Socioeconomic Impacts of Climate Variability and Change on U.S. Water Resources

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Abstract

The socioeconomic costs of floods, droughts, and water scarcity in the years 2030 and 2095 are examined under three climate scenarios: continuation of the current climate and two climate-change scenarios based on projections from the respective results of the Canadian and Hadley general circulation models. Measures of the adequacy of water supplies to meet both withdrawal and instream uses under current and future conditions are developed for the 18 major water resources regions and 99 assessment subregions in the conterminous United States. Past and likely future changes in the infrastructure available to control and distribute water, the costs of nontraditional sources of supply, water management practices, conservation opportunities, the nature of the economy, slack in the water supply system, and institutions influencing water use are examined and provide the basis for evaluating the impacts of changes in both climate and non-climate factors on U.S. water resources. The impacts of the climate changes are calculated as the changes in the costs of maintaining the projected no-climate change, non-irrigation off-stream water uses with the climate-altered supplies. The costs and benefits are estimated under three alternative management strategies that differ in the protection provided for stream-flows and irrigation. The results support several general conclusions. First, a greenhouse warming could have major impacts on the future costs of floods, droughts, and balancing water demands and supplies. Second, the contrasting hydrologic implications of the Canadian and Hadley climate models indicate that the magnitude as well as the direction of these impacts are uncertain and likely to vary significantly among water resources regions. Third, there are many opportunities to adapt to changing hydrological conditions, and the net costs are particularly sensitive to the institutions that determine how the resource is managed and allocated among users.

This report was prepared as part of the Water Assessment Sector Team's contribution to the U.S. National Assessment of the Potential Consequences of Climate Variability and Change for the Nation being conducted under the auspices of the U.S. Global Change Research Program. The climate-change scenarios used in this report were developed for use in the National Assessment.

Key Words: water and climate; climate change; socioeconomic impacts of climate change; adaptation to climate change; water management and climate change

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SOCIOECONOMIC IMPACTS OF CLIMATE VARIABILITY AND CHANGE ON U.S. WATER RESOURCES

Kenneth D. Frederick and Gregory E. Schwarz[*]

1. INTRODUCTION

The short-term variability and longer-term availability of water have important socioeconomic implications. Seasonal and annual variations in precipitation and natural streamflows have long posed challenges for planners and risk for water users and floodplain occupants. In the absence of reservoirs and dams to regulate flow, some streams regularly dry up during part of the year and flood their banks during other periods. Dams, reservoirs, pumps, canals, and levees help control flood waters and increase the reliability of water supplies. Nevertheless, floods and droughts continue to impose significant costs on the nation. And water is becoming scarcer and more expensive, making it more difficult to balance supplies with growing demands. The prospect that a human-induced climate change could affect the variability and availability of supplies and the demand for water poses additional challenges and risks.

The objective of this paper is to examine the socioeconomic impacts associated with climate variability and potential climate change in the distant future, i.e., the years 2030 and 2095. Uncertainties surrounding the factors likely to affect conditions 30 and 100 years in the future are enormous and stem only in part from the prospect of climate change. Changes in demographics, incomes, values, and technologies will alter water demands, and new technologies will affect the costs of developing new supplies. Scientific advances will provide better forecasts of precipitation and runoff, enabling water managers, farmers, and other water users to better plan and adapt to climate variability and change. Institutional changes will alter how water is managed, allocated, and used. Indeed, the institutions that provide the opportunities and incentives to use and misuse the resource and determine how tradeoffs are made among alternative water uses are critical to the ability to adapt to whatever the future might bring.

