# CHAPTER 14

# POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR THE WATER RESOURCES OF THE UNITED STATES

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# CHAPTER SUMMARY

## Context

Water supply conditions in all regions and sectors in the US are likely to be affected by climate change, either through increased demands associated with higher temperatures,or changes in precipitation and runoff patterns. Water sector concerns include effects on ecosystems,particularly aquatic systems such as lakes,streams, wetlands,and estuaries. Although competition for water supplies is extremely intense,particularly in the western US,substantial ability to adjust to changing demands for water exists in the current water management system. It is not known whether the effects of climate change will require dramatic changes in infrastructure to control flooding and provide reliable water supplies during drought. However, it is known that precipitation and temperature changes are already increasing runoff volumes and changing seasonal availability of water supply, and that these changes are likely to be more dramatic in the future.

## Climate of the Past Century

- Increases in global temperatures have been accompanied by more precipitation in the mid and high latitudes.
- Precipitation has increased an average of 10% across the US,with much of the increase attributed to heavy precipitation events.
- Nationally, streamflow has increased about three times more than the increase in precipitation. Regionally, the higher streamflows have increased in many areas,but not in the West where snowmelt dominates peak flows.
- Reductions in areal extent of snowpack in the western mountains have been observed,along with substantial retreat of glaciers.
- In snowpack-dominated streams,a shift has been observed in the timing of the peak runoff to earlier in the season.
- No significant increases in the frequency of droughts or winter-type storms have been observed on a national basis.

## Climate of the Coming Century

- Historic trends towards increased precipitation are very likely to continue.
- It is possible that there will be an increase in interannual variability, resulting in more severe droughts in some years.
- The Canadian and Hadley climate models used in the Assessment generally do not agree on precipitation impacts,with the exception of showing an increase in precipitation in the Southwest.
- Increases in temperature, even in the context of increases in precipitation,are likely to result in significant loss of soil moisture in the Northern Great Plains.
- Snowpack is very likely to be reduced even in the context of higher precipitation.
- If the number of high intensity storm events increases, flushing of contaminants into watersheds is likely to increase,causing episodic water quality problems.
- Quality and quantity impacts are very likely to be regionally specific.
- Surprises are likely, since many water-related impacts cannot be predicted.

## Key Findings

- More pressure on surface water supplies is likely to come from population shifts and changes in water right allocations to accommodate endangered species and the water rights of Native Americans. Although wetter conditions in the Southwest may alleviate some of these stresses, stress is likely to increase in the Northern Great Plains and in snowpack-dependent watersheds.
- Groundwater supplies are already over-drafted in many parts of the country, and pressure on groundwater supplies is likely to increase to offset changes in surface water supply availability. However, long-term increases in precipitation will possibly increase recharge rates in some areas.
- It is likely that aquatic and riparian ecosystems may be damaged even in the context of higher precipitation, due to higher air temperatures and reduced summer flows. It is also probable that changes in water temperature in lakes and streams will affect species composition.
- Water managers have multiple opportunities to reduce future risks by incorporating "no-regrets" changes into their operating strategies that are appropriate regardless of climate change.
- Institutions governing water rights are generally very inflexible, and are likely to prove to be obstacles to adaptation.
- Improvements are needed in monitoring efforts to identify key impacts related to water quantity and quality, biological conditions of key habitats, snowpack conditions, and groundwater supplies.

# POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR THE WATER RESOURCES OF THE UNITED STATES

## BACKGROUND

Water-related concerns are central to this National Assessment because the hydrologic (water) cycle is a fundamental component of climate and because water plays a role in every sector and region in the US. Despite many remaining uncertainties, a significant amount of research has been done on the connections between climate change and water resources in the US; a searchable bibliography of almost 900 scientific articles is available at http://www.pacinst.org.

The US has a wide variety of tools, institutions and methods for coping with water resource problems, and many of these will be useful for addressing the impacts of climate changes. Water managers already deal with climate variability; reservoirs are designed with some flexibility for extreme high and low flows; techniques and technologies are available for managing water demands. But global climate change raises some unresolved concerns for the water sector. What will be the economic costs of coping with climate changes imposed on top of existing variability? Are existing institutions sufficiently flexible to handle the additional stresses? What might be the nature of unexpected climate "surprises" for the water sector? And will water managers be willing and able to prepare in advance for conditions different from those they are normally faced with?

**Figure 1: The Central Arizona Project brings Colorado River water 330 miles uphill to Tucson and Phoenix, Arizona. Source: K. Jacobs**

Increases in greenhouse gas concentrations are very likely to affect global temperature and lead to changes in the amount, timing, and geographic distribution of rain, snowfall, and runoff. Changes are also likely in the timing, intensity, and duration of extreme events such as floods and droughts. Such changes possibly will have greater impacts on the regions and sectors than changes in average temperature or precipitation. Higher demand for water is probable in areas where increased temperature results in higher evapotranspiration. Although in most regions it is possible that increased streamflow would relieve current stress, some regions are likely to experience greater difficulty in meeting their water supply needs if precipitation increases do not offset increases in evapotranspiration. Key variables in determining likely impacts and responses include changes in soil moisture and cloud cover, seasonality of precipitation, and the response of vegetation to changes in moisture, temperature, and increased carbon dioxide availability.

While many of the most significant impacts in the agricultural, forestry, ecosystem, energy, and human health sectors relate to the basic issue of water availability, it is likely that there will be some serious impacts on water quality as well. There is a direct relationship between quantity of flows and dilution of pollutants in surface water; higher runoff is likely to improve water quality, but increased intensity of rainfall will probably result in increased erosion and flushing of contaminants into watersheds. Higher water temperature will affect the ecology of wetlands, lakes, and streams. Much less research has been done on impact-related issues.

The primary water resource issue for the US is the distribution of supply and demand, not the total quantity of water available. The nature of water concerns varies by region across the country. For much of the western US, water resources are often separated both by time and distance from water demands. As a result, substantial infrastructure has been developed to store and transport water supplies (for example, from the Colorado River and Northern California to the Southwest and Southern California). There are more than 80,000 dams and reservoirs in the US,and millions of miles of canals, pipes,and tunnels (Schilling et al.,1987,see Figure 1). Although this infrastructure is sophisticated and has allowed the development of urban and agricultural areas,it is also a source of vulnerability to climate change,partially because it has been designed based on the assumption that future conditions will be similar to the historically observed climate. Some argue that there is substantial robustness built into the system that provides some margin of safety, but failure to re-evaluate these assumptions and identify key vulnerabilities may prove to be costly in the future.

Water supply issues in the eastern US relate to aging infrastructure and inadequate storage capacity during times of drought. Flood control issues and environmental impacts of structural solutions are also of concern. In general,local surface water and groundwater supplies are available for domestic and industrial use without major water transfers between basins, but excess reservoir capacity to respond to drought is quite limited. In some areas,such as New York City, reservoir function is threatened by upstream development. New York and other cities also have serious problems on a regular basis with water main breaks causing flooding and other damage.

The initial charge of this Assessment included identifying areas of existing stress and vulnerability and evaluating new problems that climate change may bring. This has necessarily resulted in an identification of negative effects,though certain aspects of climate change are likely to improve conditions in some areas of the US. Even in the absence of climate change,adapting to existing stresses (such as aging infrastructure,inadequate water supplies for areas of rapid growth,etc.) and increased pressures from population dynamics would be expensive. Frederick and Schwarz (1999a) estimate that the annualized water-related costs associated with the demands of an increasing population are likely to approach $13.8 billion by 2030. The impacts of climate change on these costs depend on the nature of the changes. The estimated costs include investments in new water supplies and conservation measures as well as the impacts on streamflows and irrigated lands. The costs would be much higher if climate change were to significantly decrease water availability (as under the Canadian climate model scenario) or increase the magnitude and timing of extreme events. This is because the current infrastructure and management practices are designed based on the historical climate conditions.

Inadequate water and wastewater infrastructure, common along the Mexican border and in some rural areas,leads to high risk for health problems. Because the public has very high expectations regarding water quality, and perceptions of health risks are not always accurate,health issues may have a high profile and require particular attention.

Health-related issues that have been linked to changes in the hydrologic cycle include potential for increases in water-borne pathogens such as *Cryptosporidium* and vector-borne diseases such as encephalitis,as well as outbreaks in marine pathogens associated with red tide (Bernard et al., 1999). Hantavirus,a disease spread by deer mice, has also been linked to extreme climate variability associated with the El Niño Southern Oscillation (ENSO). With higher rainfall, rodent populations tend to increase,which increases the chance of human contact and disease.

Virtually all indices of vulnerability relative to water have identified the over-appropriation of western streams and rivers and over-drafting of groundwater supplies as key issues. Gleick (1990) identified indicators of water resource vulnerability for the US and found that the most vulnerable regions were the high irrigation areas along the eastern drainage of the Rocky Mountains,the Central Valley of California,and Southern California. The overall index prepared by Hurd et al.(1999a) indicates that the most vulnerable watersheds are in the West, Southwest,and Great Plains (see Figure 2).

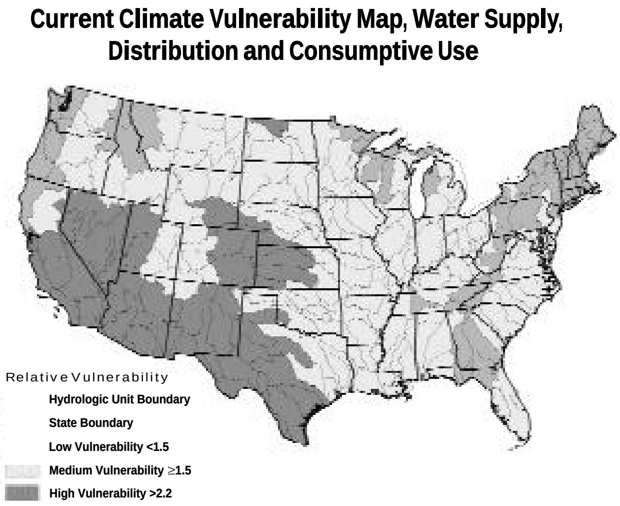

**Figure 2: Assessed vulnerability based on current climate and water resource conditions, based on data describing the following: share of streamflow withdrawn for use, streamflow variability, evapotranspiration rate, groundwater overdraft, industrial use savings potential, and water trading potential. Source: Hurd, B.J., N. Leary, R. Jones and J. Smith. (1999a).See Color Plate Appendix**

A rise in average temperature, even in the context of higher precipitation, is most likely to impact aquatic systems, including riparian habitat, and freshwater and estuarine wetlands. In some cases, this is because expected changes in precipitation do not offset increased evapotranspiration, though seasonal and regional impacts are likely to vary. Certain coastal systems, prairie potholes (small ponds and lakes formed by glacial deposits), and Arctic and alpine ecosystems are thought to be especially vulnerable. Stresses within the contiguous US are likely to come from changes in the distribution of precipitation as well as increases in its intensity.

## SOCIOECONOMIC AND INSTITUTIONAL CONTEXT

Population pressures, including shifts towards western and coastal urban areas, land use practices, and climate change are all likely to increase stress on water supply systems. The need to reserve water for instream uses, endangered species protection, recreation, and American Indian water rights settlements also places new demands on a water rights system that in many parts of the country is already seriously stressed. As society changes, its value system also evolves. Placing more value on protection of fish and wildlife habitat and recreational values is likely to force institutional change at the same time that new stresses are appearing due to climate variability and change. Although there is substantial uncertainty in the projections of changes in runoff that are derived from the climate models, socioeconomic conditions are even less predictable.

