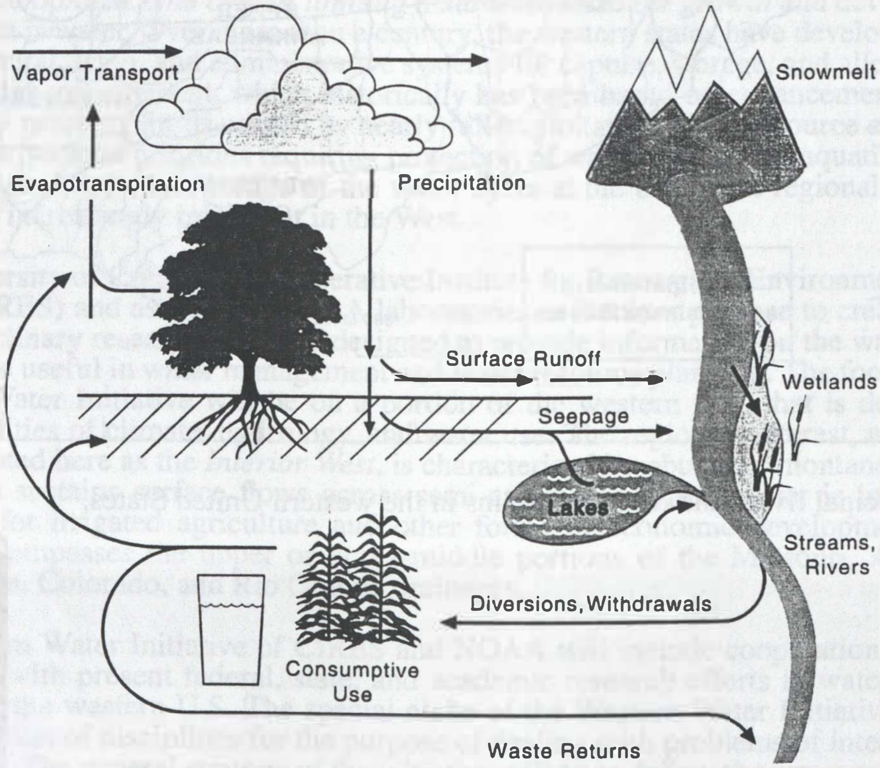
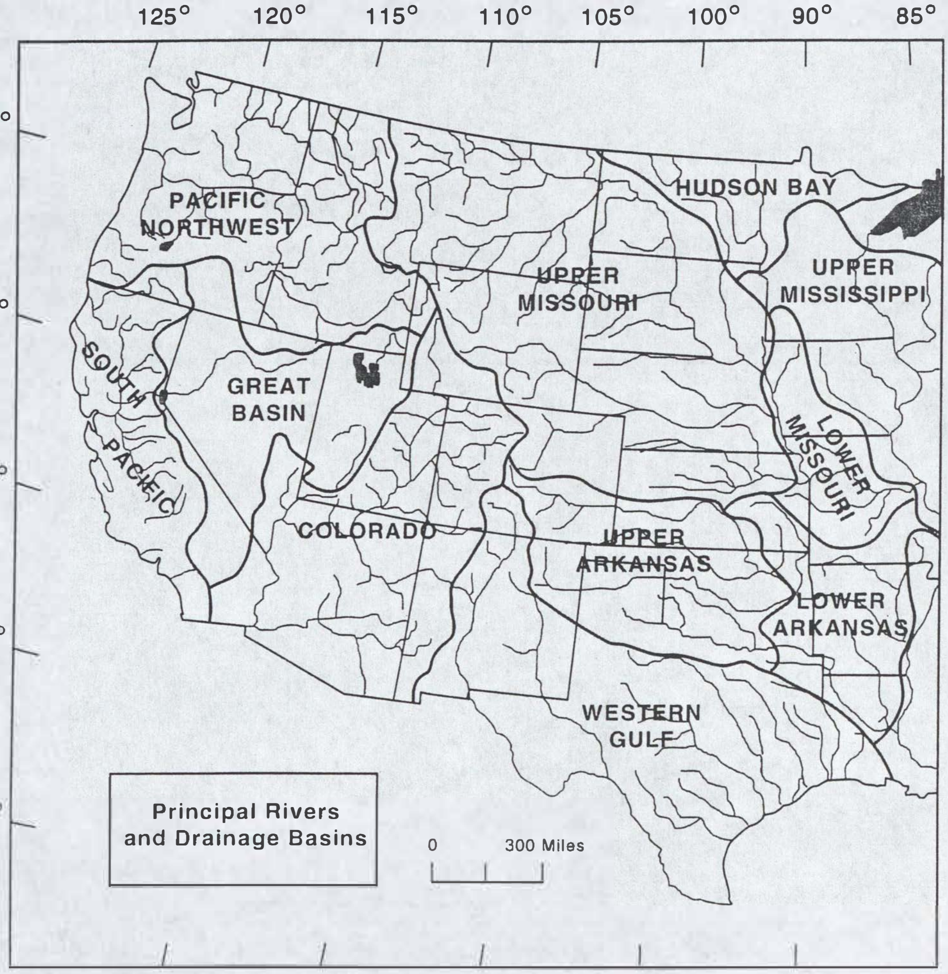
A Water Research Initiative
for the
Interior Western United States

Interdisciplinary Research in Climate, Weather, and Water on the Western Landscape
NOAA Climate Diagnostics Center and CU Cooperative Institute for Research in Environmental Sciences



NOAA-CIRES ***Climate Diagnostics Center***
Boulder, Colorado



Principal rivers and drainage basins in the western United States.

Front cover: Schematic illustration of the breadth of inquiry for a research program based on the strategy of *following the water.*

A Water Research Initiative for the Interior Western United States

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Executive Summary

The Western United States is experiencing unprecedented population growth and economic development. The overall limiting natural resource for growth and development in the West is water. Over more than a century, the western states have developed complex structural, legal, and administrative systems for capture, storage, and allocation of water. Water management, which historically has been based on enhancement of supply, is now reaching limits caused by nearly full exploitation of the resource and by the rise of new societal priorities requiring protection of water quality and aquatic ecosystems. Consequently, knowledge of the water cycle at the basin and regional scales is becoming increasingly important in the West.

The University of Colorado's Cooperative Institute for Research in Environmental Sciences (CIRES) and associated NOAA laboratories in Boulder propose to create a new interdisciplinary research initiative designed to provide information on the water cycle that will be useful in water management and water resource planning. The focus of this Western Water Initiative will be on a portion of the western U.S. that is defined by commonalities of climate, hydrology, and water use. The region of interest, which can be designated here as the *Interior West*, is characterized by abundant montane precipitation that sustains surface flows across semi-arid plains where water is intensively managed for irrigated agriculture and other forms of economic development. This region encompasses the upper or upper-middle portions of the Missouri, Arkansas, Great Basin, Colorado, and Rio Grande drainages.

The Western Water Initiative of CIRES and NOAA will include cooperation and collaboration with present federal, state, and academic research efforts in water science relevant to the western U.S. The special niche of the Western Water Initiative will be the integration of disciplines for the purpose of dealing with problems of interdisciplinary scope. The general strategy of the initiative will be to *follow the water* as it moves into the Interior West through the atmosphere, is deposited on and passes over the landscape, and returns to the atmosphere or leaves the region as surface flow. The initiative will combine elements of meteorology, hydrology, aquatic ecosystem science, water resource economics, and other disciplines in setting the foundation for a comprehensive analysis of the water cycle in the Interior West.

The scope of the Western Water Initiative can be described in terms of four components: (1) climate and weather as agents of hydrologic variation; (2) hydrology, with emphasis on prediction and causal connections to weather and climate; (3) water quality and aquatic ecosystems, as affected by hydrology and water management; and (4) water and society, including both analysis and projection of human intervention in the water cycle.

The climate and weather component of the initiative will work at temporal scales ranging from subseasonal to interdecadal. Research objectives will include mechanistic and predictive understanding of regional variation in precipitation produced by larger scale atmospheric phenomena, and creation of a basis for better prediction of extreme events in the Interior West. At longer time scales, the initiative will focus on the use of coupled atmosphere-ocean models in predicting anomalies in temperature and precipitation, and will contribute to the use of proxy records for documenting and interpreting regional climate variations.