The next section reviews the costs that floods and droughts have imposed on the United States and how these costs might be affected by a greenhouse warming. Section 3 describes the framework used for assessing water scarcity under current and future conditions, with and without climate change, and develops scarcity measures for the 1995 base year and for the years 2030 and 2095 in the 18 water resources regions and in the 99 “assessment” subregions in the conterminous United States. The futures with climate change are based on hydrologic conditions derived from two general circulation models (GCMs), the Canadian Global Climate Model and the British Hadley2 model. Section 4 describes the principal factors affecting the nation’s vulnerability to and its capacity to adapt to hydrologic extremes and increasing water scarcity and considers how these factors have changed in the past and may change in the future. Section 5 examines the potential water-related socioeconomic implications of the climate change

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scenarios, with and without adaptation through planning and institutional change. Section 6 provides a brief summary and some conclusions.

2. SOCIOECONOMIC COSTS OF EXTREME EVENTS

Hydrologic fluctuations impose two types of costs on society: the costs of building and managing infrastructure to provide more even and reliable flows and the costs of droughts and floods that occur in spite of the sizeable investments that have been made to control flood waters and increase available supplies. Floods and droughts continue to impose significant costs on the United States, and some of these costs have been rising over time.

2.1 Floods

Floodplains occupy about 160 million acres or 7 percent of U.S. land (Schilling, 1987). The proximity of these lands to water for navigation, recreation, power, domestic, and industrial use makes them particularly attractive for settlement. Federal policies provided further encouragement to development of the floodplains, mandating the construction of dams, reservoirs, and levees to control flood waters. The Flood Control Act of 1936 established as national policy that flood control was a proper activity of the federal government. Since then the U.S. Army Corps of Engineers has constructed approximately 400 major lake and reservoir projects, over 8,500 miles of levees and dikes, and hundreds of smaller local flood protection projects. The federal government has spent about $100 billion (1996 dollars) for the construction, operation, and maintenance of flood control structures. According to the Corps of Engineers' estimates, these facilities have prevented nearly $500 billion in riverine and coastal flood damages since 1950 (U.S. Army Corps of Engineers, 1998).

In spite of the Corps' efforts, flooding is the nation's most costly and destructive natural disaster and is the cause, at least in part, of most federally declared disaster declarations. Figure 2.1 graphs the National Weather Service's estimates of flood damages (in constant 1997 dollars) from 1945 to 1997. Flood damages vary widely from year to year but have increased on average about 1 percent per year in constant dollars during this period. This rate is well below the growth of the national economy and about half the rate at which urban development has expanded in the floodplains (Schilling, 1987). Flood-related deaths from 1945 to 1998, which are graphed in Figure 2.2, vary widely from year to year and have been rising 1.5 percent per year on average since 1945.

During the 1997 water year (October 1, 1996, to September 30, 1997), the most recent year for which cost estimates are available, floods resulted in estimated losses of 98 lives and damages of $8.7 billion dollars. These dollar estimates include only direct damages such as costs of repairing buildings, roads, and bridges attributable to flooding that results from rainfall and snowmelt. Indirect damages such as lost wages due to business closures or the important but unquantifiable social costs that result when families have to temporarily evacuate their homes for higher ground are not included. The estimates also exclude flooding damages attributable to wind such as hurricane storm surges.

The record 1993 floods in the upper Mississippi and Missouri rivers resulted in the highest one-year economic damages to date at $16.4 billion (equivalent to $18.5 billion 1997 dollars). The interagency committee established in response to these floods concluded: "The flood of 1993 in the Midwest was a hydrometeorological event without precedent in modern times. In terms of precipitation amounts, record river levels, flood duration, area of flooding, and economic losses, it surpassed all previous floods in the United States" (Interagency Floodplain Management Review Committee, 1994, p. 8). According to the U.S. Army Corps of Engineers, the damages would have been $19.1 billion higher without the dams, reservoirs, and levees available to control flood waters. But by encouraging settlement and development in the floodplain, the existence of these facilities may have contributed indirectly to some of the damages that did occur. Development in the floodplain reduces a basin's capacity to naturally moderate flood flows and places more people and property at risk (Interagency Floodplain Management Review Committee, 1994).

Record breaking floods as well as droughts are to be expected. Even under conditions of hydrologic stationarity, the probability that a record breaking flood or drought will be superseded by a new record breaking event is exceedingly high over the economic lives of water projects and the probability that such an event will eventually be exceeded is one (Matalas, 1997).