There is a need for more flexible institutional arrangements and more effective ways of making water policy decisions in order to adapt to changing conditions (not just changes in climate, but multiple existing stresses). The legal framework for water rights varies from state to state, with nearly infinite permutations at the local level. The one characteristic that is typical of most institutions related to water is inability to respond efficiently to changing socioeconomic and environmental conditions. This is primarily because institutions tend to reflect existing water right holders' interests, and substantial investments are made based on expectations regarding availability of supplies. Devising new legal and related institutions that can introduce the necessary flexibility into water management without destabilizing investors' expectations, while at the same time incorporating public values (ecological, recreational, aesthetic, etc.) is a significant challenge.

The state to state variations among water rights systems results in substantial complexity. In general, water rights in eastern states are not likely to be easily quantifiable, which limits management options. The prior appropriation doctrine of the western US is relatively inflexible in dealing with changing environmental and societal needs (see box, "Major Doctrines for Surface Water and Groundwater").

Some innovative institutions are developing in response to particular problems. For example, the "temporary" water banks in California to respond to drought and in Arizona to respond to long-term supply reliability issues offer some protection to existing water rights while providing much-needed flexibility. Water banks generally provide opportunities for short-term transfers of agricultural water supplies to municipal end users on a willing buyer/willing seller basis. In the case of the Arizona Water Banking Authority, excess Colorado River water is being stored underground through recharge projects to offset future shortfalls in supply. This opportunity is expected to be available on an interstate basis among the Lower Colorado Basin states in the near future. Similar types of contingency planning between jurisdictions and water rights holders could prove beneficial in responding to short-term emergencies. Longer-term changes in climatic conditions that would require permanent changes to legal systems could be more problematic.

Many have argued that an open market in water rights would help resolve conflict and increase efficiency because water would flow to the highest and best use based on willingness to pay (National Research Council, 1992; Western Water Policy Review Advisory Commission, 1998). It is widely acknowledged that market-related solutions may relieve some water supply problems, especially in the West. However, water marketing is an imperfect solution. Of particular concern are third party impacts in water transfers, and overall equity issues. Water markets are developing in many states, but they are generally regulated markets in order to protect the public interest. Mechanisms exist to identify economic values for non-market goods and services, but water rights for non-market values such as ecosystems, aesthetics, and recreation have difficulty competing with major economic forces. There is also a risk that disproportionate burdens will be placed on the social groups that can least afford them (such as rural farming communities, Native Americans, and communities along the Mexican border with inadequate infrastructure) (Dellapenna, 1999b; Gomez and Steding, 1998).

## Major Doctrines for Surface Water and Groundwater

Surface Water
Riparian doctrine – Authorization to use water in a stream or other water body is based on ownership of the adjacent land. Each landowner may make reasonable use of water in the stream but must not interfere with its reasonable use by other riparian landowners. The riparian doctrine prevails in the 31 humid states east of the 100th meridian.

Prior appropriation doctrine – Users who demonstrate earlier use of water from a particular source acquire rights over all later users of water from the same source. When shortages occur, those first in time to divert and apply the water to beneficial use have priority. New diversions,or changes in the point of diversion or place or purpose of use, must not cause harm to existing appropriators. The prior appropriation doctrine prevails in the 19 western states.

Groundwater
Absolute ownership – Groundwater belongs to the overlying landowner, with no restrictions on use and no liability for causing harm to other existing users. Texas is the sole absolute ownership state.

Reasonable use doctrine – Groundwater rights are incident to land ownership. Owners of overlying land are entitled to use groundwater only to the extent that the uses are reasonable and do not unreasonably interfere with other users. Most eastern states and California subscribe to this doctrine. Some states,such as Arizona, have modified the reasonable use doctrine by requiring state permits to use groundwater in certain high use areas.

Prior appropriation permit system – Groundwater rights are determined by the rule of priority, which provides that prior uses of groundwater have the best legal rights. States administer permit systems to determine the extent to which new groundwater uses will be allowed to interfere with existing uses. Most western states employ some form of permit system.

Sources:US Army Corps of Engineers, Volume III,Summary of Water Rights – State Laws and Administrative Procedure report prepared for US Army, Institute for Water Resources, by Apogee Research,Inc., June 1992; and US Geological Survey, National Water Summary 1988-89-Hydrologic Events and Floods and Droughts, Water Supply Paper 2375 (Washington,DC,US Government Printing Office,1991).

Dellapenna (1999a) says true (unregulated) markets have seldom existed for water rights and there are good reasons for believing that they seldom will. This is because water, like air, is viewed as a “public good,” which means that people cannot realistically be excluded from using it,at least on a subsistence basis. There is reluctance to pay the full cost of water, including the replacement cost;people are generally charged only the cost for capturing and distributing water. Key factors in developing a workable market are whether the market will enable consumers to meet their needs and whether government regulation and assistance at the margins can correct for market failures.

Numerous institutional issues related to responding to potential climate change stem from the fact that various agencies and levels of government handle water quality and water quantity issues. Water quality regulation derives primarily from federal authorities such as the Clean Water Act and the Safe Drinking Water Act. Water quantity regulation (through rights,allocations,and permits) is primarily handled by the states. An illustration of this problem is found in a study by Eheart et al.(1999), which evaluated the impact of reduced precipitation in the Midwest on ability to meet federal discharge water quality standards. They found that a 25% reduction in precipitation could reduce the critical dilution flow that determines discharge impact on water quality by 63%. They concluded that this has implications for the process of setting Total Maximum Daily Loads (TMDL) for Non-Point Discharge Elimination Permits under the Clean Water Act. Section 303(d) requires states to identify waters that do not meet water quality standards and to establish plans to achieve the TMDL standards. Eheart et al.(1999) noted that the present regulatory scheme in many midwestern states is not sophisticated enough to take into account the interplay between water quality and quantity.

## The Tennessee Valley Authority – Integrated Water Resources Management

A well-known example of integrated water resources management is the Tennessee Valley Authority (TVA), which operates in a seven-state area in the southeastern US. Founded in 1933,TVA pioneered the concept of "unified river basin development" within the Tennessee River Basin,integrating water resources development, social and economic development,power production,and natural resources conservation.

TVA's water management programs focus on the operation of a large, multipurpose reservoir system that includes more than 50 dams and reservoirs. The system is operated as an integrated unit to provide for navigation, flood control, hydropower generation,summer recreation levels,and minimum flows for the maintenance of water quality and aquatic habitat. In one of the most flood-prone areas in the US,TVA has historically taken a dual approach to flood management that combines reservoir system control with a floodplain management program to encourage appropriate shoreline development. Environmental concerns are integrated into reservoir operations,while TVA's Watershed Teams work at grassroots levels to motivate local action to control non-point source pollution. TVA also maintains web-sites and special telephone systems to facilitate public access to streamflow data,dam release information,and other system information.

TVA has a sophisticated streamflow and rainfall data collection and monitoring system,coupled with a state-of-the-art simulation and optimization modeling system. Monitoring and forecasting occur on a continuous,24-hour basis. Additionally,TVA utilizes 10-day and seasonal weather forecasts to guide reservoir planning. TVA is engaged in joint work with NOAA to better utilize seasonal forecast information. These capabilities will assist TVA in adapting to climate change and variability.

**Figure 3: TVA has more than 50 dams in seven states. Source: Tennessee Valley Authority**

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The institutions that have been successful in managing water resources tend to use an integrated approach to management,and to incorporate natural watershed boundaries rather than political boundaries for management areas. Relatively innovative water management districts have been formed in many states to address specific resource conditions (see box,"Tennessee Valley Authority – Integrated Water Resources Management").

## CLIMATE VARIABILITY AND CHANGE

Historic trends show that the surface temperature of the Earth has increased by about 1˚F (just over 0.6˚C) over the 20th century, with 1998 the warmest year on record. Higher temperatures have resulted in reductions in snow cover and sea ice extent.

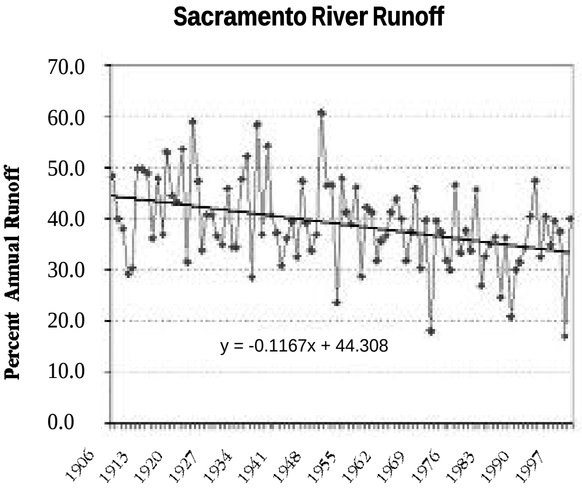
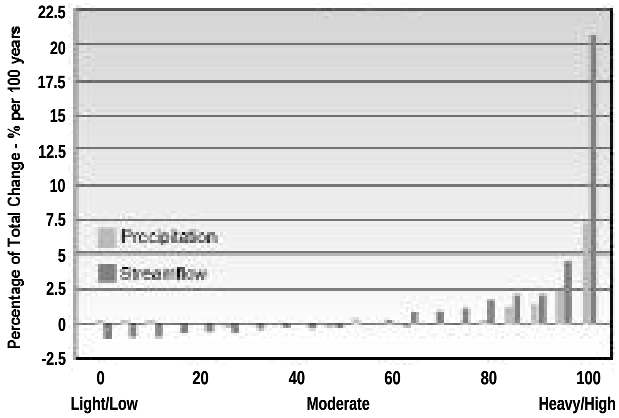


**Figure 4: In some western watersheds, runoff timing appears to be shifting from spring to winter, suggesting a change in snowfall and snowmelt dynamics. Source: Gleick, P.H. and E.L. Chalecki. (1999) JAWRA. Dec. pp. 1429-1442.**

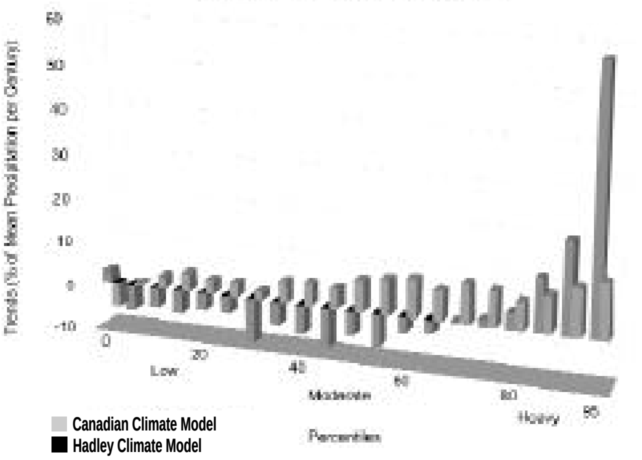
Trend analysis shows that since WWII,there has been significant retreat of snow cover in spring (Groisman,1999). At the same time,there appear to be shifts in the seasonality of runoff in some western rivers consistent with what would be expected from changes in snowfall and snowmelt dynamics due to warming (Gleick and Chalecki,1999;Union of Concerned Scientists,1999) (see Figure 4).

Increases in global temperatures have been accompanied by more precipitation in the mid and high latitudes (based on Northern Hemisphere land-surface records) and increases in atmospheric water vapor in many regions of North America and Asia where data are adequate for analysis (IPCC,1996). Karl et al.(1996) show that the meteorological drought indices suggest that there have been more wet spells,but no significant changes in drought on a national basis. The precipitation increase in the US has been attributed primarily to an increase in the heaviest precipitation events (Karl and Knight, 1998;Groisman et al.,1999;Karl et al.,1996). These changes are statistically significant and most apparent during the spring,summer, and autumn months in the contiguous US. Based on recent work by Lins and Slack (1999),the warm season precipitation increases may be responsible for increases in streamflow in the low to moderate range (i.e.the flow values that are most commonly observed during the summer and early autumn months). Using discharge data from a national network of stream gages for the period 1944-1993,Lins and Slack (1999) found statistically significant increases in the annual median streamflow at 29% of the stream gages nationwide and decreases at only 1% of the stream gages. Most trends were even more positive for the lower streamflow quantiles. Fewer significant trends were observed in high streamflows. Only 9% of the gages, for example,had significant trends in the annual maximum streamflow and,of these,more showed decreases than increases. Groisman et al.(2000) show that high streamflow in the mountainous West has not changed despite increases in heavy precipitation events. They attribute this to a trend toward reduced snow cover extent leading to a lower and earlier peak in the annual cycle of runoff. In the East and South however, increasing trends in high and very high streamflow are shown to relate to increases in heavy and very heavy precipitation events. In fact,there is an amplification of the trends in precipitation across the highest precipitation and streamflow rates by a factor of about three. It is well-recognized (Karl and Reibsame,1989) that small changes in precipitation can be amplified into large changes in streamflow (see Figure 5).