The hydrologic component of the Western Water Initiative will be guided by recent attempts at a national level to redirect and broaden the hydrologic sciences. One emphasis of the Initiative will be observational closure of the water budget in the Interior West by application of emerging technologies for the observation of precipitation, use of existing observational networks for estimation of surface discharge, and novel uses of data on soil moisture and evapotranspiration leading to observational closure of a regional water budget. The hydrology portion of the initiative will be strengthened by coupling with existing observational programs including the GEWEX Continental-scale International Project (GCIP), which will be focusing in 1999-2000 on the upper Missouri basin.

Studies of water quality and aquatic ecosystems are typically disjunct from studies of climate, meteorology, and hydrology. The Western Water Initiative will connect these traditionally separate areas of study through recognition of the causal linkages between water quality, aquatic ecosystems, and hydrology. Topics of special interest include prediction of ecosystem responses to hydrologic variation, secular change in aquatic ecosystems and water quality caused by trends in hydrology and water use, and design of analytical systems that account for the combined ecosystem influences of climate, weather, and anthropogenic effects on water quality and aquatic ecosystems.

The Western Water Initiative will also deal directly with human intervention, which has a potent influence on water routing, water budgets, water quality, and aquatic ecosystems in the Interior West. This program component will extend beyond analysis of present human influences on the water cycle to forecasting the future consequences of water use in the Interior West.

Water science presently is a coalition of disciplines with loose interactions. In contrast, societal issues related to water and the phenomenology of the water cycle both involve tight interactions between physical, chemical, biological, and societal processes. The objective of the Western Water Initiative is to create a framework for research on causal relationships between climate, hydrology, water quality, aquatic ecosystems, and water management in the Interior West. Timeliness of the initiative derives partly from the increasing complexity of and societal stake in optimum water management, and partly from new observational tools and models that encourage integrated study of water across traditionally separate disciplines.

Introduction

The United States incurs great economic and societal loss as a result of hydrologic variability associated with droughts and floods. Improved forecasting of weather and climate, which are the agents of hydrologic variation, could save the nation billions of dollars through mitigation of damages caused by these extreme events. Even prediction of more modest forms of hydrologic variation linked to weather and climate could greatly extend the value of water resources through increased efficiency of water management. As population increases, the value of improved predictive capability is likely to increase steeply, both for extreme events and for hydrologic variation more generally.

Quantity, quality, location, and schedule of availability influence the value of water. For example, annual water consumption in the western U.S. averages 44% of renewable supplies, while in the rest of the U.S. the average is 4%. As a result of its low availability, water can have a value above $150 per acre foot in the West, as compared with 5% of this amount in the eastern U.S. (Frederick et al. 1995). Where the value of water is high, as it is in the West, a mechanistic understanding of the water cycle is of special importance.

Hydrologic variation has potent economic consequences in the West. Extended periods of high precipitation amply supported agricultural and other consumptive uses of water during the 1920s and early 1980s. In contrast, periods of extended drought, as occurred during the 1930s and 1950s (Figure 1), have shown the vulnerability of the West to water shortage, and have also provided opportunities for analysis of climate.

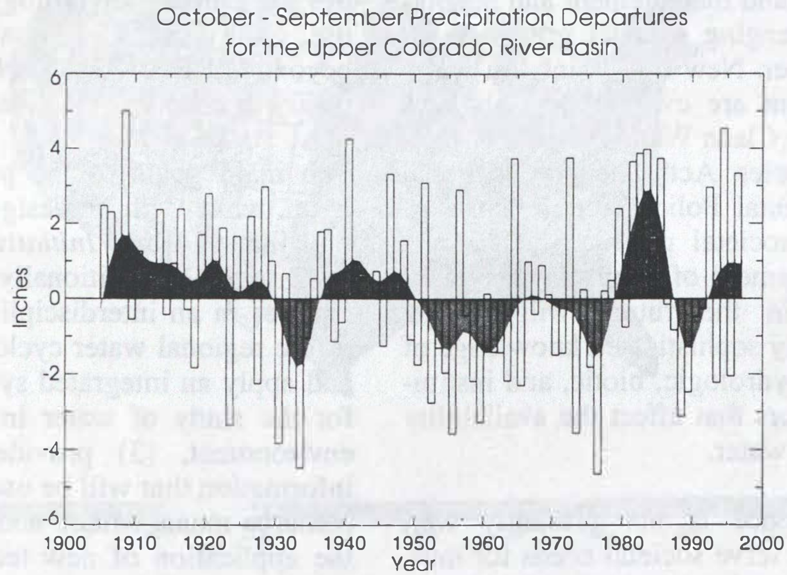

Figure 1. Precipitation time series for the upper Colorado River Basin. Bars denote deviation from the long-term mean (from CDC, ERL, NOAA).

Societal effects of hydrologic variation have been compounded by a strong upward trend in the population of the West since the end of World War II. Since the 1990s, the Rocky Mountain states and the Northwest have experienced larger proportional increases in population than any other region of the U.S. The increasing demand for water that follows this demographic trend suggests a growing need for better understanding of the causes and consequences of hydrologic variation.

Western hydrology reflects a complex history of human settlement, large-scale water management projects, unique kinds of water policy and law, and constant change in water use (NRC 1991a). Enhancement of water supply, which has been a cornerstone of western water management, has reached physical, legal, and cultural limits. Water management in the future will turn increasingly from enhancement of supply to demand management and adaptation to changing societal priorities for use of water. New constraints on water management are evident through laws such as the Clean Water Act, the Endangered Species Act, and the National Environmental Policy Act. Because of changing societal priorities and limits on enhancement of supply, water management in the future will require increasingly sophisticated knowledge of climatic, hydrologic, biotic, and institutional factors that affect the availability and use of water.

Water science is not presently well adapted to serve societal needs for multidimensional evaluation of water resources (NRC 1991b, Lewis et al. 1995, Naiman et al. 1995). Whereas water science is a loose coalition of disciplines, problems within the sphere of water science are tightly coupled clusters of physical, chemical, biological, and social phenomena. Thus water science could be made more effective in dealing with problems of broad scope through greater integration of disciplines and definition of new interdisciplinary research agendas.

The University of Colorado and NOAA, through the Cooperative Institute for Research in Environmental Science at CU, have built and sustained a broad interdisciplinary program in atmospheric sciences. The present proposal describes a plan for creation of a comparable interdisciplinary water science initiative with orientation toward basic science in the service of national needs. The new initiative would have a regional focus on the Interior Western U.S., as defined in this proposal by commonalities of climate, hydrology, and water use, and could ultimately expand beyond CIRES, CU, and NOAA as necessary to meet its objectives.

The main goals of the proposed program, which will be designated here as the *Western Water Initiative*, are to: (1) bring together traditionally separate disciplines in an interdisciplinary analysis of the regional water cycle, (2) develop and apply an integrated system concept for the study of water in the regional environment, (3) provide new basic information that will be useful for water resource management, and (4) facilitate the application of new technologies to the analysis of the regional water cycle.

Defining the Region: The Interior West

The Western United States as a whole receives less than one-third of the average precipitation in the Eastern United States. Even so, the Western U.S. is quite heterogeneous climatically and hydrologically. The Western Water Initiative focuses on a portion of the western U.S. showing the following combination of characteristics: (1) mountains with abundant precipitation (Figure 2), primarily in the form of snow, and (2) adjacent plains with scarce precipitation, where there is (3) intensive water management that involves interception, storage, and consumptive use of water. The region defined by this combination of characteristics does not coincide with specific political or geographic boundaries; it is defined instead by elements of the water cycle and by water use. This region, which we will refer to for convenience as the *Interior West*, encompasses at a minimum portions of the Missouri, Arkansas, Great Basin, Colorado, and Rio Grande drainages.

Water in the Interior West is intensively managed; approximately two times the annual flow resides in reservoirs (Figure 3). Use of water, much of which is for irrigated agriculture, has increased significantly in this region over the last four decades (Figure 4). Increasing consumptive demands for water include not only agriculture, but also municipal and industrial use as well as cooling for power generation. Because of the intensity of water management, the usefulness of water science is particularly high in the Interior West.