Climate change could alter both the frequency and magnitude of large floods. The Intergovernmental Panel on Climate Change (1996a,b) concluded that a greenhouse warming is likely to increase flood frequencies in many areas, although the amount of the increase for any climate scenario is uncertain and the impacts will vary by region. On the other hand, floods may become less frequent in other areas. Flood frequencies are most likely to increase in the higher latitudes where the GCMs project the largest increases in precipitation, in basins where snowmelt is a primary determinant of runoff, and in coastal areas where higher sea levels and increased storm surges are likely effects of a greenhouse warming. Warmer temperatures would shift the relative amounts of snow and rain and the timing of snowmelt and runoff. Accelerating the rate of spring snowmelt and shortening the snowfall season could result in faster and earlier spring runoff. Mountainous areas where snowmelt is the primary source of runoff would be particularly vulnerable to increased flooding.

2.2 Droughts

In the 19th century and again in the 1930s droughts led to large-scale migrations and many deaths in the United States; they continue to produce such misery in some parts of the world. While the United States is now much more able to adapt, extended droughts continue to produce substantial adverse regional economic and social impacts. Quantifying these impacts is difficult, however, and no agency systematically provides estimates of drought impacts. Damage estimates are available for only a few drought events.

Agriculture is the sector that is most susceptible to short-term and prolonged water shortages. Droughts may result in reduced crop production, soil losses from dust storms, or higher water costs. But, as was evident in the 1987-1992 California drought, a prolonged drought affects virtually all sectors of the economy. Urban water users were subjected to higher water rates and residential users were also required to make behavioral changes to conserve water. Reduced precipitation, higher water prices, and restrictions on water use resulted in widespread losses of investments in landscaping and gardening and jobs in the green industry. Hydropower, which has provided about one-third of California's total electrical energy supply in normal years and as much as 40 percent in wet years, fell to less than 20 percent during the drought. To compensate for the decline in hydroelectric power generation, the state's ratepayers spent an estimated additional $3.8 billion for electricity during the drought. The impact on recreation was adverse, also. Visits to state parks declined by 20 percent between 1987 to 1991, and water-based activities such as skiing and reservoir fishing declined. Agricultural losses were limited by idling land, pumping more groundwater, concentrating available supplies on the most productive soils and higher value crops, and purchasing water in spot markets to prevent the loss of tree crops. Consequently, direct economic losses to California's irrigated agriculture in 1991 were estimated at only $250 million, less than 2 percent of the state's total agricultural revenues (U.S. Army Corps of Engineers, 1994). These costs, however, do not include any longer-term increases in pumping costs that might result from the increased drawdown of groundwater stocks during the drought.

Environmental resources such as fish and trees may have suffered the most severe impacts of this prolonged California drought. Most of the state's major fisheries suffered sharp declines, but it is difficult to separate out the impacts of the drought from other factors, such as over-fishing, affecting fish populations. Many trees in the state's forests were weakened or killed by the drought, increasing the risk of forest fires (Nash, 1993: U.S. Army Corps of Engineers, 1994).

Some groups may actually benefit from the hardships droughts impose on others. For example, drought-induced agricultural losses are likely to increase the prices received by farmers whose crops are unaffected by a drought. And a decline in the production of hydropower increases the demand and the price for alternative sources of energy. When these income transfers are included in the analysis, the aggregate costs of drought to producers tend to decline as the scale of the drought impact assessment is increased. Thus, drought events that are costly at the local level, may be less expensive at the regional level, and negligible at the national level. An analysis of the agricultural economic impacts (measured as the sum of consumer and producer surplus) of drought on California and the nation in 1991 indicated that the national costs of California's drought were less than 30 percent of the impacts on the state for the crops modeled (U.S. Army Corps of Engineers, 1991, 1994).