**Observed Changes In Streamflow and Precipitation (1939-99)**

**Figure 5: The graph shows changes in the intensity of precipitation and streamflow, displayed in 5% increments, during the period 1939-99 based on over 150 unregulated streams across the US with nearby precipitation measurements. As the graph demonstrates, the largest changes have been the significant increases in the heaviest precipitation events and the highest streamflows. Note that changes in streamflow follow changes in precipitation, but are amplified by about a factor of 3. Source: Groisman, et.al. (2001).**



**Projected 21st Century Change in US Daily Precipitation**

**Figure 6: These projections from the Hadley and Canadian models show the changes in precipitation over the 21st century. Each models' projected change in the lightest 5% of precipitation events is represented by the far left bar and the change in the heaviest 5% by the far right bar. As the graph illustrates, both models project significant increases in heavy rain events with smaller increases or decreases in light rain events. Source: National Climatic Data Center.See Color Plate Appendix**

Understanding historic changes,or projecting future changes in streamflow conditions will require more evaluation of the complex role of changing precipitation and temperature patterns as well as the role of land-use change on streamflow. These unresolved issues further reinforce the importance of maintain-

**Projected Changes in Average Annual Runoff Based on Two GCMs**

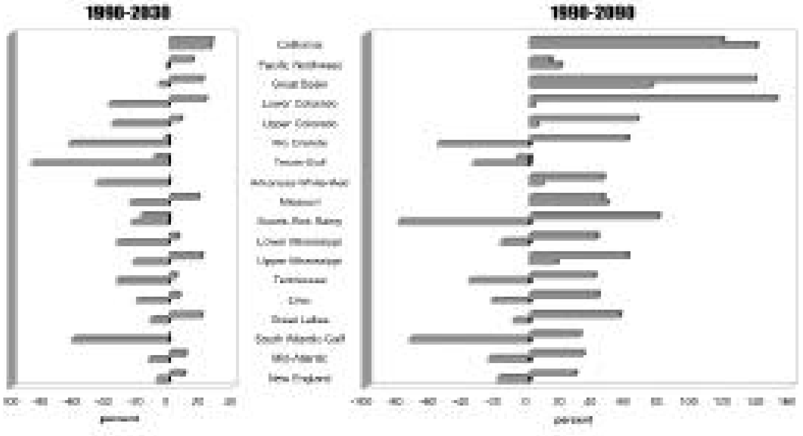


**Figure 7: The estimated percent changes in average annual runoff based on the Canadian and Hadley models are not well correlated. The Canadian model predicts declines in runoff in all regions except California, while the Hadley model projects increases in most regions, particularly in the Southwest. The models differ in precipitation predictions in part due to underlying model construction. Source: Wolock, D.M. and G.J. McCabe, 1999a. See Color Plate Appendix**

ing adequate nationwide networks of precipitation and streamflow gages to help describe and predict changes in average streamflow and,more importantly, streamflow variability.

In addition to a trend analysis of climatic conditions over the past 100 years,this Assessment has evaluated scenarios from two General Circulation Models (GCMs),one from the Canadian Centre for Climate Modelling and Analysis (henceforth referred to as the Canadian model),and the second,the “HadCM2” model from the Hadley Centre for Climate Prediction and Research of the Meteorological Office of the United Kingdom (henceforth referred to as the Hadley model). The Canadian and Hadley models used in this Assessment both project significant warming (5-9˚F or 3-5˚C) in most parts of the US by 2090. However, with the exception of the southwestern US,where both models show a large increase in precipitation in the future,especially in winter (Felzer and Heard,1999),the changes in precipitation predicted by the two models are strikingly different. In general,the Hadley model suggests much wetter conditions than the Canadian model. When comparing output of multiple GCMs,the Hadley model increases in precipitation are the most extreme. The precipitation increase in Southern California and Arizona is related to increases in sea surface temperatures in the eastern Pacific and southward shifts in the jet stream that loosely resemble the El Niño pattern. Differences between the two models are explained in part by differences in the land surface models relating to soil moisture and moisture availability in summer (Felzer and Heard,1999) (see Figure 6 and figures on precipitation change in the Climate and West Chapters).

Precipitation is a key climatic variable,but it is difficult to predict changes at the local level because they are affected by land surface features that are at smaller scales than the GCM outputs (Felzer and Heard,1999). Precipitation itself is a sub-grid-scale process,meaning that clouds and convection occur on scales smaller than GCM grids. Both models show increases in heavy precipitation events and increased storminess over the eastern Pacific,off the West Coast of the US (Lambert,1995;Carnell and Senior, 1998; Felzer and Heard,1999). However, precipitation patterns will vary regionally. An important issue for improving the utility of GCM output is the ability to downscale the models to a regional or watershed level where the information can be most useful to water managers.

Differences in temperature and moisture levels over land and sea are crucial in determining precipitation levels along the coasts. Over oceans, warming leads to increased evaporation and more precipitation because of the limitless supply of water. In contrast, because of the limited moisture holding capacity of the land, warming may cause drying and less precipitation. Globally, the models show decreased storm frequency, with increases in intensity. Over the US, the models do not produce a consistent projection regarding storm frequency (Lambert,1995;Carnell and Senior, 1998; Felzer and Heard,1999). No trends have been identified in North America-wide storminess or in storm frequency variability in the period 1885-1996 (Hayden,1999a).

Wolock and McCabe (1999a) have used a water-balance model and output from the two GCMs to estimate the effects of climate change on mean annual runoff for the major water resource regions of the US. The model includes the concepts of climatic water supply and demand,seasonality in climatic water supply and demand,and soil-moisture storage. Inputs to the model are monthly precipitation and potential evapotranspiration,which is calculated from monthly temperature using the Hamon equation (Hamon,1961). To evaluate the model’s reliability to estimate mean annual runoff for the 18 water-resources regions in the coterminous US,VEMAP-gridded monthly climate data for 1951-80 were used in conjunction with the water-balance model to estimate mean annual runoff. These estimated runoff data were compared with measured data for the same period. The water-balance model reasonably simulated measured mean annual runoff for most of the water-resources regions. In general,the results from these two GCMs are not well correlated,and project different changes in mean annual runoff (see Figure 7). The difficulty of projecting combined effects of changes in precipitation,temperature,and seasonality of events make projections of impacts based on GCM output uncertain.

On the other hand,both large-scale climate models and regional hydrologic models agree that if changes in temperature of the magnitude identified in the climate models occur, substantial changes in the amount of precipitation that falls as snow versus rain and earlier melting of snowpack are very likely to result in changes in the runoff regime (Frederick and Gleick,1999;Hamlet and Lettenmaier, 1999; McCabe and Wolock,1999;Leung and Wigmosta, 1999). Snowpack is very likely to be reduced even in the context of higher precipitation because of the warming trend (see Figure 8). The effects of changes in the timing and volume of runoff will probably be felt in most sectors and regions that are snowpack-dependent (Gleick,1998),although changes in runoff regimes will probably be highly regionally specific. For example,Leung and Wigmosta (1999) assessed the effects of climate change from the NCAR Community Climate Model (downscaled through a regional climate model) on the American River and the Middle Fork Flathead watersheds in the Pacific Northwest. There was a 61% reduction in snowpack on the American River, accompanied by a major shift in streamflow. On the Middle Fork Flathead there was an 18% reduction and no major shift in runoff. In both watersheds, there was a higher frequency of extreme low and high flow events.

Hamlet and Lettenmaier (1999) used four GCMs to evaluate runoff implications of climate change for various watersheds along the Columbia River. Altered streamflow information was simulated and used to drive a reservoir model to evaluate impacts on water management. Relatively large increases in winter runoff volumes and reductions in winter snowpack resulted in all cases. The March snow water equivalent averaged 75-85% of the base case for 2025,and 55 to 65% of the base by 2045. The earlier snowmelt,coupled with higher temperatures, reduced runoff volumes in spring,summer, and early fall. The researchers found that while higher temperatures increase the potential evapotranspiration, reduced soil moisture in the summer is likely to ultimately limit the actual evapotranspiration.

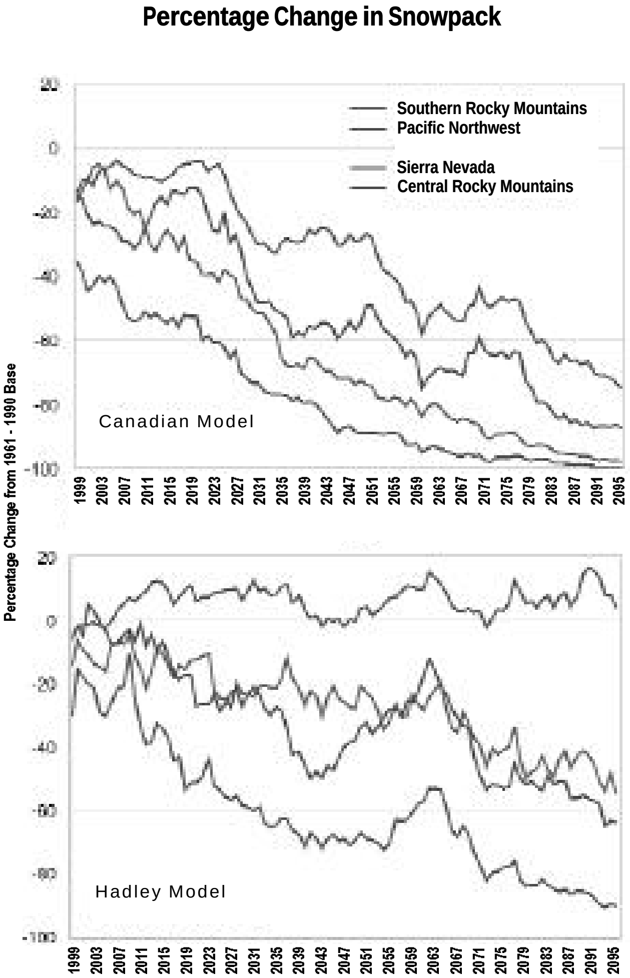


**Figure 8: Percentage change from the 1961-90 baseline in the April 1 snowpack in four areas of the western US as simulated for the 21st century by the Canadian and Hadley models. April 1 snowpack is important because it stores water that is released into streams and reservoirs later in the spring and summer. The sharp reductions are due to rising temperatures and an increasing fraction of winter precipitation falling as rain rather than snow. The largest changes occur in the most southern mountain ranges and those closest to the warming ocean waters. Source: McCabe, G.J. and D.M. Wolock. 1999. See Color Plate Appendix**

Hamlet and Lettenmaier also evaluated the impact on various water management objectives of the projected changes in streamflow (see Figure 9). From a water supply perspective,Hamlet and Lettenmaier found that on average,comparing the base case with output from four transient GCMs negatively affected four water resources objectives:non-firm hydropower production,irrigation,instream flow for fish,and recreation at Lake Roosevelt. The Hadley model also showed negative impacts on flood control and navigation,due to the significantly wetter conditions in that model. Hamlet and Lettenmaier noted that an adaptive strategy would be to shift the