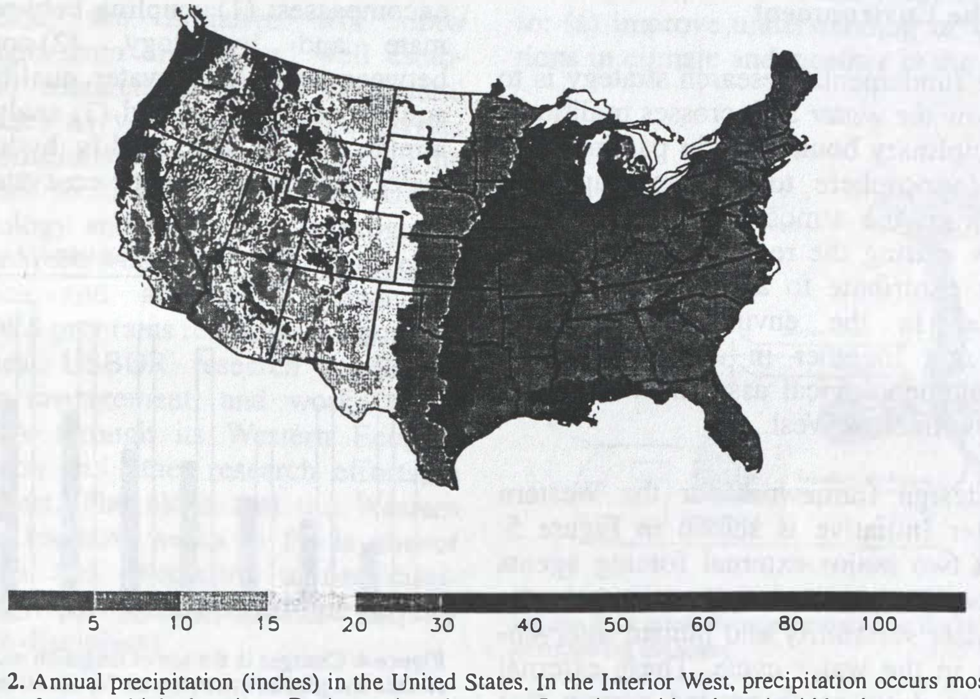

Figure 2. Annual precipitation (inches) in the United States. In the Interior West, precipitation occurs mostly in the form of snow at high elevations. During spring, the water flows into arid and semi-arid lands.

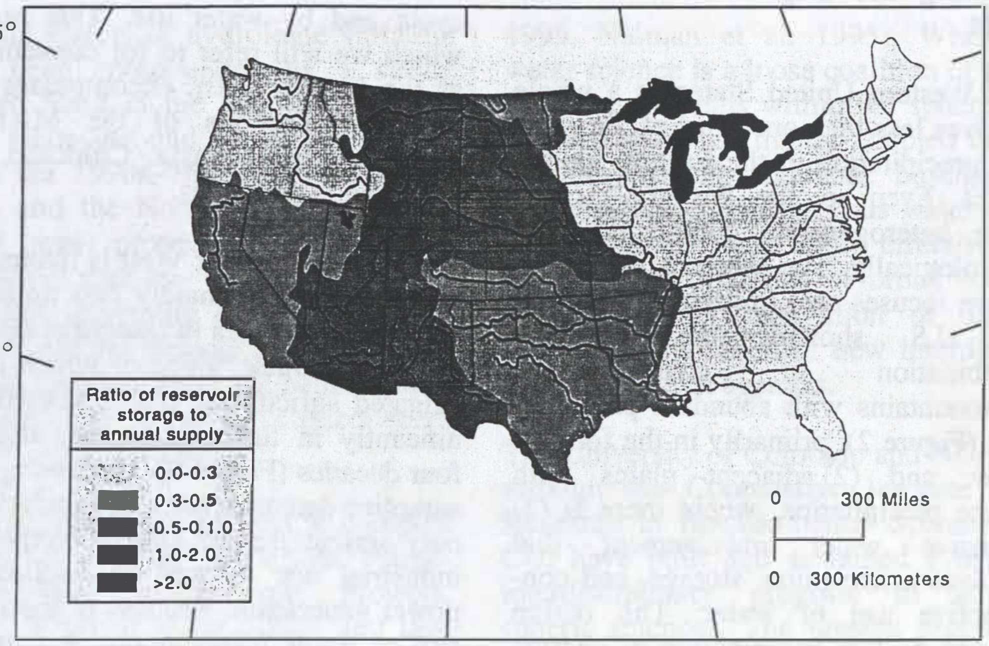

Figure 3. Ratio of reservoir storage to annual water supply in the western United States (modified from Hirsch et al. 1990).

Defining the Initiative Around Water in the Environment

The fundamental research strategy is to *follow the water* as it crosses traditional disciplinary boundaries in passing from the atmosphere to the landscape and back to the atmosphere or to surface flow exiting the region. All disciplines that contribute to an understanding of water in the environment will be brought together in a comprehensive phenomenological assessment of water in the Interior West.

A design framework for the Western Water Initiative is shown in Figure 5. The two major external forcing agents that affect the regional water cycle are climate variability and human intervention in the water cycle. These external forces drive an integrated system that determines quantity and quality of water. Study of this integrated system encompasses: (1) coupling between climate and hydrology, (2) coupling between hydrology, water quality, and aquatic ecosystems, and (3) analysis of human factors that modify hydrology, water quality, and aquatic ecosystems.

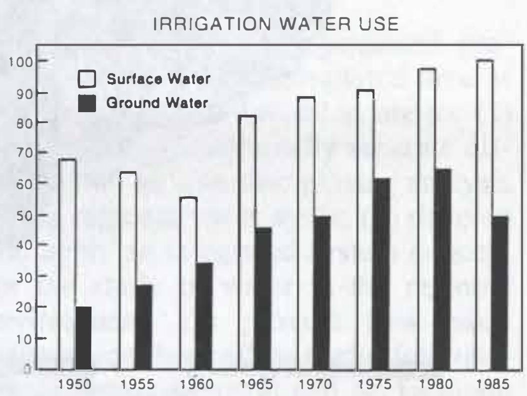

Figure 4. Changes in the use of irrigation water from surface and groundwater sources for the 20 states that have the highest amounts of irrigation (modified from Bajwa et al. 1992).

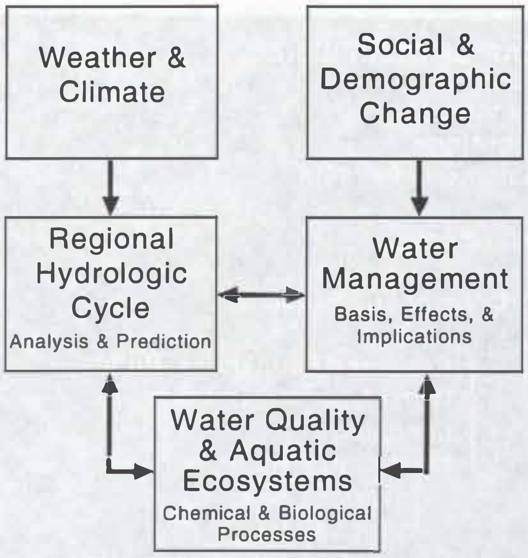

Figure 5. Design framework for the Western Water Initiative.

The Western Water Initiative has important connections to atmospheric science programs within NOAA and CIRES. In addition, the Initiative will draw strength from diverse and well established research programs of federal agencies as well as state and private organizations that deal with water in the Interior West. These include the USGS hydrology and water quality programs in the West, which now encompass earth science and also biotic resources; USFWS programs related to endangered species; USBOR research related to water management; and work of the USEPA through its Western Ecology Division and other research efforts in the West. The niche that the Western Water Initiative seeks to fill is one of breadth and integration across disciplines, rather than specialized inquiry within disciplines.

Research themes that cover the full breadth of the water cycle are suggested by Figure 6, which summarizes the physical mechanisms, feedbacks, and transfers associated with water in the Interior West. Figure 6 indicates the breadth of inquiry implicit in the strategy of following the water, and shows the justification for an integrated approach. Figure 6 also can be rendered as a cluster of disciplines, as shown in Figure 7.

CIRES, as an interdisciplinary institute of the University of Colorado and a NOAA cooperative institute, is particularly well situated to conduct a focused, long-term program capable of encompassing the full breadth of issues surrounding water in the Interior West.

Scope of the Western Water Initiative

Fundamental goals of the Initiative are to: (a) improve understanding of variations in climate and weather in the Inte-

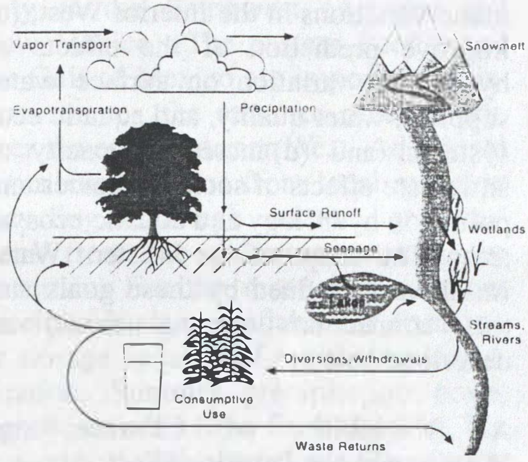

Figure 6. Schematic illustration of the breadth of inquiry for a research program based on the strategy of following the water.