The impacts of a greenhouse warming on the frequency, intensity, and duration of future droughts are uncertain. According to an IPCC (1996b) report, the frequency and intensity of droughts could increase in some areas as a result of reduced precipitation, higher evapotranspiration, and more frequent dry spells. Other areas, however, could experience increased runoff and fewer droughts. The regional as well as the net national implications would vary widely depending on which of the very different climate futures described in section 3.4 proves to be more accurate.

3. WATER SCARCITY: THE IMPLICATIONS OF CLIMATE CHANGE

3.1 The Analytical Framework

This section examines how a greenhouse warming might affect water scarcity in the years 2030 and 2095. A water scarcity measure is developed and applied first to current conditions, then to projected future conditions with the current climate, and finally to projected future conditions with climate change. A comparison of the futures with and without climate change is an indication of the potential impacts of a greenhouse warming on water scarcity.

The Second National Water Assessment developed a framework for examining the adequacy of water supplies to meet both offstream and instream uses under average as well as wet and dry conditions (U.S. Water Resources Council, 1978). That framework is described and used in this section to examine the adequacy of supplies to meet consumptive and instream uses on a sustainable basis (i.e., without depleting groundwater stocks) under current and projected future conditions. The analysis was done for the 18 major water resources regions in the conterminous United States and 99 “assessment” subregions (Figure 3.1). These subregions are groupings of smaller drainage areas that were defined and used in the Second National Water Assessment to simplify the analysis. Water adequacy for the current and projected future climates is analyzed for two streamflow conditions, mean annual flow and an 80 percent exceedence level or dry condition supply.

The measure of water scarcity is cumulative total water use (in the terminology of the Second National Water Assessment) as a percent of renewable water supplies. Cumulative total water use in a subregion is the sum of “desired” or “critical” instream flows at a basin’s outflow point plus consumptive use in the subregion and in all upstream subregions. To simplify the terminology, cumulative total use is referred to as desired use or critical use depending on whether it is calculated with desired or critical instream flows. Percentages less than 100 suggest renewable water supplies are sufficient to provide for withdrawal and the respective instream uses. Percentages greater than 100 suggest the designated instream flow is not being met and/or groundwater stocks are being depleted.

The Second National Water Assessment estimated desired instream flows as the higher of the flow required to maintain fish and wildlife populations or navigation. Fish and wildlife dominated water use in all subregions. The assessment’s desired streamflow estimates are “conservative on the side of identifying more water for instream uses than further study might reveal to be justified.” (Bayha, 1978, p. 4). These desired flows range from 46 to 94 percent of mean renewable baseline flows in the 18 water resources regions surveyed, and they are equal to or exceed renewable dry-condition streamflows in 12 of the 18 water resources regions. The implications of failing to meet these desired flows are not clear but would depend in part on the extent and duration of the shortfall.

For purposes of this analysis, critical instream flow is defined as 50 percent of the desired flow. The critical flow levels are equivalent to 40 to 47 percent of mean renewable base-year supplies in the eastern water resources regions and from 23 to 40 percent in the western regions. Analysis done for the second assessment of the implications of low streamflows suggests that failure to meet these critical flow levels for sustained periods would adversely impact fish and wildlife. For example, it was observed that flows of 30 percent of the mean renewable supply would be sufficient to provide survival habitat but would result in significant declines in fish and wildlife populations if these flows became the norm (Bayha, 1978). In addition to the adverse impacts on fish and wildlife, it is likely that instream flows at or below these critical levels in either a dry year or on a persistent basis would result in reduced values for other instream uses such as water-based recreation, navigation, and hydroelectric power generation.

Renewable supply (assessed total streamflow in the terminology of the second assessment) is the water available in a region’s rivers and streams for withdrawal and instream uses. Renewable supply is calculated as a region’s natural streamflow minus the net amount of water exported to other basins and evaporated from artificially constructed reservoirs. Natural streamflow is an estimate, derived from the historical record, of what the flow would be in the absence of any human influence such as diversions and reservoirs.