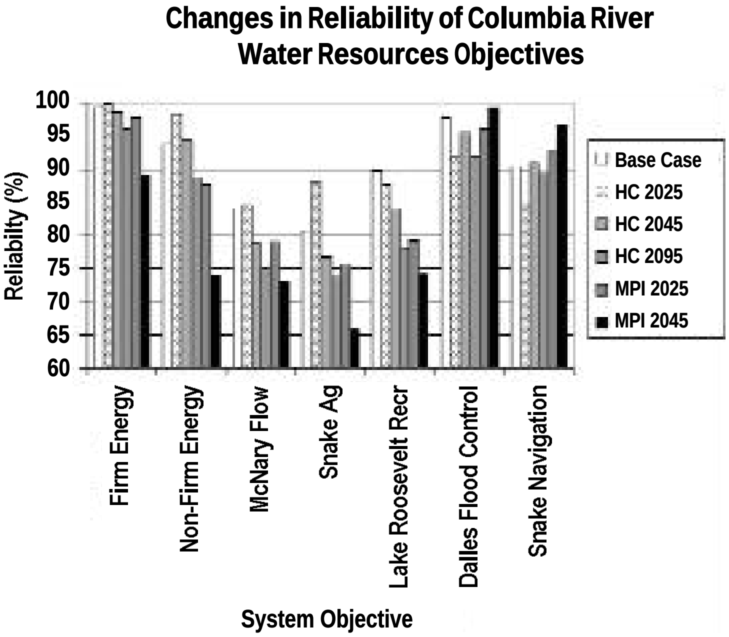


**Figure 9: Four major objectives are impacted by low summer streamflow and reservoir storage: non-firm energy production; irrigation; instream flow; and recreation at Lake Roosevelt. Source: Hamlet, A.F. and D.P. Lettenmaier, 1999. See Color Plate Appendix**

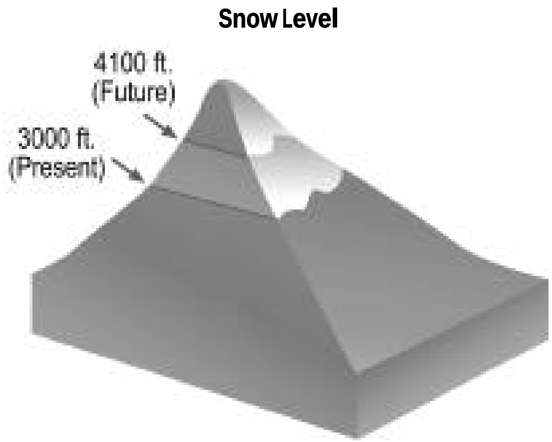


**Figure 10: Rough estimate of how much snowlines in the Pacific Northwest are likely to shift by 2050, assuming about 4ºF warming. Source: R. Leung, Pacific Northwest National Laboratory.**

hydropower production period in the Columbia to the summer, using stored winter flows. However, an important consideration is that while re-operation of the reservoirs can improve conditions within one management objective, impacts to one or more objectives cannot be avoided unless the total system demands are reduced. This is difficult to accomplish as the regional population increases.

As has been noted by many researchers attempting to model regional impacts, inadequate spatial resolution of climate models to capture the topographic features is a key problem in downscaling from the global models to local hydrologic features. The resulting disparity between GCMs in precipitation predictions must be addressed before water managers will be confident of likely outcomes. However, major advances have been made in the use of regional climate models to drive hydrologic models in the Pacific Northwest (Leung and Ghan, 1999; Leung and Wigmosta, 1999; Georgakakos et al., 1999). In the Southwest, the Regional Climate System Model has been used since 1995 for 48-hour precipitation and streamflow predictions with good success, including during the 1997-1998 El Niño season. This is one of the first global-to-mesoscale-to-watershed-basin scale predictions of this type (Miller et al., 1999).

A key variable in predicting water supply conditions is the impact of CO$_2$. Higher CO$_2$ tends to stimulate plant growth, resulting in feedback effects. The water requirements to support more biomass could possibly reduce the runoff associated with a given level of precipitation. However, higher CO$_2$ levels increase stomatal resistance to water vapor transport, which could decrease water use of plants (Frederick and Gleick, 1999). Under arid conditions, an increase in biomass from elevated CO$_2$ is likely to reduce runoff to streams, thereby leaving more water on the landscape. Under conditions of ample water for plant growth, elevated CO$_2$ causes partial stomatal closure with a consequent decrease in transpiration per unit of leaf area. However, leaf area likely will be increased, so it is difficult to predict overall impacts on water use. The CO$_2$ effect has been observed in several ecosystems, and varies by species (Kimball, 1983).

Natural variability in climate has been traced to a number of phenomena related to ocean temperatures and changes in global circulation patterns. Some of the resulting weather patterns can now be predicted with some accuracy, such as those associated with the El Niño Southern Oscillation (ENSO). The ability to develop forecasts useful to water managers based on these patterns is increasing, allowing for adaptive responses. It is not yet clear how these patterns will be affected by global changes in climate. Both models show more intense storms, but they do not agree on changes in storm frequency (Felzer and Heard, 1999).

Substantial water quality and temperature changes could result from changes in flow regimes. It should be noted that climate change could either increase or decrease the availability of water. While the hydrologic implications of the Canadian model project modest reductions in water supplies (<25%) in some regions,the Hadley model projects relatively large increases in water availability (25-50%) in most regions of the US. However, there are significant regions of precipitation decrease throughout the US in both seasons in the Canadian model and in summer in the Hadley model. The increases in precipitation are greater than the decreases principally because of the large projected increase in the Southwest (Felzer and Heard,1999).

## KEY ISSUES

Five key issues have been identified:

- Competition for water supplies
- Surface water quality
- Groundwater quality and quantity
- Heavy precipitation, floods,and droughts
- Ecosystem vulnerabilities

### 1. Competition for Water Supplies

Water supply

Changes in water supply availability for economic activities and environmental uses are likely to be affected by changes in average temperature and precipitation as well as by altered frequency of extreme events such as floods and droughts. There is general consensus among climate modelers that a warmer world is very likely to lead to more precipitation at mid and high latitudes as well as an increase in heavy precipitation events in these areas. More precipitation will typically lead to more runoff, but in some regions,higher temperatures and increases in evapotranspiration rates may possibly counteract this effect. Several modeling studies for the western US show that precipitation rates would need to increase by as much as 10-15% just to maintain runoff at historical levels because of increased evapotranspiration (Gleick and Chalecki,1999).

Changes in the timing of water supply availability are also very likely to occur. Surface water supplies that are dependent on snowmelt are likely to be affected by changes in the amount of precipitation that falls as rain versus snow, changes in snowpack volume,and earlier melting due to warmer temperatures. There is a strong consensus among researchers that there is very likely to be a shift in the peak volume and timing of runoff for watersheds that are affected by winter snowpack, resulting in earlier spring runoff, higher winter flows and lower summer flows (Frederick and Gleick,1999).

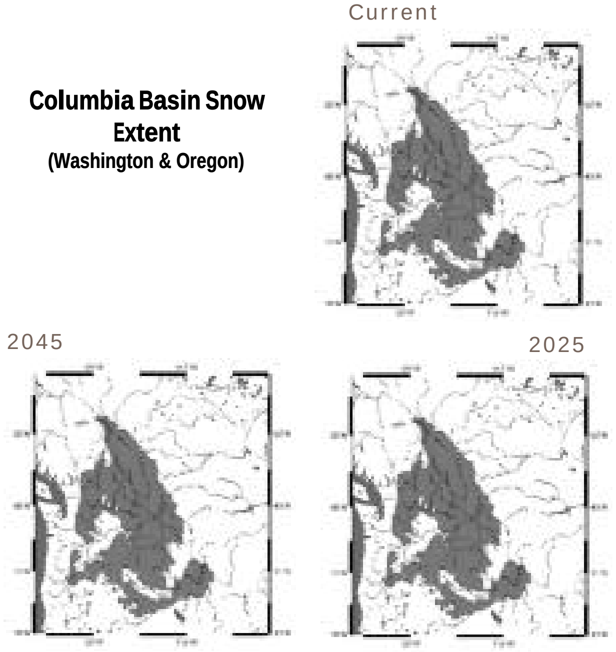


Figure 11: Complete loss of snow cover is projected at lower elevations. These maps are generated by downscaling output from global to regional climate models. Output shown from these models relates to the Columbia Basin; no projections are included for the blank areas outside the basin. Source: Mote, et.al. (1999) Impacts of climate variability and change in the Pacific Northwest, University of Washington. See Color Plate Appendix

**Projected Streamflow Effects from Climate Change in the Pacific Northwest**

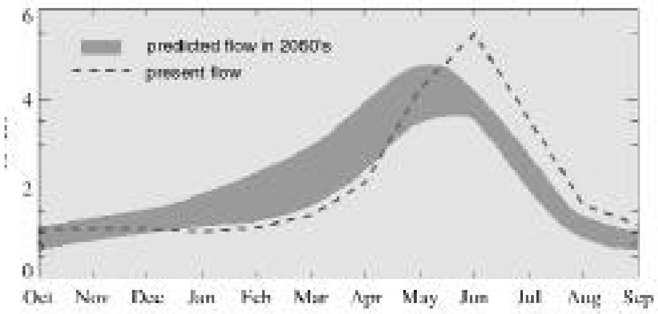


Figure 12: Relative to present flows (dashed), the wetter winters and drier summers simulated by climate models are very likely to shift peak streamflow earlier in the year, increasing the risk of late-summer shortages. Though the Columbia system is only moderately sensitive to climate change, allocation conflicts and a cumbersome network of interlocking authorities restrict its ability to adapt, producing substantial vulnerability to these shortages. Source: Hamlet, A.F. and D.P. Lettenmaier. 1999.

**Water Withdrawals and Population Trends**

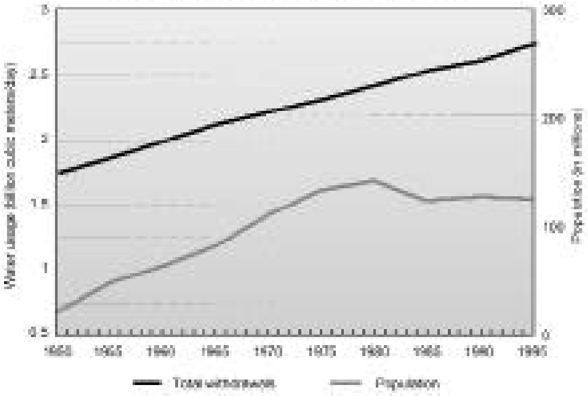


**Figure 13: Although US population has continued to increase, withdrawals have declined on a per capita basis. Reductions are due to increased efficiency and recycling in some sectors, and a reduction in acreage of irrigated agriculture. Source: Solley, W.B., R.R. Pierce, and H. A.Perlman, 1998.**

**Consumptive Water Use by Sector**

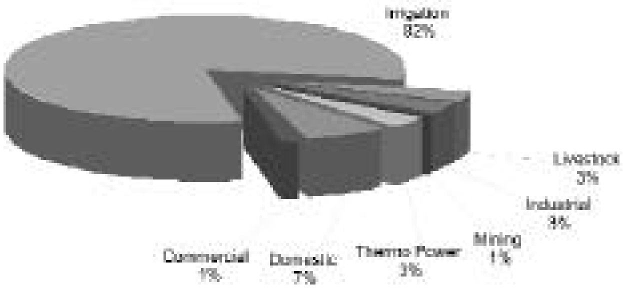


**Figure 14: Agricultural water use is the highest consumptive use sector. Source: Data from Solley, W.B., R.R. Pierce, and H. A.Perlman, 1998. See Color Plate Appendix**

An important area of vulnerability as a result of climate change is associated with summer water supply from Pacific Northwest (PNW) snow melt and transient snow river basins that are at moderate elevations. Under current climate conditions,summer streamflows in these moderate elevation basins are strongly affected by snow accumulation,which functions as winter storage. As the temperature rises,snow lines move up in elevation (see Figure 10) and overall snow extent is reduced (see Figure 11). As a result,maximum streamflows tend to be shifted towards the winter, with corresponding reductions in summer streamflow volumes (see Figure 12). High-elevation basins,which are below freezing for much of the winter season,are less affected by the changes in temperature,and the timing changes are less pronounced. For regional scale watersheds like the Columbia River Basin,which integrate both of these responses,the effects are intermediate. The lower summer flows that result from the shift in the hydrograph are likely to exacerbate existing conflicts between summer water supply for human use (e.g.,irrigation east of the Cascades and municipal use west of the Cascades),and maintenance of summer instream flow for ecological purposes (such as protecting salmon habitat). In the Pacific Northwest Regional Workshop it was concluded based on the 1995 Max Planck Institute climate model scenario that the most significant vulnerability to climate change is the potential for declining summer water supply in the context of rising demand (Pacific Northwest Regional Report,1999).