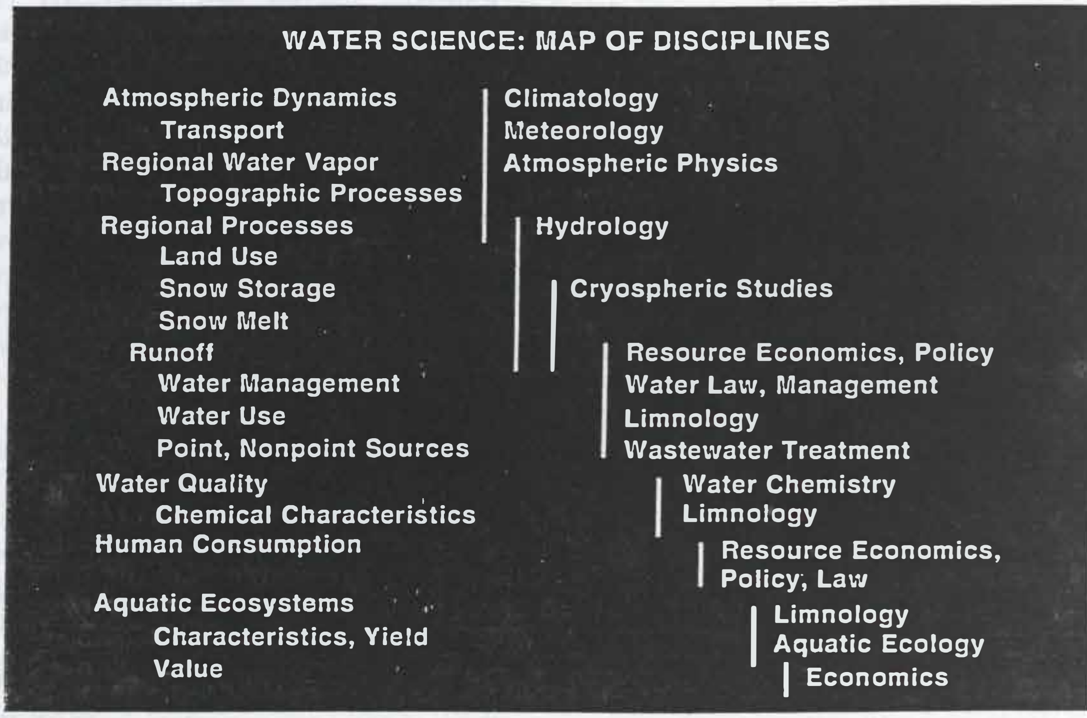

Figure 7. Relationship between traditional disciplines and general research objectives in water science.

rior West, especially as related to precipitation; (b) analyze connections between the hydrologic cycle and climatic variations in the Interior West; (c) improve prediction of the effects of hydrologic variation on surface water supplies, water quality, and aquatic ecosystems; and (d) increase capacity to anticipate effects of societal choices and policy on hydrology and aquatic ecosystems. The scope of the Western Water Initiative is defined by these goals and the connections among them, as described below.

A. Variability of Climate and Weather in the Interior West

An essential element of the strategy of following the water is to enhance understanding and prediction of weather and climate variability in the Interior West and, in particular, of the hydrological cycle of this region. This research component directly supports NOAA's strategic plan goals, which include improving monitoring and prediction of weather and climate at both short range (less than a month) and seasonal to multidecadal time scales.

The Interior West poses particular challenges in understanding and predicting weather and climate variability. Many of these challenges differ substantially from those faced in prior studies of other regions, such as the Mississippi basin (a primary focus of GCIP). Critical factors include complex terrain and correspondingly strong topographic influences, multiple moisture sources and precipitation mechanisms, pronounced seasonal and interannual climate variability, and large changes in storage related to snowpack. Major variations in weather and climate occur over a broad temporal spectrum ranging from sub-seasonal through multi-decadal time scales, with corresponding pronounced influences on local and regional water budgets.

General background on climatology and variability

Precipitation in the Interior West is largely associated with transport of water vapor from the Pacific Ocean and the Gulf of California (Waggoner 1990, NRC 1991a), with secondary contributions from the Gulf of Mexico, particularly in spring and summer. Through much of the region, there are two annual precipitation maxima: one in the cold season (winter to spring) associated with synoptic-scale storms and orographic forcing, and the other in summer associated with the American southwest monsoon. The relative magnitudes and timing of the two maxima vary significantly through the region, and also display substantial year-to-year variations that are of critical importance to the hydrologic budgets throughout the region.

In winter, variability of water vapor is related to changes in the large-scale atmospheric circulation. Sub-seasonal variability in winter can be characterized by storm periods and inter-storm periods. During storm periods, water accumulates in the region over relatively large areas from synoptic-scale storms and through upslope orographic flow that produces copious snow in the mountains. During inter-storm periods, water storage as snowpack is reduced by surface energy exchange processes such as evaporation and sublimation caused by intense solar radiation. Some of the snowpack is redistributed by strong winds.

Winter and early spring precipitation, while a dominant element of the water budget for the Interior West, becomes available for most human uses only during the late spring runoff. A particularly important hydroclimatic prediction problem deals with the timing and intensity of these meltwater pulses. Many damaging floods in the West occur when heavy rain falls on winter snowpack, producing rapid melting. Forecasts of temperature, or more generally the surface heat budget, precipitation, and land-surface conditions are especially critical during these times.

The American monsoon brings precipitation to the Interior West in summer, but generates significant surface runoff only in the Southwest (Arizona and New Mexico). The eastern Pacific and the Gulf of Mexico are important moisture sources for summer precipitation over the entire Interior West. Additional contributions come from local moisture recycling, although relative contributions from the different sources are uncertain. For the most part, summer precipitation is unavailable for diversion or storage because of rapid evapotranspiration. Summer precipitation poses significant risks from flash flooding, but is a critical moisture source for ecosystems that cannot persist from one winter to the next without this rainfall, for dryland agriculture, and as a moisture supplement for irrigated crops.

Mechanisms that control the annual cycle and interannual variability in precipitation of the Interior West are only partially understood. There is, however, substantial evidence that the El Niño - Southern Oscillation (ENSO) phenomenon plays an important role in interannual variability in this region. Anomalous tropical heating of the atmosphere associated with ENSO has significant effects on weather patterns over North America, including much of the Interior West. During ENSO warm events, precipitation often is high in the Southwest and much of the Interior West; during ENSO cold events, precipitation in this region usually is low. ENSO also appears to have a significant influence on the likelihood of extreme climate events over large portions of the Interior West. Risks of drought in the Southwest are considerably higher in winter and spring under La Niña conditions, and high winter precipitation is more likely to occur under El Niño conditions (Figure 8).

Emerging capabilities to predict the development of tropical Pacific sea surface temperatures and associated climate anomalies suggest that ENSO can serve as an important initial basis for forecasting seasonal temperature and precipitation patterns in the western United States (NRC 1996a). Individual ENSO events differ substantially in the timing and location of maximum anomalous rainfall and the intensity of anomalous heating, with corresponding implications for the potential atmospheric response. The sensitivities of the climate response over this region to ENSO variations and timing will require careful assessment.

Longer-term climate variations throughout the Interior West have major implications for the hydrology of the region. Large decadal-scale variability may be partly related to changes in the frequency of ENSO events. This decadal-scale variability is correlated with changes in annual streamflow for the Colorado River basin and with lake and ground-water levels in the Great Basin. Tree-ring data suggest that the early part of the 20th Century (from 1906-1930) was characterized by anomalously high runoff (Meko et al. 1991). Many environmental and legal problems have arisen subsequently because this period of high runoff was used in estimating water availability for the Colorado River Compact of 1922.

Proxy records such as tree rings and isotopic composition of various closed-basin lakes suggest that, since the end of the last glaciation (the last 10,000-12,000 years), the Western US has shown significant changes in temperature and precipitation. Multi-decadal dry periods, some more pronounced than any dry interval of the last two centuries, are evident in the paleoclimate record of the last 1000 years. This information has profound implications for water resources in the Interior West, and also has a bearing on water management issues in the face of potential anthropogenic global climate change (Nash and Glieck 1993). An improved understanding of these interannual and longer-term climate variations and the factors controlling them is of primary importance in the development of new products for use in water management policy.