Water scarcity indices for the 1995 baseline and 2030 and 2095 futures are developed for three situations: desired use relative to mean flows, critical use relative to mean flows, and critical use relative to dry condition flows. In order to simplify the analysis and focus on conditions that are likely to result in adverse socioeconomic and environmental impacts, the desired use with dry condition flow situation is not analyzed. In view of the high estimates of desired instream flows in the Second National Water Assessment, a temporary failure to meet these streamflows would not necessarily result in serious losses.

The comparison of annual water use with annual supplies as a measure of water scarcity does not address some important water issues that might be affected by climate change. Intra-annual supply and demand variations are ignored. The national assessment developed monthly measures of water adequacy, but monthly water supply and demand data are not available for this study. Intra-annual supply variability is less of a concern in basins with abundant storage. However, seasonal differences in water demands could present problems in satisfying both offstream and instream uses even with substantial storage.

The scarcity measure also ignores potential water quality concerns. The use of consumptive rather than withdrawal water use implicitly assumes that water withdrawn from but eventually returned to a usable ground or surface water source does not affect the adequacy of water supplies. No allowance is made for the possible impacts of the returnflows on the quality or timing of supplies.

3.2 The 1995 Baseline

The base year represents assumed average conditions as of about 1995; this assumption reduces the influence of unusual climate conditions. Table 3.1 presents the mean and dry condition (i.e., 80 percent exceedence) renewable supplies used for the 1995 baseline for the 18 major water resources regions. These flows were derived by adjusting the second assessment’s estimates of renewable streamflows as of 1975 for changes in net exports and reservoir evaporation from 1975 to 1995. Evaporation losses are assumed to have changed by the same percentage as the change in storage volume for large reservoirs calculated from the National Inventory of Dams (U.S. Army Corps of Engineers, 1996). Net water exports among regions are based on the second assessment’s projections of water transfers for the year 2000.

Table 3.2 presents the 1995 baseline estimates of consumptive use, the second assessment’s estimates of desired instream flow, and desired and critical water use for the 18 major water resources regions analyzed. Consumptive use is based on the U.S. Geological Survey’s water use estimates for 1995 (Solley, Pierce, and Perlman, 1998).

Table 3.3 shows the scarcity indices in the 1995 base year for the 18 water resources regions, and Figure 3.2 maps the water scarcity indices in the 99 subregions. These indices suggest that mean renewable supplies are sufficient to meet desired use in all but three regions: the Rio Grande, Lower Colorado, and Great Basin. Groundwater overdrafts provide some base year water uses in all three of these regions. Mean supplies are insufficient to meet even critical water uses in the Lower Colorado. Dry condition supplies fall short of critical use in the Texas-Gulf as well as in the Rio Grande, Lower Colorado, and Great Basin.

3.3 Impact of Non-Climate Factors on Future Water Scarcity

Future water scarcity will be affected by many factors including population and income growth, technological and institutional changes influencing the opportunities and incentives to use and conserve the resource, and the climate. Developing a future baseline without climate change is essential for assessing the implications of alternative climate scenarios. The assumptions underlying the 2030 and 2095 baselines and their implications for meeting consumptive and instream demands with renewable supplies are described in this section.

The future scenarios without climate change assume renewable water supplies as well as desired and critical instream flows are unchanged from the 1995 base year. However, demands for domestic, industrial, and agricultural water are expected to increase as population and incomes grow. The implications of these growing demands on the water scarcity measure depend on how they affect consumptive water use.

For most of this century, offstream water use increased faster than population. Per capita withdrawals increased nearly four-fold from 1900 to 1990 (Brown, 1999). These increases, almost all of which occurred before 1975, were driven largely by economic growth, a willingness to ignore the adverse impacts on streamflows, and planners seeking to provide virtually unlimited supplies at low prices (Frederick, 1991a).