Since spring runoff events are likely to be earlier, reservoir management will need to become more sophisticated in managed watersheds. For example,optimized dynamic reservoir operation rules will likely become more appropriate than traditional rule curves. Relying more on medium and long-term predictions of weather will likely maximize supply and minimize risk of flooding (Georgakakos et al.,1999).

Depending on the degree to which river systems are managed, water supply effects can be dampened by storage and release regimes. However, a study of potential impacts on the Colorado River under current "Law of the River"operating procedures indicates that even small decreases in average runoff could lead to a dramatic decrease in power generation and reservoir levels (Gleick and Nash, 1993) as the system tries to maintain committed deliveries of water. Many storage systems,like the Colorado,can readily handle year-to-year variability but may have more difficulty with long-term change.

Water demand

Water withdrawals increased faster than population growth for most of this century and reached 341 billion gallons per day in 1995. However, since 1975 water use has been decreasing on a per capita basis,and total withdrawals have declined 9% since their peak in 1980 (Solley et al.,1998,see Figure 13). Per capita consumptive use is expected to continue to decline in some areas,due primarily to reductions in irrigated acreage,improvements in water use efficiency, recycling and reuse,and use of new technologies. Brown (1999) developed water-use forecasts to the year 2040 under several scenarios. Total withdrawals would increase only 7% by 2040 with a 41% increase in population under the middle population projection. However, even with reduced per capita use,urban demand is increasing in major metropolitan areas along the coasts and in the Southwest,due to population increases. Agricultural irrigators will likely continue to have competition from municipal users for available supplies. Under drought conditions,competition for water between the agricultural and urban users is likely to intensify (see Figure 14).

Increased water use efficiency is believed to be a key solution to the increasing stress on water supplies. It is widely thought that potential exists to reduce total demand for water without affecting services or quality of life. However, as more and more waste is taken out of the system,future demand is less easily reduced in response to drought or short-term delivery problems. This “hardening of demand”is widely recognized by water managers. Conservation investments generally need to be renewed over time,since the effectiveness of many programs declines over time (including the impacts of conservation pricing and the effectiveness of low water use plumbing devices).

Changes in average temperature,precipitation and soil moisture caused by climate changes are likely to affect demand in most sectors,especially in the agriculture, forestry, and municipal sectors. Increased temperatures and decreased soil moisture are very likely to increase irrigation water needs for some crops. There is a clear linkage between weather patterns and water demand in these sectors (see Figure 15).

In 1995,irrigation accounted for 81% of total consumptive freshwater use and 39% of total water withdrawals in the US (Solley et al.,1998). Total use of water in agriculture has been declining since 1980,with the exception of the Southeast,where a 39% increase in irrigated acreage of row crops was identified between 1970 and 1990 (Irrigation Journal,1996). McCabe and Wolock (1992) used an irrigation model to demonstrate that increases in mean annual water use in agriculture are more likely to result from increases in temperature than from decreases in precipitation. This finding may be important because runoff is also affected by increased temperatures.

Hydropower and navigation are not consumptive uses,but they are affected by both the volume and the timing of streamflows. Demand for electricity is very likely to increase with higher temperatures due to corresponding demands for summer air conditioning,but the water available for hydropower and cooling at electric generating plants may decrease because of increased pressure to divert more water for other uses. Climate change could possibly affect navigation by changing water levels in rivers, reservoirs,and lakes (e.g.,Great Lakes,Mississippi River, and Missouri River;see Midwest chapter),as well as by changing the frequency of floods and droughts.

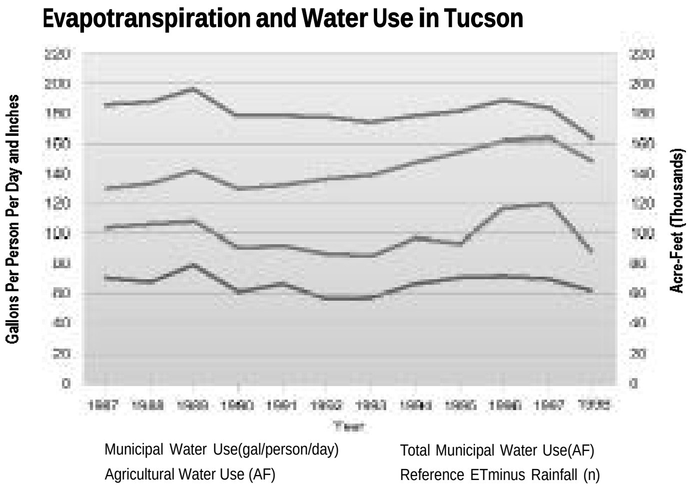


**Figure 15: Water demand in the agricultural and municipal water use sectors correlates strongly with evapotranspiration rates. Source: Arizona Deptartment of Water Resources. See Color Plate Appendix**

In the Pacific Northwest, hydropower and endangered species preservation are in increasing conflict because minimum streamflows must be maintained for habitat or water must be diverted away from turbines to protect migrating fish. Changes in seasonal runoff, even with no change in precipitation, could represent a very serious additional complication. Outflows from some power plants contain waste heat,which affects water temperature in the area of discharge. Although these discharges are regulated, changes in demand for electric power are likely to affect aquatic habitat. Precipitation changes in specific regions,such as the Pacific Northwest and portions of the eastern US,will affect hydropower capacity in the future.

Water issues for Native American communities are particularly critical,in part because of geographic and legal limitations and competition for resources. Significant concerns exist related to fisheries and aquatic habitat,especially with regard to Native subsistence economies. These concerns are particularly important in the Pacific Northwest. Because Indian reservations are found throughout the US, water issues vary substantially by geographic region. In most cases,the tribal culture is tied to a specific place and traditional survival strategies.

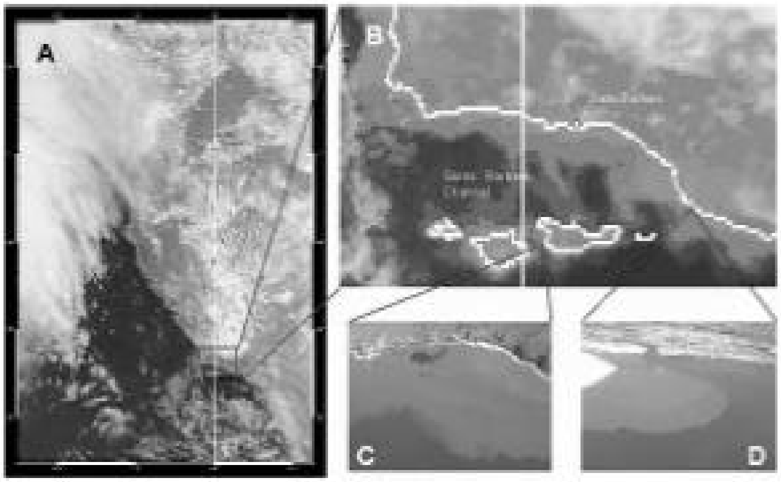


**Figure 16: Sediment flow off Santa Barbara caused by El Niño storm runoff. Source: Mertes, L., The Plumes and Blooms Project, ICESS/UCSB.** ***See Color Plate Appendix***

**Figure 17: Coastal mudslide on Highway 50, California following vegetation removal and heavy rainfall. Source: Eplett, R.A., California Governor's Office of Emergency Services.**

The viability of the Hopi reservation, for example,is linked to the availability of water on their reservation. This results in added vulnerability to climate change impacts.

Many American Indian communities possess senior, but unexercised water rights. As these rights are put to use,new stresses are very likely to be introduced in the affected watersheds. Quantifying and litigating the water rights claims of Indian communities is a major ongoing issue in many western states.

## 2. Surface Water Quality

Major improvements have been made in the quality of surface water in the US,largely attributable to the success of the Clean Water Act in reducing industrial pollution and discharge of sewage. In 1994,83% of the rivers and 87% of the lakes were considered suitable sources for drinking water supply (all surface water must be treated before use),while 95% of the rivers and 82% of the lakes were suitable for fish habitat (US Dept of the Interior, 1997). Remaining water quality problems were attributed primarily to non-point sources of pollution,such as nutrients, bacteria,and siltation deriving from agriculture,and urban runoff (US Dept.of the Interior, 1997).

Water quality issues associated with potential climate change impacts are more subtle than supply issues and include potential impacts on human health and ecosystem function, changes in salinity associated with changes in stream flow, and changes in sediment regimes. Non-point source pollution and agricultural byproducts are likely to become more problematic depending on the change in precipitation patterns;an increase in extreme precipitation events is considered likely (IPCC,1996),which may increase risk of contamination. A balancing effect is that with some exceptions,higher precipitation will result in lower concentrations of organic and inorganic constituents in surface water, due to dilution. Water quality is greatly influenced by flow variability, and some significant water quality problems are episodic,e.g.,episodic acidification from snowmelt,and algal blooms due to nutrient increases (Mulholland and Sale,1998;Meyer et al., 1999). Increasing salinity related to irrigation return flows (water returning to streams and aquifers after use by agriculture) and greater diversions of surface water are ongoing issues,especially in the West. Changes in streamflow associated with increased precipitation are likely to reduce salinity levels,especially in winter, while lower flows and higher temperatures could exacerbate this problem in summer. Flooding associated with more intense precipitation can also affect water quality by overloading storm and wastewater systems,and damage sewage treatment facilities,mine tailing impoundments,or landfills,thereby increasing risk of contamination.

Many of Santa Barbara's beaches were closed in 1998 due to high bacterial counts from the intense El Niño storm runoff. More winter runoff is likely to bring larger sediment flows to coastal waters,while lower summer streamflow is likely to increase salinity and impact estuarine species (see Figure 16).

A combination of increased precipitation and warmer, drier summers could increase fire hazard in some ecosystems. Sedimentation,landslides,and mudslides frequently follow removal of vegetation by fire (see Figure 17).

Drinking water supplies are very likely to be directly affected by sea-level rise in coastal areas,both through saltwater intrusion into groundwater aquifers and movement of the freshwater/saltwater interface further upstream in river basins. In the case of New York City, if the salt front moves further up the Hudson River, it will threaten emergency water supply intakes (Northeast Regional Report, in preparation). Periodic storm surges can also affect water quality and these are likely to be exacerbated by rising sea levels in a warming climate.

It is likely that climate change will affect lake, reservoir, and stream temperature through direct energy transfer from the atmosphere and changes in dam operations. Increased temperatures in surface water are likely to eliminate some species (such as salmon and trout) that are already near their habitat temperature threshold (see Figure 18). Higher temperatures result in reduced dissolved oxygen in water, which is a measure of ecosystem condition. Hurd et al.(1999) used dissolved oxygen stressed watersheds as an indicator of ecosystem vulnerability, and found that the most vulnerable regions are in Wisconsin, northern Illinois, southern Appalachia, South Carolina, and large portions of east Texas, Arkansas, Louisiana, and Florida (see Figure 19). Changes in temperature regimes are also likely to affect ice cover, and mixing and stratification of water in lakes and reservoirs, conditions that are key to nutrient balance and habitat value (Meyer et al., 1999).