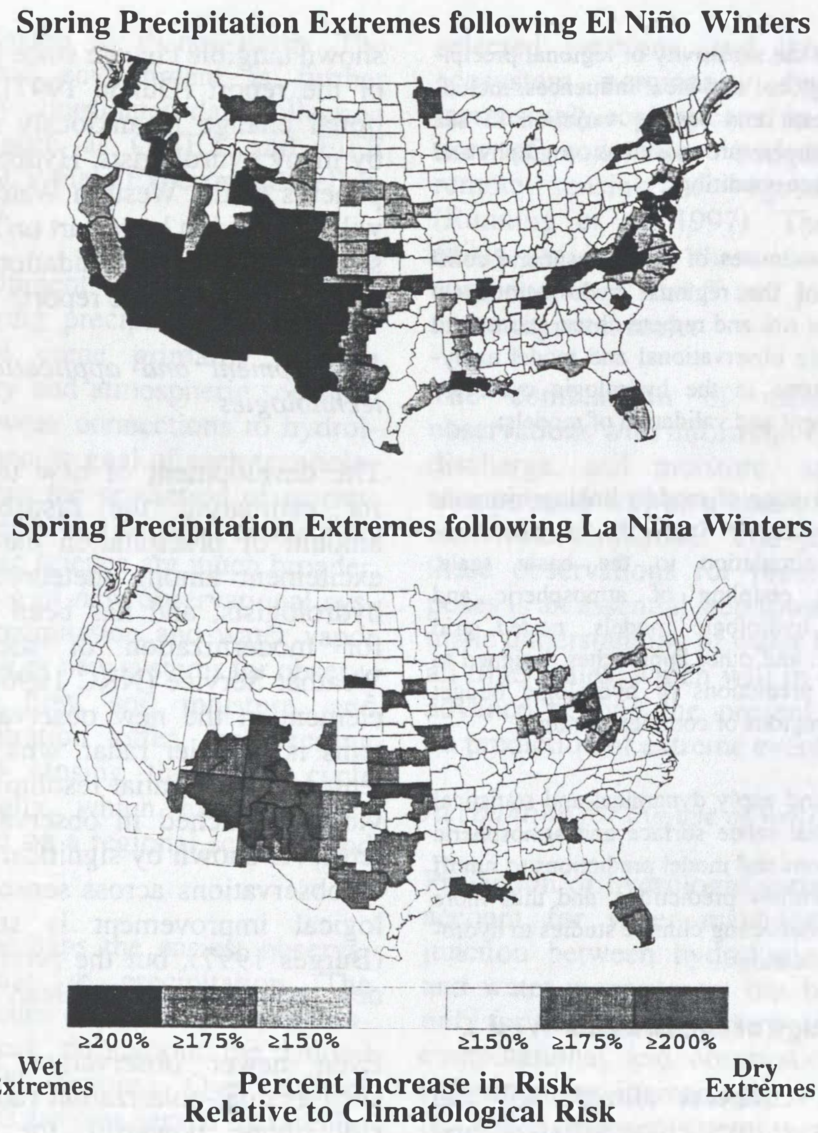

Fig 8. Regions with significant increases in likelihood of U.S. spring precipitation extremes occurring after winters with either El Niño (top panel) or La Niña (bottom panel) conditions. From CDC, ERL, NOAA (Wolter, Dole, Smith).

Research agenda

Primary research goals related to weather and climate variability in the Interior West are to:

- document and interpret the causes for past climate variations in precipitation in this region using both modern observational and paleoclimate data, with particular emphasis on changes in drought and flood frequencies, magnitudes and durations, and potential implications for future climate variability;

- determine the sensitivity of regional precipitation to global and local influences, including adjacent and remote variation in sea surface temperature as well as orography and land-surface conditions;

- improve estimates of the atmospheric components of the regional hydrologic cycle through *in situ* and remote observations, and to compare observational and model analyses of terms in the hydrologic cycle for development and validation of models;

- develop a suite of models linking hydroclimatic variability from the global atmospheric circulation to the basin scale, including coupling of atmospheric and regional hydrologic models, nested grid modeling, and other approaches designed to improve predictions of hydrologic budget terms in regions of complex terrain;

- develop and apply dynamical and statistical models that relate surface and atmospheric observations and model predictions to runoff and streamflow predictions, and thus more directly connecting climate studies to hydrologic applications.

B. Hydrology of the Interior West

Hydrology connects climatology and meteorology to characteristic and extreme discharges, water management, water quality, and status of aquatic ecosystems. Consequently, hydrology is a critical component of the Western Water Initiative.

Hydrology is passing through an era of reassessment and realignment with other disciplines. An analysis of the past, a diagnosis of current problems, and a blueprint for change were set forth in the influential Eagleson Committee report (NRC 1991b). Hydrology has shown tangible change since publication of the report (Dunne 1997), but additional change is anxiously anticipated by many hydrologists. Hydrologic components of the Western Water Initiative will be based in large part on the conclusions and recommendations of the Eagleson Committee report.

Development and application of new technologies

The development of new technologies for estimating the distribution and amount of precipitation has generated excitement among meteorologists and hydrologists, and has been a stimulus for modernization of the National Weather Service (NRC 1996b). A key element in the new observational systems is Doppler radar, which provides temporal and spatial resolution not previously matched in observational systems. As shown by significant deviation of observations across sensors, technological improvement is still needed (Burges 1997), but the promise of this new technology seems clear.

Even newer observation techniques, such as dual-polarization radar, may be still more powerful for estimating amount and distribution of precipitation. Simultaneously, new methods are being developed for measurement of water vapor (e.g., differential absorption lidar and Raman lidar) and precipitable water (dual-channel microwave radiometry). Coupled with wind profiling radars, instruments of this type could allow measurement of vapor flux into an entire region. Ground-based methods could be used in conjunction with a variety of satellite remote-sensing techniques from operational NOAA satellites and the

NASA Mission to Planet Earth. The observational environment is further enriched by coordinated data collection programs such as GWEX and FIFE (First ISLSCP Field Experiment: Sellers et al. 1993).

The development of new technologies for measuring precipitation and water vapor have come primarily through meteorology and atmospheric sciences, with only weak connections to hydrology. The specific goal of such technologies has been the prediction of storms, but the benefits of a stronger connection to hydrologic science are much broader. The coupling of new observational systems for precipitation and water vapor with existing or new systems for observing stream flow, soil moisture, and evapotranspiration offer the exciting prospect of closing the water cycle observationally, which has not been achieved yet on a regional scale (Wood 1997).

Runoff is perhaps the easiest observational linkage to precipitation. The USGS operates an extensive observational network throughout the United States (7,000 stations). Over half of these stations are now served by satellite linkages, which make the data highly accessible.

Other elements of the regional water budget include soil moisture (soil water storage) and evapotranspiration. Both are known to some extent through observational programs, but the use of the observational data is largely disjunct from meteorologic or hydrologic observations and models at present. As Wood (1997) points out, the USDA's ARS maintains soil moisture records for selected locations, and the terrestrial ecosystem community has become increasingly sophisticated in the prediction of soil water budgets through remote sensing of vegetative cover (Running et al. 1997). The prospect exists for joining these water budget components to runoff and precipitation at the regional scale.

The combination of meteorological observations with information on stream discharge, soil moisture, and evapotranspiration will be a goal of the Western Water Initiative. The junction of these observations for predictive purposes is an essential step toward mechanistic understanding of water budgets on all time scales, which will in turn be an advance beyond the present emphasis on prediction of extreme events.

Accounting for the use of water

Projection of hydrologic variation must account for water management. The junction between hydrologic variation and water management has been made only for very selective purposes, but the computational and observational environments are increasingly well suited for much broader attempts to predict hydrology with water management constraints superimposed on natural variation. The output of such models can be expressed not only in terms of water availability, but also in terms of water quality and status of aquatic ecosystems.

Research agenda

The objectives for the hydrologic component of the Western Water Initiative are as follows:

- participate in the development and application of new technologies for collection of synoptic data on precipitation;
- improve prediction of runoff from precipitation at the watershed and basin scales;
- create models capable of combining hydrologic prediction with water management requirements.