Although water demands have continued to grow with population and incomes, total withdrawals have changed little since 1975 because of the high costs of developing new supplies, environmental concerns, a growing appreciation for the values of instream flows, and efforts to improve water quality. Conservation is now the principal means of balancing demands with supplies. The combination of price incentives, water transfers, technological advances, and regulations have reduced inefficient and low-value water uses and encouraged development and adoption of more water-efficient practices. These changes are reflected in national water use trends. Per-capita withdrawals peaked in 1975 and declined 29 percent in the following two decades. Total withdrawals have declined 9 percent since their peak in 1980. Total consumptive use was unchanged but per capita consumptive use declined 14 percent between 1980 and 1995 (Solley, et al., 1998).

For reasons described in section 4, the opportunities for increasing water supplies in most of the United States are expensive relative to current water prices and often environmentally damaging. Conservation is now often less expensive than developing new supplies and is projected to continue for the foreseeable future to be the primary means of balancing future water supplies and demands. But estimating how the various factors influencing the supply and demand for water will affect the withdrawal and consumptive use of water in the various regions of the United States involves enormous uncertainties.

Brown (1999) estimated water use out to the year 2040 for the major water resources regions in the United States. Brown's projections, which were done as part of the Forest Service's periodic assessment of long-term resource supply and demand conditions, are based on population projections of the Bureau of the Census and income estimates of the Bureau of Economic Analysis. His water use projections reflect regional variations in water scarcity and continued improvements in water-use efficiency encouraged by rising water costs.

Brown's projections of the percentage changes in consumptive water use from 1995 to 2030 are presented in Table 3.4. These projections are used to calculate the water scarcity indices presented in Table 3.5 and illustrated in Figure 3.3. Using the Census Bureau's middle projection of a 33 percent increase in population by the year 2030, national water withdrawals are projected to rise 5 percent and consumptive use is projected to rise 8 percent. The implied reduction in per capita withdrawals is largely attributable to assumed continued improvements in water-use efficiency in municipal, industrial, and thermoelectric uses; a modest increase in total irrigated acreage; and a relative shift in irrigation from the western to the eastern United States where less water is applied per acre (Brown, 1999). Consumptive use is projected to decline in six of the nine western water resources regions. But despite the current scarcity of water, consumptive use is projected to increase in the Lower Colorado and Great Basin.

The longer term projections to 2095 assume that consumptive use in each water resources region continues to change at the same rate as Brown's projected changes between the years 2030 and 2040. Nationally, Brown projects an increase of only 0.8 percent in consumptive use during that decade. But underlying this modest change in aggregate water consumption are significant regional variations that are reflected in the projected percentage changes in consumptive use between 1995 and 2095 presented in Table 3.4.

A comparison of the water scarcity indices in the 1995 baseline (Table 3.3 and Figure 3.2) with the futures without climate change (Tables 3.5 and 3.6 and Figures 3.3 and 3.4) indicates only modest changes in water scarcity. The Rio Grande, Lower Colorado, and Great Basin are still the only basins where mean renewable supplies are insufficient to meet desired use in 2030. By 2095 water is scarce in only the latter two basins. However, underlying the small projected changes in consumptive use are assumed improvements in water use efficiency prompted in part by higher water prices and regulations mandating greater water efficiency in new toilets, shower heads, and other high water-using items. Water prices and costs are indicators of scarcity but are not reflected in this water scarcity index. The opportunities for and costs of balancing supplies and demand through development of alternative sources of supply such as recycling and desalination and through conservation measures such as fixing leaks and installing water-efficient toilets and showers are examined in sections 4 and 5.

3.4 Climate Change and Future Water Scarcity

A greenhouse-induced change in the climate would affect both the demand and the supply of water. On the demand side, irrigation, which accounts for about 81 percent of the nation’s consumptive water use (Solley, et al., 1998), is particularly sensitive to climatic conditions. Hotter and drier conditions would likely increase the demand for water for both agricultural and landscape irrigation. Simulation studies of irrigated grain production in Nebraska and Kansas under different climate scenarios suggest that a 1^{o}C increase in temperature combined with a 4-inch reduction in annual precipitation would increase irrigation water use by 14 to 39 percent (Frederick, 1991b). These increases in irrigation water use, however, are reduced when allowance is made for the impacts of increased atmospheric carbon dioxide, which tends to increase the growth and water-use efficiency of plants. Increasing atmospheric CO_2 from 350 to 450 parts per million in the Nebraska and Kansas simulation study reduced estimated water use an average of 7 percent.