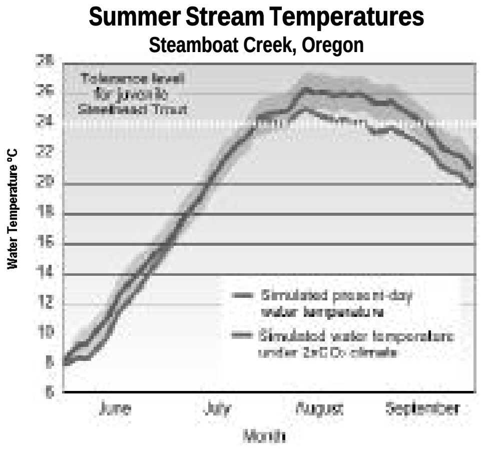


Figure 18: Simulated summer stream temperatures under present day climate (blue) and simulated temperatures under about a twice current $CO_2$ climate (red). The dashed line at 24 ºC (75 ºF) on the "water temperature" axis indicates the summer temperature tolerance of juvenile steelhead trout. Under doubled $CO_2$, the model suggests that the length of time within the year when the temperature tolerance limit is exceeded is more than twice as long as under simulated present-day climate conditions. Shaded area surrounding the doubled $CO_2$ temperature curve indicates an estimate of uncertainty. Source: US Geological Survey Circular 1153, Robert S. Thompson, et al. See Color Plate Appendix

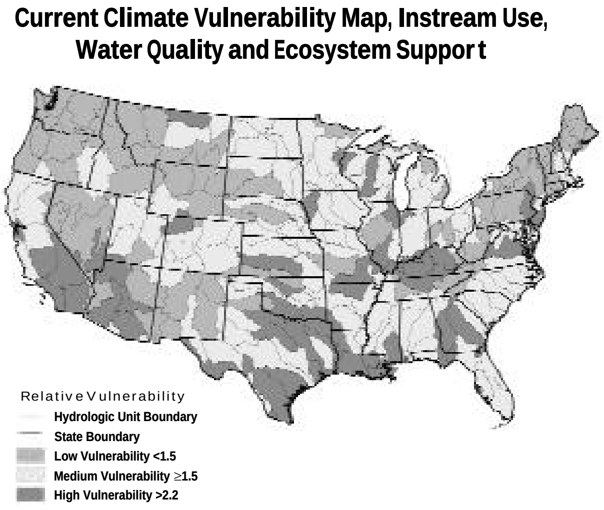


Figure 19: Instream Use, Water Quality, and Ecosystem Support Assessed Vulnerability based on current climate and water resource conditions, based on data describing the following: flood risk population, navigation impacts, ecosystem tolerance to cold and heat, dissolved oxygen stress, low streamflow conditions, and number of aquatic species at risk. Source: Hurd, B.J., N. Leary, R. Jones and J. Smith, 1999a. See Color Plate Appendix

## 3. Groundwater Quantity and Quality

Groundwater is the source of about 37% of irrigation water withdrawals (Solley et al., 1998), and supplies drinking water to about 130 million Americans (USGS, 1998). Though groundwater supplies are less susceptible to variations in climate than surface water, they may be more affected by long-term trends. More frequent or prolonged droughts are likely to increase pressure on groundwater supplies, which commonly serve as a buffer during shortages of surface water supplies. Depletion of groundwater is significant on the High Plains, the Southwest, parts of the Southeast, and in the Chicago area (USGS, 1998). Groundwater overdraft can cause substantial long-term effects, because in some areas the available groundwater supply is essentially nonrenewable or because land compaction prevents groundwater recharge (see Figure 20). Where the rate of recharge of groundwater aquifers is slower than use, long-term groundwater pumping becomes unsustainable. However, increases in precipitation are likely over a significant portion of the US, and many groundwater aquifers are likely to benefit. Despite the importance of groundwater to water supply in many regions, effective institutions to manage groundwater are the exception, rather than the rule (Dellapenna, 1999; National Research Council, 1997).

Groundwater is managed through a different mechanism in virtually every state, though there are

**Figure 20: Land subsidence fissure,, caused by over-pumping of groundwater, can result in earth fissures such as this near Eloy, Arizona. Source: K. Jacobs.**

**Figure 21: Artificial recharge in Santa Ana riverbed. Artificial groundwater recharge in the Santa Ana Riverbed, Orange County Water District, California. Source: Orange County Water District.**

three basic systems of groundwater rights (see box, "Major Doctrines for Surface Water and Groundwater").

Groundwater maintains the base flow for many streams and rivers,and lowering groundwater levels may reduce the seasonal flows and alter the temperature regimes that are required to support critical habitat,especially wetlands. Although conjunctive management (using groundwater and surface water in combination to meet demand) is frequently cited as a solution to water supply problems,this approach is only sustainable if the groundwater supplies are periodically recharged using surplus surface water or other alternative supplies (see Figure 21). In order to ensure a sustainable supply, aquifers may need to be artificially recharged,which involves consideration of multiple issues including changes in water quality in the aquifer. In some cases,such as portions of the Ogallala Aquifer in the Great Plains, groundwater supplies have already been over utilized and no source of renewable supplies is available.

Groundwater in storage is affected by seasonality, volume,and persistence of surface water inflows, and discharges from groundwater to surface water. Groundwater/surface water interactions are poorly understood in most areas. Changes in precipitation and temperature may have long-term effects on aquifers that are relatively subtle and difficult to identify. Groundwater is frequently found in horizontal layers within an aquifer, separated by relatively impermeable layers of silt and clay or rock. The water quality is affected by the substrate that the water flows in,and the amount of time it has been in storage. In some areas,only the surface zone is contaminated by human activities. An understanding of the aquifer's geology, including such characteristics as location of impermeable layers and the direction of water flow, is necessary in designing appropriate management options.

Industrial pollution is the largest groundwater quality issue in urban areas. Common problems include solvents and petrochemicals. Recently released data from the USGS National Water Quality Assessment indicate that volatile organic compounds (VOCs) were detected in 47% of urban wells tested between 1985 and 1995. The most common VOCs found were the fuel additive MTBE (methyl tertiary butyl ether) and various solvents such as tetrachloroethene,trichloroethene and trichloromethane (Squillace et al.,1999). Contamination of drinking water supplies presents serious challenges to water managers,especially in large urban areas. Cleanup of contaminated aquifers is extremely expensive and in some cases is not practical.

Agricultural chemicals and wastewater treatment byproducts such as nitrates also affect groundwater quality in some areas.Continued degradation is anticipated in some metropolitan areas. It is unclear whether climate change will have a significant effect on groundwater contamination.

Increased pressure on groundwater supplies has resulted from the Safe Drinking Water Act (SDWA) regulations. The Surface Water Treatment Rule now requires filtration of all surface sources. As a result, many small surface water systems are now uneconomical,and have either combined to form larger systems or switched to groundwater, for which filtration is not required. O'Connor et al.(1999) surveyed 506 community water system managers in the Pennsylvania portion of the Susquehanna River Basin,and found that half of all the community water systems in Centre County switched to groundwater or regionalized their surface water systems in response to SDWA regulations.

Another key groundwater quality concern is saltwater intrusion in coastal aquifers. As pumping of groundwater increases to serve municipal demand along the coast,freshwater recharge in coastal areas is reduced,and sea level rises, groundwater aquifers are increasingly affected by infiltration of seawater. Seawater intrusion is already a major issue in Florida,the Gulf Coast,southern California,Long Island,Cape Cod,and island communities. The global sea level is estimated to have risen 4 to 8 inches (10-20 cm) over the past 100 years (Gornitz, 1995);in some areas,the relative sea-level rise has been greater because land surface elevations are sinking in some regions of the coast. Further increases in sea level are very likely to accelerate intrusion of salinity into aquifers and affect coastal ecosystems. The adaptation strategies for dealing with this problem — importation of alternative sources of supply, desalination,and artificial recharge — can be extremely expensive.

Because surface water and groundwater supplies are interconnected and transportation of water across hydrologic and political boundaries is common, issues related to surface water/groundwater interactions will possibly be exacerbated by climate change. Even in the context of higher average precipitation,increased temperatures and changes in seasonality of runoff are likely to reduce streamflows during the warm season,a key period for ecosystem maintenance. Increased urbanization, which generally results in increased channelization of streambeds and higher runoff rates is likely to reduce opportunities for recharge of groundwater near areas of high groundwater demand. Water transfers may increase pressures on areas of origin from the perspective of water supply and ecosystem health. Particularly in arid and semi-arid regions, effects on surface water or groundwater resources resulting from climate change are likely to impact riparian systems that support a high percentage of biological diversity. In many cases,higher precipitation is likely to have a positive effect on groundwater levels and riparian habitat.

**Cumulative Number of Large Dams Built in the US**

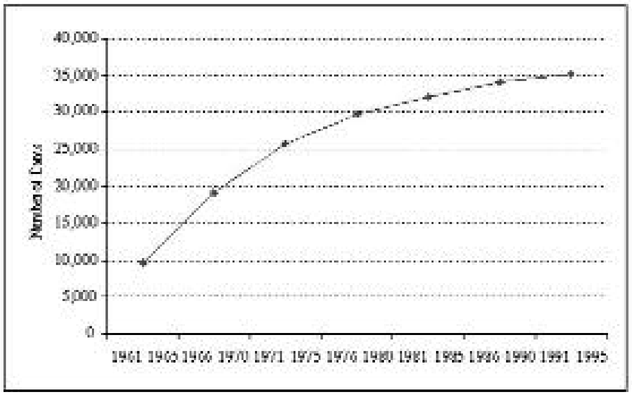


**Figure 22: The number of large dams built in the US has declined in recent decades, data yearly. Source: US Army Corps of Engineers. 1996. National Inventory of Dams.**

**Average Volume of US Reservoirs Built**

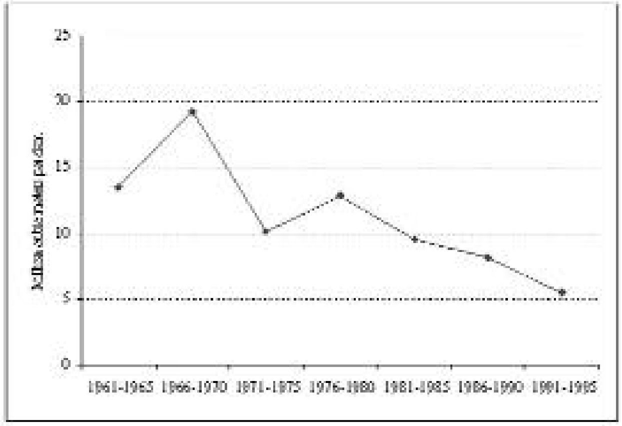


**Figure 23: The average volume of reservoirs built in each five-year period since 1960 has declined, data five year interval. Source: US Army Corps of Engineers. 1996. National Inventory of Dams.**

## 4. Heavy Precipitation, Floods and Droughts

Floods,especially those related to flash floods from intense short-duration heavy rains,are likely to increase in magnitude or frequency in many regions. Changes in seasonality of flood flows are very likely to occur in those areas affected by a higher proportion of rain to snow (yielding earlier peak flows of shorter duration). Intensity of droughts is also likely to increase in some areas due to higher air temperatures causing greater evaporation and water use by plants.