C. Water Quality and Aquatic Ecosystems

The water quality and aquatic ecosystems of the western U.S. reflect a unique combination of circumstances involving extreme variation in the spatial and seasonal availability of water. In addition, human alteration of the hydrograph, strong perturbation of water quality, and management of extreme events have influenced aquatic ecosystems in ways that are still poorly known (e.g., NRC 1996c). Because of growing societal interest in aquatic ecosystems and biota, water management must be based on a more thorough understanding of the linkage between physical, chemical, and biological phenomena in the drainage network. This need defines the scope of the water quality and aquatic ecosystem segment of the Western Water Initiative.

Hydrologic influences on water quality and aquatic ecosystems

The distinctive hydrologic characteristics of the Interior West are reflected in the water quality and aquatic ecosystems of the region. The annual hydrograph is dominated by spring release of water from snowpack. Snowmelt leads to a predictable spring peak in the natural hydrograph, followed by base flow conditions during fall and winter. This characteristic seasonal discharge pattern supports native aquatic ecosystems that depend upon annual flushing flows sufficient to move fine sediment and, in the plains regions, to sustain wide braided channels with numerous adjacent wetlands and backwaters.

The predominance of snowmelt as a water source also ensures low conductance, low nutrient content, and low organic matter transport as the baseline conditions for most aquatic ecosystems. Causal connections between water management and ecosystem change still are not well understood; they present a challenge for the Western Water Initiative. Analysis of the relationships between hydrology and aquatic ecosystems is an important feature of this Initiative.

Human intervention in the water cycle has modified the natural hydrograph drastically (Figure 9). These modifications have had strong effects on the physical and chemical conditions that maintain aquatic ecosystems (Collier et al. 1996). While peak spring flows are still characteristic of most rivers at high elevation, seasonal peak flows are strongly suppressed at lower elevation through capture and storage of water for consumptive use. In addition, seasonal low flows have been altered by diversions leading in some cases to dewatering of aquatic habitats, and in other cases to augmentation of low flow through recharge of groundwater by irrigation. These hydrologic changes have induced geomorphic changes in channels, including accumulation of fines, narrowing and downcutting, isolation and desiccation of riparian zones, and creation of large new aquatic resources consisting of storage reservoirs, as well as both augmentation and depletion of groundwater.

Societal influences on water quality and aquatic ecosystems

Many of the hydrologic changes that have occurred in the Interior West antedate environmental concerns. There is now a rising interest in restoration and maintenance of biodiversity in aquatic ecosystems, and multi-use evaluation of water management (NRC 1992a,b). Traditionally, however, the connection between hydrology, which is the driving force for physical change, and aquatic ecosystems has received very little scientific attention because of the historical disjunction between physical, chemical, and biological branches of the environmental sciences (Naiman et al. 1995, Lewis et al. 1995). Closure of this gap is critical for sustainable management of water and aquatic resources, to which society and government have already shown large commitments (NAE 1996).

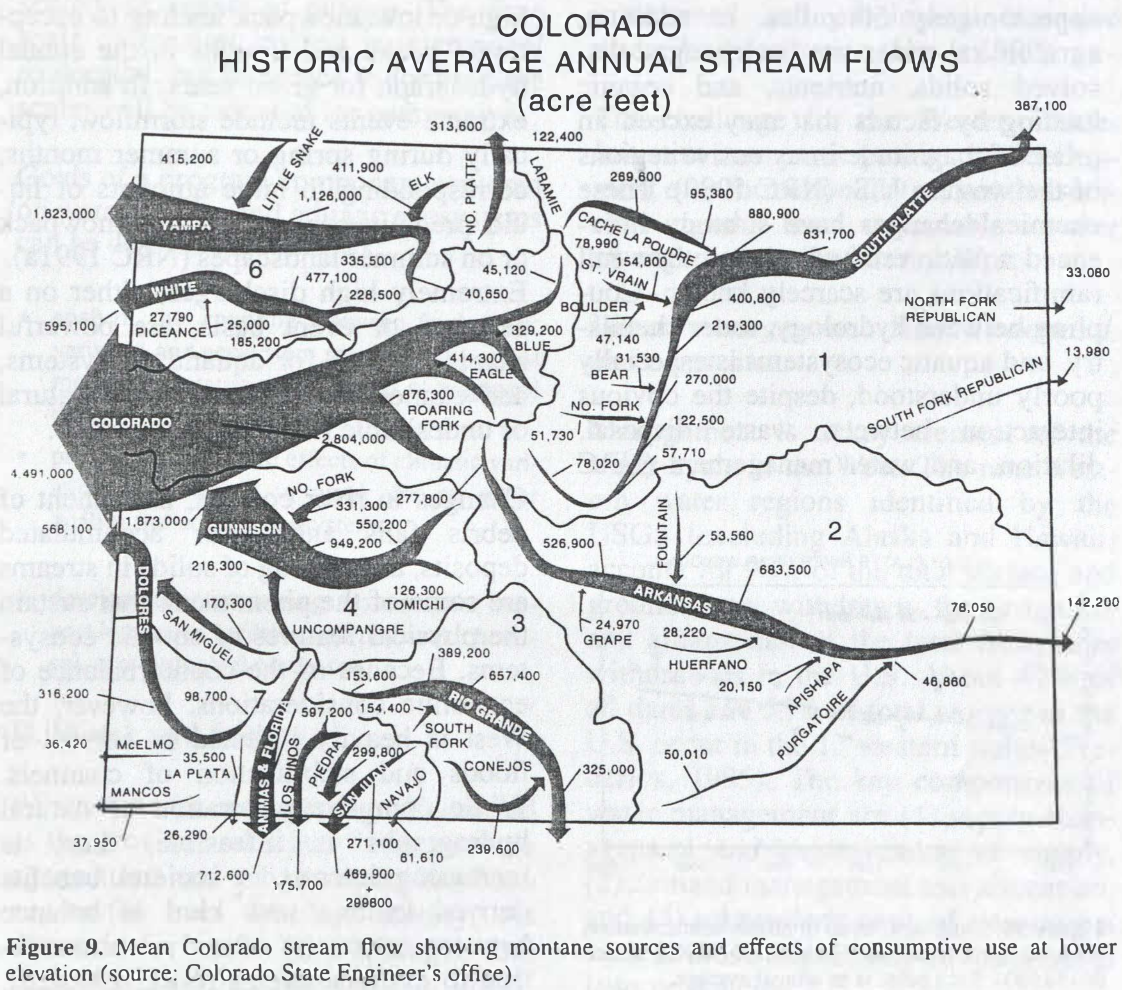

Figure 9. Mean Colorado stream flow showing montane sources and effects of consumptive use at lower elevation (source: Colorado State Engineer's office).

Water quality in the Interior West

The chemical features of aquatic ecosystems have been strongly influenced by agricultural and economic development in the Interior West (Figure 10). Whereas the native flows sustained by montane snowmelt were low in dissolved solids, nutrients, and organic matter, human settlement in the plains region has created strong point sources (industrial and municipal discharges) of nutrients and waste. For example, the Denver Metro region contains more than 160 permitted wastewater discharges to the South Platte River over a distance of approximately 50 miles. In addition, agricultural water use has changed dissolved solids, nutrients, and organic loading by factors that may exceed an order of magnitude in extensive regions of the western U.S. (NRC 1989). These chemical changes have strongly influenced aquatic ecosystems, but their full ramifications are scarcely known. Coupling between hydrology, water chemistry, and aquatic ecosystems is especially poorly understood, despite the obvious interaction between waste disposal, dilution, and water management (NRC 1991a). The physical, chemical, and biological aspects of the water resource need to be brought into a common framework using both modeling and empirical studies to promote the understanding of physical, chemical, and biological phenomena, with full accounting for human influence.

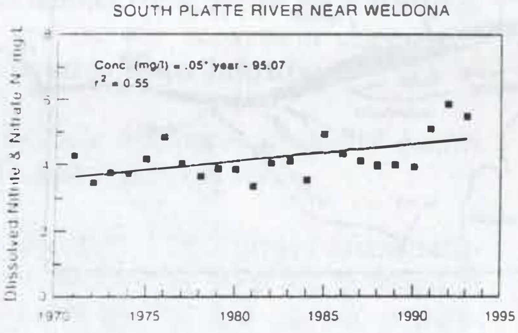

Figure 10. Long-term trend in nitrate concentrations on the South Platte near Weldona,CO (USGS station 06158500). Each point is an annual average.