McCabe and Wolock (1992) used an irrigation model to simulate the effects of hypothetical changes in temperature, precipitation, and stomatal resistance on annual plant water use in a humid-temperate climate. Their results suggest that increases in mean annual water use are strongly associated with increases in temperature and less strongly associated with decreases in precipitation. A 2^{o}C increase in temperature increased plant water use even with a 20 percent increase in precipitation. But plant water use was even more sensitive to stomatal resistance, which increases with atmospheric CO_2, than to temperature. Water use declined with a 20 percent increase in stomatal resistance and a 2^{o}C increase in temperature; a 40 percent increase in stomatal resistance reduced water use even when temperature was raised 6^{o}C.

Domestic water use, especially for showers and watering lawns and gardens, is also sensitive to climate variables (Frederick and Gleick, 1999; Frederick and Major, 1997). Boland (1997) forecast water use in the year 2030 for each county and city in the Washington, DC metropolitan area for a stationary climate and five alternative climate scenarios derived from GCM results. In comparison with the stationary climate, forecasted changes in water use in the climate-change scenarios ranged from -13 to +19 percent during the summer and -8 to +11 percent annually.

Climate also influences demands for industrial, thermoelectric power, and instream water. The demand for cooling water would be affected by higher water temperatures that reduce the efficiency of cooling systems and higher air temperatures that alter the demand for air conditioning and space heating. Higher water temperatures might also increase the demand for instream flows to protect aquatic ecosystems.

The net effect of any climate scenario on water demands and how those demands might affect consumptive use or instream needs are uncertain. But in view of the opposing forces influencing irrigation water use, the climate impacts on water demands are likely to be small in comparison with those on supplies. Thus, analysis of the impacts of climate change on water scarcity focuses on the supply side and assumes no change in consumptive use or desired instream demand. This assumption probably understates the impact of a greenhouse warming on water scarcity.

Estimating the effects of a greenhouse warming on water supplies starts with predictions of regional atmospheric and surface variables such as temperature and precipitation derived from a long-term general circulation model. Changes in climate variables would affect a region's renewable water supplies by altering both its natural streamflows (i.e., flow in the absence of human influence) and evaporation losses from constructed reservoirs. Wolock and McCabe (1999) have used predictions of future climate conditions from the Canadian Global Climate Model (CGCM) and the British Hadley2 model to estimate the effects of climate change on future natural streamflows. Future evaporation losses from constructed reservoirs are estimated using these same climate conditions. The runoff and evaporation results for the 2,100 eight-digit hydrologic units in the conterminous United States have been aggregated to the 99 water assessment subregions and the 18 major water resources regions included in the analysis. Table 3.7 presents estimates of the percentage changes in natural streamflows, evaporation losses, and renewable supplies from 1995 to 2030 under the Canadian and Hadley models. Table 3.8 presents comparable data for the 1995 to 2095 period.

The changes in natural streamflows derived from results of the two GCMs are strikingly different. With the exception of California, which is projected to receive 28 percent more streamflow in 2030, and the Souris-Red-Rainy, which is projected to receive 18 to 24 percent less, the results suggest very different scenarios. Streamflow declines in all regions except California using projections from the Canadian model. In 2030 streamflow is more than 20 percent below the 1995 level in two-thirds of the regions and increased evaporation contributes to water scarcity in 11 of these regions. In contrast, streamflow increases in 14 regions using the Hadley model and only the Souris-Red-Rainy indicates a streamflow decline of more than 3 percent. Net evaporation increases in only four regions but declines in three regions using projections from the Hadley model.