There are two types of socioeconomic costs related to floods and droughts:the costs of building and managing the infrastructure to avoid damages,and the costs associated with damages that are not

## Impacts of Potential Climate Change on Aquatic Ecosystem Functioning and Health

(adapted from Meyer et al.,1999)

| Region | Potential Climate Effect | Ecosystem Considerations |
|---|---|---|
| Great Lakes/ Precambrian Shield | Warmer, more precipitation,but drier soils possible,depending on the magnitude of precipitation increase. | Altered mixing regimes in lakes (e.g.,longer summer stratification.<br>Changes in DOC concentration, changes in thermocline depth and productivity.<br>Decreased habitat for cold and cool water fishes,increased habitat for warm water species.<br>Alteration of water supply to wetlands will affect composition of plant communities and carbon storage as peat. |
| Arctic and sub-Arctic North America | Much warmer, increases in precipitation | Loss or reduction of deltaic lakes.<br>Reduction in area covered by permafrost,leading to drainage of lakes and wetlands,land slumping,sedimentation of rivers.<br>Increased primary productivity, but perhaps not enough to compensate for increased metabolic demands in predatory fish.<br>Shift in carbon balance of peatlands. |
| Rocky Mountains | Warmer | Changes in timberline would affect stream food webs.<br>Increased fragmentation of cold-water fish habitat.<br>Fishless alpine lakes sensitive to changes in nutrient loading and sedimentation.<br>Current anthropogenic changes are threatening aquatic ecosystems. |
| Pacific Coast Mountains and western Great Basin | Warmer, less snow but more winter rain,less summer soil moisture | Increases in productivity in alpine lakes.<br>Increased meromixis and decreased productivity in saline lakes.<br>Altered runoff regimes and increased sediment loads leading to decreases in channel stability and negative impact on economically important fish species. |
| Basin and Range,Arid Southwest | More precipitation, warmer, overall wetter conditions | Aquatic ecosystems highly sensitive to changes in quantity and timing of stream flow.<br>Intense competition for water with rapidly expanding human populations. |
| Great Plains | Warmer with less soil moisture | Historical pattern of extensive droughts.<br>Reduced water level and extent of open water in prairie pothole lakes with negative effects on waterfowl.<br>Increasing warming and salinity in northern and western surface waters threatening endemic species.<br>Reduction in channel area in ephemeral streams. |
| Mid-Atlantic England | Warmer and and New somewhat drier | Potentially less episodic acidification during snowmelt.<br>Possible increase in bioaccumulation of contaminants.<br>Bog ecosystems appear particularly vulnerable.<br>Current context:stresses from dense human populations and a long history of land use alterations. |
| Southeast | Warmer with possible precipitation increases and greater clustering of storms | Increases in rates of primary productivity and nutrient cycling in lakes and streams.<br>More extensive summer deoxygenation in rivers and reservoirs.<br>Loss of habitat for cold-water species like brook trout,which are at their southern limit.<br>Drying of wetland soils.<br>Northward expansion of nuisance tropical exotic species.<br>Increased construction of water supply reservoirs. |

avoided, including ecosystem impacts. About $100 billion has been spent by the federal government since 1936 in the US for the construction, operation and maintenance of flood control features, yet damages associated with floods continue to rise (Frederick and Schwarz, 1999b). Flood damage estimates by state are provided by the National Center for Atmospheric Research and the US Army Corps of Engineers. The 1993 flood in the Mississippi and Missouri Rivers caused record damages of over $23 billion. These are only the official damage estimates, and do not take into account total social costs. The 1999 North Carolina flood, resulting from Hurricane Floyd, offers a recent example of the massive dislocations and multi-billion dollar costs that often accompany such events. Dams and levees have also saved billions of dollars of investment, but these facilities, together with insurance programs, encourage development in floodplains, thereby indirectly contributing to damages (Frederick and Schwarz, 1999b). In addition, structural flood control features have high environmental costs. Climate change may affect flood frequency and amplitude, with numerous implications for maintenance and construction of infrastructure and for emergency management. Erosion and deposition rates in rivers and streams are likely to change under different precipitation regimes. The reduction in reservoir construction along with the buildup of sediment in reservoirs will affect the resilience of water supply systems and their ability to handle flood flows (Frederick and Schwarz, 1999b) (see Figures 22 and 23).

Flood risks are ultimately a function of many factors, including populations exposed to floods, the nature and extent of structures within river floodplains and in coastal areas subject to storm surges, the frequency and intensity of hydrologic events, and kinds of protection and warning available. To the extent that each of these factors can be addressed economically and in a timely and integrated manner, future damages can be limited. Wetlands restoration in managed watersheds can reduce the impact of storm water runoff to waterways by slowing down or absorbing excess water. Providing wetland protection including buffer areas beyond the wetland boundary is a viable method of avoiding flood damage or the cost of flood protection.

**Palmer Drought Severity Index Change**

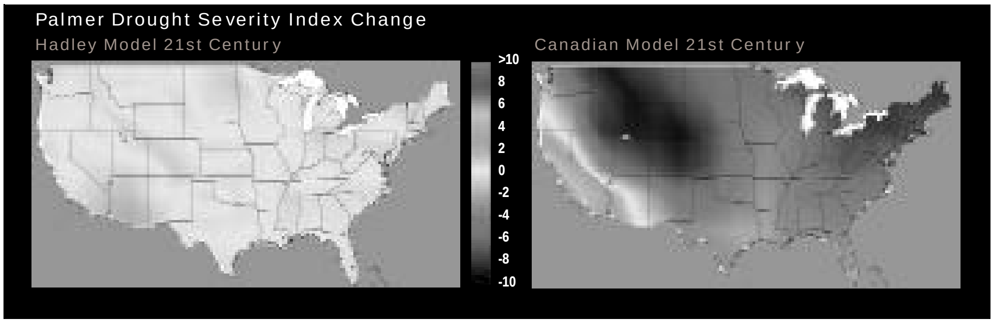


**Figure 24: The Palmer Drought Severity Index (PDSI) is a commonly used measure of drought severity taking into account differences in temperature, precipitation, and capacity of soils to hold water. These maps show projected changes in the PDSI over the 21st century, based on the Canadian and Hadley climate scenarios. A PDSI of -4 indicates extreme drought conditions. The most intense droughts are in the -6 to -10 range, similar to the major drought of the 1930s. By the end of the century, the Canadian scenario projects that extreme drought will be a common occurrence over much of the nation, while the Hadley model projects much more moderate conditions. Source: Felzer, B. UCAR. — See Color Plate Appendix**

**Figure 25: Prairie potholes are considered to be especially vulnerable to drying conditions in the northern Great Plains.**

There are many different kinds of droughts, from short-term localized reductions in water availability to long-term and widespread shortages. Severe droughts have had widespread and devastating effects, particularly on agriculture. The drought of the 1930s affected 70% of the US and caused substantial economic dislocations (Woodhouse and Overpeck, 1999). Prolonged droughts affect all sectors of the economy, and may be especially devastating for ecosystems. An evaluation of the paleoclimatic record indicates that droughts of Dust Bowl severity are not unprecedented, at least at a regional level. Agricultural interests in the Great Plains region are particularly concerned about the increased likelihood of drought with global warming (see Figure 24). In the Canadian model, severe and extreme drought becomes the norm for the Great Plains, but in the Hadley model such drying is not evident. Better information is needed on changes in drought risks from climate changes.

Droughts also affect the ability of waterways to support transportation, particularly on the Great Lakes and major river systems like the Mississippi and Missouri. Climate change is likely to affect the volume and timing of streamflows, the amount of sediment carried and deposited in shipping channels, and the extent of ice blockage in the northern waterways (Hurd, et al., 1999).

## 5. Ecosystem Vulnerabilities

Climate changes are very likely to have a wide variety of effects on ecosystems. Other human-induced changes (such as impacts of changing land use on water quantity and quality, sediment load, and competition from exotic species) are expected to be of greater magnitude in most parts of the country than climate change. However, climate change may add another layer of stress to natural systems that have lost much of their resiliency. From an ecological perspective, the Arctic, Great Lakes, and Great Plains (especially Prairie Potholes, see Figure 25) regions appear most vulnerable (see summary table adapted from Meyer et al., 1999). Aquatic and riparian ecosystems in the arid Southwest are also vulnerable to changing precipitation and runoff regimes, but the nature of predicted climate change in that region may alleviate existing stresses (Meyer et al., 1999), see table on page 424.

Evidence of the current warming trend can be found in Alaska, where the area of sea ice is shrinking, glaciers are melting, and land that has been supported by permafrost for centuries is transitioning to a new ecological regime. Although the impact on river flows in Alaska has not been sufficiently studied, it is clear that major changes are occurring which have already affected species composition and subsistence hunting and fishing. Changes in climatic conditions in Alaska are very likely to be even more dramatic in the future, as albedo (reflectivity) is reduced by reduced ice and snow cover and evaporation rates increase in the summer (Felzer and Heard, 1999).

Impacts on lakes and wetlands from climate change are likely to include changes in water temperature, sedimentation and flushing rates, length of ice cover, amount of mixing of stratified layers, and the inflow of nutrients and other chemicals. Montane and alpine wetlands with temperature-sensitive species will probably be vulnerable because they have little potential for migration (Kusler and Burkett, 1999). Minor changes in maximum and minimum temperatures and seasonality of precipitation can have significant impacts on wetland habitat (Kusler and Burkett, 1999). Wetlands that are directly dependent on precipitation are likely to be more vulnerable to climate change than those that are dependent on groundwater outflows due to the significant buffering capacity of regional aquifer systems (Winter, 1999). Riparian habitats are of great concern in part because 55% of threatened and endangered species are dependent on them (Herrmann et al., 1999).

Species live in the larger context of ecosystems and have differing environmental needs. A change that is devastating to one species may encourage the expansion of another to fill that niche in the system. It is not possible to determine a single optimum environmental condition for all species in the ecosystem (Meyer et al., 1999). Extreme conditions such as floods, droughts, and fire are critical to sustaining certain ecosystems. Hydrologic conditions affect nutrient cycling and availability in streams and lakes, which affects productivity. Ecological responses to changes in flow regime will depend on the regime to which it is adapted; a system that is historically variable can be severely disrupted by stabilizing the hydrologic regime (which happens when dams are used to regulate flow, as on the Colorado River).

# ADAPTATION STRATEGIES

Water management has become more complex as values related to water supply and demand have shifted and regulations have proliferated, both prescribing and proscribing many solutions. Most of the options available for responding to the impacts of climate change and variability on water resources are alternatives that are already used to respond to existing challenges. However, it should be noted that optimizing water resource management under increasing constraints (including regulatory constraints) narrows the options available. In addition, responding to climate changes may require a broader set of information than is usually available to decision-makers.

Current water management practices and infrastructure throughout the country are designed to address problems caused by existing climatic variability. In general, engineering approaches to system design rely on historic data, assuming that future climatic

## Key Climate Messages for Water Managers

- Climate is not static and assumptions made about the future based on the climate of the recent past may be inaccurate. Water managers should factor in the potential for climate change when designing major new infrastructure. Assumptions about the probability, frequency, and magnitude of extreme events should be carefully reevaluated.
- There is substantial stress on the water sector even in the absence of climate change. There are numerous watersheds that are already over-appropriated,and new stresses are coming from population dynamics,land use changes,and changes in international economies. In some areas,the new demands associated with instream flow needs for habitat protection and Indian water rights settlements may cause major shifts in water supply and water rights. Climate change may pose additional stresses and could result in thresholds being reached earlier than currently anticipated.
- Waiting for relative certainty about the nature of climate change before taking steps to reduce risks in water supply management may prove far more costly than taking proactive steps now. (The suggested risk-reducing or "no regrets"steps are those that would have other beneficial effects and so are appropriate regardless of climate change.)
- The types of changes encountered in the future may not be gradual in nature. Non-linearities and surprises should be expected, even if they cannot be predicted.
- The problems that are likely to result from climate change are intergenerational. Decisions made today will commit future generations to certain outcomes. It is important to evaluate benefits of projects over long time frames,and develop an educated citizenry.