Extreme events and the status of aquatic ecosystems

Extreme events of the natural hydrologic regime in the Interior West are of two types: (1) seasonal, and (2) event-based. Seasonal extremes are caused by high or low snowpack leading to exceptional peaks and troughs in the annual hydrograph for given years. In addition, extreme events include stormflow, typically during spring or summer months, corresponding to large amounts of liquid precipitation on melting snowpack or on summer landscapes (NRC 1991a). Extremely high discharges, either on a seasonal or event basis, are powerful shaping agents for aquatic ecosystems, and cannot be discounted as unnatural or undesirable from this perspective.

Changes in river courses, movement of debris fans and other accumulated deposits, and sorting of solids in streams are some of the phenomena that sustain the physical features of aquatic ecosystems. Because of the counterbalance of economic considerations, however, the West is heavily invested in control of floods and stabilization of channels. While complete restoration of natural hydrographs is infeasible, there is increasing interest in societal benefits derived from a new kind of balance between constraint of and accommodation to extreme events (NRC 1996c,d).

The balance must be defined through knowledge of connections between extreme hydrologic events, aquatic ecosystems, and human valuation of the water resource.

Research agenda

Work on water quality and aquatic ecosystems must be connected to studies of climate variation, hydrology, and societal control of water in the Interior West. The emphasis should be on prediction encompassing the physical, chemical, and biological features of aquatic systems, with recognition of climate and society as agents of change. The time scale of greatest interest is interannual to decadal, but reference to longer time scales will be essential for perspective.

Goals of a program component centered on water quality and aquatic ecosystems can be described as follows:

- analyze the coupling between hydrologic variation and ecosystem responses by use of models and statistical treatment of empirical data;
- predict the combined effects of climatic variation and changes in water use on water quality and aquatic ecosystems;
- develop new monitoring systems that support integrated prediction of physical, chemical, and biological processes.

D. Water and Society

Western water management, if defined as the provision of water for large-scale agricultural and urban needs, has been successful over the last century. As demands for water have changed and expanded, however, the costs of developing additional water sources through enhancement of supply have become both prohibitively expensive and socially unacceptable. Many western water supply networks are approaching the characteristics of "closing systems," for which users must acknowledge their interdependence and their need to negotiate (Kennedy 1994). Laws, regulations, operational rules, design of control systems, and institutional constraints can reduce the adaptability of water management systems to hydrologic variation. Socially responsible decisions require broad public participation channeled through appropriate institutions and employing extensive scientific information (Howe 1990).

The challenge for the Western Water Initiative is to participate in the development of information that serves the societal need for sustainable water management in the Interior West.

Water management: Supply, demand, and constraints

Management is a key element of the water cycle in the West. The nine western water regions identified by the USGS (excluding Alaska and Hawaii) account for 90% of the total surface and groundwater withdrawn for irrigation and almost half of the total freshwater withdrawals in the U.S. About 47% of all dams and 55% of total storage in the U.S. occur in the 17 western states (Frederick, 1995). The key components of water management are (1) supply management and augmentation of supply, (2) demand management and allocation, and (3) acknowledgment of constraints such as those imposed by environmental laws or policies.

The interaction of demographic, institutional, and climatic factors can produce unexpected challenges for water management. For example, a recent study by the consortium of western water resources institutes (the Powell Consortium) has shown that the Lower Colorado River Basin, while drier than the Upper Basin, is less vulnerable than the Upper Basin to severe, long-term drought because of the legal requirement that Lower Basin and Mexican Treaty commitments be satisfied first (8.25 maf water/yr).

States also vary in their application of the appropriation doctrine for water distribution. For instance, New Mexico closes claims on surface and groundwater when total claims approach some "safe yield," whereas Colorado does not. This means that New Mexico has proportionately fewer but more reliable water rights than Colorado. Utah protects public non-market values generated by water (instream flows, habitat, fisheries, recreation) in the establishment and transfer of water rights, but Colorado protects only water users. Thus, Colorado stream systems may be under greater environmental stress than those of Utah or New Mexico.

The factors most affecting present and future water resources management in the Interior West are increasing population and consumption, uncertain reserved water rights (in particular those of Native Americans), increasing transfer of water rights to cities, deteriorating water quality, environmental water allocation, ground-water overdraft, outmoded institutions, aging urban water infrastructures, and changes in the interaction of federal, state, and local governments (U.S. Congress 1993).

As demands for water have expanded, the costs of developing additional water sources through large-scale structural solutions have become prohibitively expensive because (1) the best reservoir sites have already been developed, (2) as storage capacity on a stream increases, the quantity of water that the system can supply with a high degree of probability grows only at a diminishing rate, and (3) the opportunity cost of storing and diverting water has risen as society has placed higher values on instream flows (Frederick et al. 1995). The rising expense of augmenting water supply suggests that demand management will play an increasing role in balancing the demand-supply relationship. Demand management places a high priority on prediction of water availability, and thus on sound knowledge of the regional water cycle.

Societal vulnerability to hydrologic extremes

Preliminary estimates of societal vulnerability to hydrologic extremes in the river basins of the Interior West indicate that water management has reached critical thresholds related to storage, consumptive depletion, dependence on hydroelectric power, streamflow variability, and groundwater use (Figure 11; Gleick 1990). The U.S. Bureau of Reclamation has indicated that during a dry period such as that of 1931-40, the water needs of the lower Colorado River Basin would not be met. Such an event would also have significant effects on both the Missouri and Rio Grande basins. For instance, one study showed that hydropower production and reservoir storage would decline to about half their present values under 1931-1940 conditions (Frederick 1995). Four out of the five costliest weather-related disasters between 1980-1997, excluding hurricanes, occurred within the basins of western states. Each exceeded $1 billion in damages and costs, with the recent 1996 drought in Texas reaching $5 billion. Even in the water-rich Pacific Northwest, conflicts among hydropower, irrigation, and flow requirements of salmon have brought allocation systems to their limits.

While water banking and inter-basin transfers have been used to mitigate the effects of short-term drought, the maintenance of supply during periods of severe long-term droughts of 10 to 100 years, such as those that have occurred in the West over the past 1000 years, is as yet untested. The spatial extent and persistence of drought may produce shortages also in neighboring regions that otherwise provide surplus water for inter-basin transfers. On the other hand, the Red River flood in North Dakota during the spring of 1997 provides a recent reminder of what can happen when too much water arrives in too short a time. Increases in flood and drought variability would require a re-examination of emergency design assumptions, operating rules, system optimization, and contingency measures for existing and planned water management systems (Stakhiv 1993).

Research approach: Improving efficiency, quality, and value

The Western Water Initiative will include an assessment of different systems of water supply and management in the headwater regions and major rivers of the Interior West. From a resource management standpoint, information is needed on present and future availability of water, on present and future demand, and on consequences of management for aquatic ecosystems and biotic resources. The overall goal from the scientific viewpoint is to improve predictions on the temporal and spatial scales that are most relevant to the management of water resources.

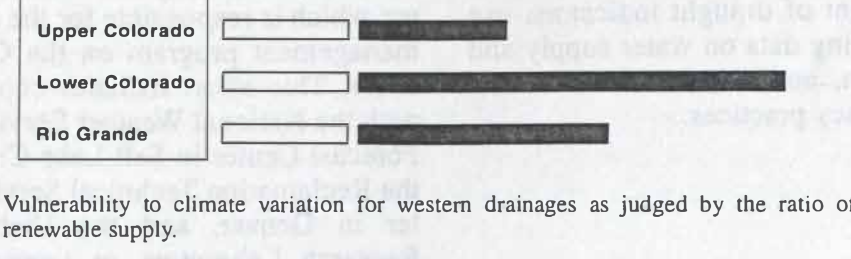

Figure 11. Vulnerability to climate variation for western drainages as judged by the ratio of consumptive depletion to renewable supply.

Research goals for this component include:

- document the social and economic trends that will alter demand;
- estimate the future vulnerability of water for agriculture, recreation, power, and other uses;
- determine the potential for increasing the flexibility of water allocation among users in response to interannual variability and longer-term climate trends;
- estimate the benefits of applying new hydrologic products and forecasts in mitigation measures employed by water managers and decision-makers.

Use of new scientific information will require transformation and communication of relevant research, including forecasts, to meet specific needs of decision-makers (Crowley et al. 1995). Innovative procedures such as adaptive management will require new kinds of information for balancing consumptive uses with other uses, such as recreation and maintenance of endangered species (Pulwarty and Redmond 1997).

Mitigation measures to which the Western Water Initiative can contribute include improvements in streamflow and demand forecasting, assessment of water transfers and re-allocation, use of advance decision support systems, development of drought indicators, use of monitoring data on water supply and distribution, and assessment of water-use efficiency practices.

Programmatic Linkages

Increasing demand on western water resources has stimulated numerous kinds of monitoring, research, and analysis by federal agencies, universities, and other organizations. The Western Water Initiative can be closely linked to a number of these efforts.

A recent report by the National Association of State Universities and Land-Grant Colleges (NASULGC) highlights the problems and opportunities confronting the U.S. in the area of water resources management. Many of the themes of the Western Water Initiative appear in the NASULGC Report.

The Western Water Initiative also complements present, multifaceted water research of the U.S. Geological Survey, the U.S. Bureau of Reclamation, and the U.S. Army Corps of Engineers. A recent Department of Interior report titled "Effects of Climatic Change on Water Resources Management in the United States: A State-of-Knowledge Assessment" points to a number of areas where cooperation between NOAA, CIRES and the federal agencies could be useful.

Established collaboration of NOAA and CIRES with the USGS and Bureau of Reclamation includes joint studies between NOAA's CDC and the Grand Canyon Monitoring and Research Center, which is responsible for the adaptive management program on the Colorado River. This effort includes cooperation with the National Weather Service River Forecast Center in Salt Lake City Utah, the Reclamation Technical Service Center in Denver, and the Utah Water Research Laboratory in Logan, Utah.

These activities provide information for the Western Water Policy Review, the Powell Consortium (the consortium of water resources institutes in the western U.S.), and the Western Governors' Association. The Western Water Initiative also complements integrated assessments being carried out under NOAA auspices at the University of Washington, Seattle, and the University of Arizona, Tucson, for the Columbia River Basin and the Lower Colorado.

Within NOAA, the Office of Global Programs has been leading a multi-agency effort (NOAA, NASA, NSF, USGS), GCIP (GEWEX Continental International Project), which is designed to improve understanding and prediction of the hydrometeorology of the Mississippi River basin. GCIP is the first program to bring together hydrologists and meteorologists for the analysis of water resources over an entire river basin. The final phase of the GCIP project (1999-2000) covers the Missouri River basin, the upper portion of which is directly relevant to the Western Water Initiative. The new Western Water Initiative will join with GCIP in studies of the upper Missouri River basin and will expand the interdisciplinary philosophy of GCIP to encompass not only hydrologists and meteorologists, but also ecosystem scientists and specialists in water use and management.

Other NOAA/OGP program elements and themes with close ties to the Western Water Initiative are Climate Change Data and Detection, Climate Dynamics and Experimental Prediction, Global Ocean-Atmosphere-Land System (GOALS), Paleoclimatology and the Economics, and Human Dimensions of Climate Fluctuations.

Conclusion

The goal of the Western Water Initiative is to create a framework for research on causal relationships between climate, hydrology, water quality, aquatic ecosystems, and water management in the Interior West. Societal benefits include better predictive capabilities in the service of hazards mitigation and optimized resource use. Timeliness of the Initiative derives partly from the increasing complexity and societal stake in optimum water management, and partly from new observational tools and models that encourage integrated study of water across traditionally separate disciplines.

References

Bajwa, R.S., W.M. Crosswhite, J.A. Hostetler, and O.W. Wright. 1992. Agriculture, irrigation, and water use. U.S.D.A. Agricultural Information Bulletin #638.

Burges, S.J. 1997. Streamflow prediction--Capabilities, opportunities, and challenges. Water Science and Technology Board Proceedings National Academy Press, Washington, D.C. (In press).

Collier, M., R.H. Webb, and J.C. Schmidt. 1996. Dams and Rivers: A Primer on the Downstream Effects of Dams. USGS Circular 1126. Tucson, AZ.

Crowley, T., W. Nowlin, B. McCarl, and J. Mjelde. 1995. Benefits of improved climate prediction. National Association of State Universities and Land-Grant Colleges. (Unpublished).

Diaz, H.F. and C.A. Anderson. 1995. Precipitation trends and water consumption related to population in the southwestern United States: A reassessment. *Water Resources Research* **31**, 713-720.

Dunne, T. 1997. A Reassessment of opportunities in the Hydrologic Sciences. Water Sciences and Technology Board, NRC. National Academy Press, Washington, D.C. (In press)

Frederick, K., T. Vandenberg, and J. Hanson. 1995. Economic values of freshwater in the United States. EPRI Report WO3713-02 and Resources for the Future, Washington, D.C.

Frederick, K.D. 1995. America's water supply: status and prospects for the future. *Consequences*. **1**, 14-23.

Gleick, P. 1990. Vulnerability of water systems. In P.E. Waggoner, (ed.). Climate Change and Water Resources. John Wiley and Sons, N.Y.

Hirsch, R.N., J.F. Walker, J.C. Day, and R. Kallio. 1990. The influence of man on hydrologic systems. In The Geology of North America. Geological Society of America special publication vol. 0-1, p. 329-359.

Howe, C. 1990. Technology, institutions and politics: still out of balance. *Water Resources Research* **26**, 2249-2250.

Kennedy, D. N. 1994. Integrating drought management with western water policy: Challenges for the future. In Wilhite, D., and D. Wood, (eds.). Drought Management in a Changing West. IDIC Tech. Report Series 94-1, University of Nebraska, Lincoln, p. 39-44.

Lewis, W.M. et al. 1995. Challenges for Limnology in North America: An Assessment of the Discipline in the 1990's. *Bull. Am. Soc. Limnol. Oceanogr.* **4**, 1-20.

Meko, D., M. Hughes, and C. Stockton. 1991. Climate change and climate variability: The paleorecord. In National Research Council. Managing Water Resources in the West under Conditions of Climate Uncertainty. National Academy Press, Washington, D.C., p. 71-100.

Naiman, R.J., J.J. Magnuson, D.M. McKnight, and J.A. Stanford (eds.). 1995. The Freshwater Imperative: A Research Agenda. Island Press, Washington, D.C.

Nash, L.L. and P.H. Gleick. 1993. The Colorado River Basin and Climatic Change: The Sensitivity of Streamflow and Water Supply to Variations in Temperature and Precipitation. EPA Report #230-R-009.

National Academy of Engineering. 1996. Engineering Within Ecological Constraints. National Academy Press, Washington, D.C.

National Research Council. 1989. Irrigation-Induced Water Quality Problems. National Academy Press, Washington, D.C.

National Research Council. 1991a. Managing Water Resources in the West Under Conditions of Climate Uncertainty. National Academy Press, Washington, D.C.

National Research Council. 1991b. Opportunities in the Hydrologic Sciences. National Academy Press, Washington, D.C.

National Research Council. 1992a. Sustaining Our Water Resources. National Academy Press, Washington, D.C.

National Research Council. 1992b. Restoration of Aquatic Ecosystems. National Academy Press, Washington, D.C.

National Research Council. 1996a. Learning to Predict Climate Variations Associated with El Niño and the Southern Oscillation. National Academy Press, Washington, D.C.

National Research Council. 1996b. Assessment of the Hydrological and Hydrometeorological Operations and Services. National Academy Press, Washington, D.C.

National Research Council. 1996c. River Resource Management in the Grand Canyon. National Academy Press, Washington, D.C.

National Research Council. 1996d. A New Era for Irrigation. National Academy Press, Washington, D.C.

Pulwarty, R., S., and K., Redmond, 1997: Climate and salmon restoration in the Columbia River Basin: The role and usability of seasonal forecasts. *Bull. Amer. Met. Soc.* **78**, 381-397.

Sellers, P.J., F.G. Hall, G. Asrar, D.E. Strieml, and R.E. Murphy. 1993. An overview of the first international satellite land surface climatology project (ISLSEP) field experiment (FIFE). *Journal of Geophysical Research* **97**, 18345-18371.

Stakhiv, E., 1993: Water resources planning and management under climate uncertainty. In Ballentine, T. and E., Stakhiv, *Proceedings of the First National Conference on Climate Change and Water Resources Management*, Army Corps of Engineers Institute of Water Resources. Section IV, p. 20-35.

U.S. Congress, Office of Technology Assessment, 1993: Preparing for an Uncertain Climate. U.S. Government Printing Office. Washington, D.C.

Waggoner, P.E. (ed.). 1990. Climate Change and U.S. Water Resources. Wiley, N.Y.

Wood, E.F. 1997. Hydrologic measurements and observations: An assessment of needs. Water Science and Technology Board Proceedings, National Academy Press, Washington, D.C. (In press).