## Other Key Considerations for Water Managers

- The water delivery, wastewater, and flood control infrastructure,particularly in the eastern US is aging and sometimes inadequately maintained and therefore vulnerable. The likely additional stresses that may result from climate change should encourage upgrading of key infrastructure to limit vulnerability to extreme events.
- As has been observed by many, the days of building large dams and expensive supply-side solutions are nearly over. More innovative solutions will be required in the future. Managers will need to prepare contingency plans to face water quality and supply challenges regardless of changes in climate. Promising options include conservation and efficiency improvements, water banking, water transfers,conjunctive use of surface and groundwater systems,and cooperative arrangements with other jurisdictions and communities.
- There are currently multiple disincentives to efficient utilization of water supplies. Subsidies and failure to reflect the full value of water supplies affect water pricing in virtually every sector. Americans view water as a "public good," believing supplies should be cheap,plentiful,and contain virtually no health risk factors. Agricultural water use is generally the most highly subsidized,but there are few municipal water suppliers that assign a value based on the replacement cost. As stresses increase on the water sector, water costs will definitely increase. Equity issues should be fully evaluated.
- Policies related to floodplain management and insurance currently encourage risky behavior such as rebuilding in floodplains and low-lying coastal areas after floods and storm surges. At both a national and local level, encouraging people to move away from high-risk areas would be beneficial. Incorporating wetland protection in buffer areas beyond current wetland boundaries would offer additional resilience to cope with potential flooding from more intense storms.
- Catastrophic events such as floods and fires are required to sustain some ecosystems over the long term. Management of these ecosystems should allow for continued benefits from these events.
- Hydrologists have developed valuable new models of watershed and regional-level hydrology that are ready for use. Effective use of mid- and long-range forecasts can improve the management of water resources and would be a significant step in developing the flexibility and resilience needed to cope with climate change.
- A key component of either conservation programs or improved water rights administration is metering or measuring of individual uses. This is a basic step to understanding water use and in educating consumers about proper water management. Many large cities in the US (including Fresno and Sacramento,California) currently do not measure water deliveries;most agricultural water use,especially groundwater use,is also not properly monitored.
- Improved management opportunities are available when watersheds are managed as a hydrologic unit.
- A key question that should be considered by policy makers is how much risk is acceptable to the public. It is not reasonable to manage for or expect no risk or zero damages from natural hazards.

conditions won't deviate significantly from those experienced in the recent past. Adaptation strategies for dealing with climate change range from relatively inexpensive options such as revising operating criteria for existing systems,to re-evaluating basic engineering assumptions in facility construction,to building new infrastructure with substantial capital costs. Strategies also include water conservation technologies and policies,use of reclaimed wastewater and other alternative supplies,and improved mechanisms for water transfers. Insufficient work has been done to evaluate the costs and benefits of alternative adaptation strategies. However, improved management of existing systems would certainly be valuable in managing changes in the ranges projected in this Assessment.

Improved efficiency of water use is likely to result from both regulatory requirements and higher water costs,which are expected outcomes of growing demands for clean and adequate water supplies. A move towards marginal-cost pricing (where costs reflect the price of the next available supply) and more extensive water markets may develop.

Water managers are currently not adequately engaged in the process of evaluating the risks of climate change. There is much debate about whether this is because they understand the nature of the risks,but have concluded that the current tools they have are sufficient,or whether they simply do not have the information they need in order to respond more appropriately (Stakhiv and Schilling,1998; Frederick and Gleick,1999). Results of a recent survey of western water managers (Baldwin et al., 1999) indicate that water managers who routinely deal with variability that is an order of magnitude greater than predicted climate changes see little reason to respond. Perhaps this is because they do not understand that potential climatic changes may be imposed on top of existing variability. However, availability of information and a greater understanding of the issues are likely to affect management practices. For example,if managers knew that there is a high probability that the magnitude of flood events is likely to increase in their region even if frequency remains the same,this information could be incorporated into planning activities. Even without this kind of information,however, some water organizations are beginning to push for commonsense actions by water managers. The American Water Works Association published recommendations for water managers calling for a re-examination of design assumptions,operating rules,and contingency planning for a wider range of climatic conditions than traditionally used (American Water Works Association,1997). The goal was to identify opportunities for reducing the risks associated with future climatic changes.

Various potential water management adaptations have been suggested to respond to either existing stresses or new stresses associated with climate change. They include the following:

- Increase ability to shift water within and between sectors (including agriculture to urban); this could increase flexibility but may require changes to institutional structures.
- Use pricing and market mechanisms proactively to increase efficiency of water use.
- Incorporate potential changes in demand and supply in long term planning and infrastructure design.
- Create incentives or requirements to move people and structures out of floodplains.
- Identify ways to manage all available supplies, including groundwater, surface water and effluent,in a sustainable manner.
- Restore and maintain watersheds as an integrated strategy for managing both water quality and water quantity. For example, restoring watersheds that have been damaged by urbanization, forestry, or grazing can reduce sediment loads, limit flooding, reduce water temperature,and reduce nutrient loads in runoff.
- Reuse municipal wastewater, improve management of urban stormwater runoff, and promote collection of rainwater for local use to enhance urban water supplies.
- Increase the use of forecasting tools for water management. Some weather patterns,such as El Niños,can now be predicted with some accuracy and can help reduce damages associated with extreme weather events.
- Enhance monitoring efforts to improve data for weather, climate,and hydrologic modeling to aid understanding of water-related impacts and management options.

### Communication Strategies

Information on the impacts of climate change is only helpful if it is usable by water managers, landowners,emergency response teams,and other decision-makers. They need to understand the range and probability of potential outcomes. This will require timely, detailed information at the scale needed to address local conditions. In addition, since most adaptation strategies incur costs, whether they are in response to existing or new stresses,it will be important to communicate the risks,costs,and opportunities. The need for better information argues for improved monitoring and modeling to link climate information with hydrologic impacts.

There is significant concern that results from GCMs will be misunderstood. While they do not predict the future,they are useful tools for exploring future scenarios. GCM outputs would be more useful to water managers and researchers if the models'underlying concepts were better known. It has been suggested that converting the outputs into information about weather systems,storm tracks,and likely weather events would be helpful.

Balancing water supply and water quality issues while maintaining natural ecosystems and quality of life even in the absence of any climate change is daunting. Adding the overlay of potential climate change increases the difficulty of achieving these goals. One general conclusion of work done to date is that humans have many options for adapting water supply and demand systems to climate change,while unmanaged ecosystems may be more vulnerable to imposed changes. Human adaptation,however, is very likely to come at substantial economic and social cost. In addition,it should be understood that some impacts are likely to be unpredictable or unavoidable because of the very nature of atmospheric and climatic dynamics.

In many parts of the US,the water supply and demand picture is a complex web of imported and local supplies,interconnected physical infrastructure,and overlapping institutions and jurisdictions. Difficulties in downscaling climate models to a useful level for decision-makers continue to limit the utility of the information produced to date. Depending on the geography of particular regions,local predictions of changes in climate may be nearly impossible in the near term. For example,in much of the Southwest,quantitative knowledge of the current hydrologic cycle is quite limited due to the large temporal and spatial variability in precipitation, runoff, recharge, evaporation,and plant water use within basins. Much of the uncertainty is caused by the high degree of diversity in the basin and range topography. Likewise,when predictions of local water supply conditions are aggregated into regions, the resulting picture may be meaningless. Although generalizations are necessary in order to communicate major concepts,they may have little value when applied to particular circumstances without appropriate caveats.

There are,however, some major messages that need to reach water managers. Despite the inability to provide clear, detailed information about many regional impacts,large-scale climatic changes are likely to occur. These changes will very likely affect water supply and demand in ways that may not be anticipated by current water managers,and these changes may be imposed on top of existing climatic variability and hydrologic risks. While many different alternatives for coping with impacts on the nation's water resources are available, we do not yet understand how effective these will be,how expensive they will be,or what surprises and unavoidable impacts may occur.

## CRUCIAL UNKNOWNS AND RESEARCH NEEDS

### Strategic Monitoring Needs

- Sophisticated analysis of climate change or its impacts requires continuous data sets provided through environmental monitoring. Monitoring should be enhanced from a strategic perspective in order to integrate key unknowns,particularly groundwater conditions,surface water quality, and biological factors in key habitats. Existing programs are not adequately integrated,and there are critical gaps in both space and time. Recent decreases in funding for stream gages and water quality sampling activities are especially problematic. Monitoring provides important services for society, such as improved predictive capability for weather events and reservoir management.
- Additional data on snowpack,depth, extent,snow water equivalent,etc., would be helpful to scientists and water managers whose supplies are dependent on snowmelt.
- Tools are needed to interpret water quality data and make data readily accessible to decision-makers.
- Engineering/Management Research Needs
- Improved understanding of the demand side of the water resource equation is needed.
- More quantitative evaluation of costs and effectiveness of adaptation strategies is needed.
- Better analyses are needed of the ability of existing infrastructure's capability to adapt. How much flexibility is there in existing systems to deal with variability? Further investigations into the impact of increased precipitation, flooding, and changes in water levels on the nation's infrastructure are needed. For instance,these climate-related changes may adversely affect air and water transportation.
- Design criteria (e.g., for 100-year floods) should be reevaluated to reduce risk to infrastructure in the context of climate change.

- More flexible institutional and legal arrangements should be instituted that facilitate the ability to respond to changing conditions.
- Research is needed to compare and evaluate innovative floodplain management strategies at the local,state,and federal levels to improve resiliency to climate change.

## Climate Research/Modeling

- Projecting future changes in streamflow conditions will require more evaluation of the complex role of changing precipitation and temperature patterns as well as the role of land-use change on streamflow.
- There is a need to continue to refine existing GCMs,and improve model validation and comparison. Runoff modeling could be improved if differences between the models were better understood. Output should be tailored to users needs. Key areas for model development include better physically based parameterizations for groundwater/surface water interactions,atmospheric feedbacks,and variability of precipitation and land surface characteristics at a watershed scale.
- Additional research is needed to explore the current causes of climate variability, such as the El Niño/Southern Oscillation and Pacific Decadal Oscillation. This will enable evaluation of impacts if such conditions become more persistent in the future.
- Existing models can be used to explore the vulnerabilities of various regions to changes in climate. These evaluations should lead to improved understanding of critical changes in evapotranspiration and runoff regimes.
- Increased data and analysis of paleoclimatic records will provide substantial insight into the nature and range of climate and hydrologic variability (e.g.,the incidence of droughts and floods).

## Integrated Assessment Research

- Improved tools are needed for translating climate changes into water resource impacts and issues of public interest. For example,to be useful in river basin management,GCMs must more accurately simulate inter-annual climate variability (persistence of extreme events) and probability of extreme events. This could subsequently be linked to economic costs and potential management decisions,such as land use restrictions.
- There is a need to focus on groundwater implications of climate change. Groundwater recharge rates are controlled by many factors that are poorly understood. The response of deep and shallow aquifers to historic drought should be evaluated,as well as stream/aquifer interactions, the extent of interactions between aquifers,and impacts on riparian habitat.
- Water quality changes that result from existing climatic variability, and the impacts of extreme events on ecosystems,need further evaluation.
- Research is needed on highlighting thresholds of change in natural ecosystems,and key areas of vulnerability including impacts of flooding and drought. There are likely to be time lags as ecosystems respond to change,but these have not been identified or modeled so the indicators are not well understood.
- Biotic responses are not being accounted for adequately in modeling efforts,particularly feedbacks associated with changes in land cover, stomatal resistance due to increased $CO_2$, etc.
- Better integration is needed of human and ecological risk assessment relative to assessments of climate change. Risk factors and willingness to pay for damages caused by climate change should be evaluated as inputs to decision making.
- There is a need to improve communication between scientists and water managers. For purposes of technology transfer, the value and adequacy of integrated climate, hydrologic,and management systems should be demonstrated in prototype applications. Demonstration projects could engage managers of surface water supply systems in applications of reservoir management for their own systems. This could prove helpful in building relationships between modelers and real-world managers.

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