By 2095, with the exception of a 19 percent reduction in streamflow in the Texas-Gulf and a modest change in the Pacific Northwest, the nation is projected to be much wetter using the Hadley model. The Canadian model indicates a further drying in the East and an increase in water supplies in much of the West.

The water scarcity indices for the year 2030 using projections from the Canadian and Hadley GCMs are presented in Tables 3.9 and 3.10. Under the Canadian model, mean renewable supplies are less than desired use in 12 regions and less than critical use in 5 regions. Dry condition flows are less than critical use in 9 regions. Under the Hadley model, mean renewable supplies are less than desired use in 3 regions but exceed critical use in all regions. Dry condition flows are less than critical use in 4 regions. Figure 3.5 illustrates the differences in water scarcity for the 99 assessment subregions as measured by the ratio of mean flow to desired use under the three climate scenarios (no climate change and projections based on the Canadian and Hadley GCMs) for the year 2030.

The water scarcity indices for the year 2095 using projections from the Canadian and Hadley GCMs are presented in Tables 3.11 and 3.12. Under the Canadian model, mean renewable supplies are less than desired use in 9 regions and less than critical use in 4 regions. Dry condition flows are less than critical use in 5 regions. Under the Hadley model, mean renewable supplies are less than desired use in 1 region but exceed critical use in all regions. Dry condition flows are less than critical use in 2 regions. Figure 3.6 illustrates the differences in water scarcity for the 99 assessment subregions as measured by the ratio of mean flow to desired use under the three climate scenarios for 2095.

4. ADAPTING TO HYDROLOGIC EXTREMES AND WATER SCARCITY

Vulnerability to and the resulting socioeconomic impacts of hydrologic extremes and water scarcity depend on many factors, including the infrastructure available to control and distribute water over time and space; the opportunities for and costs of developing non-traditional sources of supply through wastewater reclamation, desalination, cloud seeding, vegetation management, and interbasin transfers; the efficiency with which existing supplies are distributed and managed; conservation; the nature of the economy; the slack in the system; and the institutions that provide the incentives and opportunities to use, abuse, conserve, and transfer water to other uses. Changes in these factors during this century and their implications for current and likely future vulnerability to hydrologic variability and water scarcity are considered below.

4.1 Water Resource Infrastructure

The socioeconomic impacts of hydrologic variability have changed significantly during this century in part because the infrastructure available to manage water resources has grown. In 1900, the United States had little control over its water resources. The risk of either too much or too little water was an obstacle to settling and developing about one-third of the conterminous United States. The welfare and even the survival of countless people living in arid, semiarid, and floodprone areas depended on benign precipitation patterns.

Water projects designed to overcome the limits posed by a region’s natural hydrology became catalysts for development and for reducing the risks of climate variability. Dams, reservoirs, canals, pumps, and levees were built to collect, control, and contain surplus flows and to distribute water on demand during high and low flow periods. In the quarter century following World War II, dams were being built at a rate of nearly four a day as water planners sought to provide domestic, industrial, and agricultural users with virtually unlimited quantities of water at the lowest possible prices. The construction pace peaked in the 1960s when more than 19,000 new dams and more than 250 million acre-feet (maf) of storage were added (see Table 4.1).

The nation’s water infrastructure consists of more than 80,000 dams and reservoirs; 25,000 miles of navigation channels supported by over 200 miles of locks and dams; tens of thousands of groundwater pumps; and millions of miles of canals, pipes, and tunnels (Schilling, 1987). This infrastructure increased the capacity to control and store surface waters, tap groundwater supplies, and transport the resource long distances out of its natural channels. Streams once unreliable were transformed into controlled and more reliable sources of supply.

Technological advances made it feasible to pump water from deeper aquifers where supplies are less susceptible to climate variations. And the ability to transport water within and among basins increased the ability to provide water to communities during drought. Isolated communities dependent on single, highly vulnerable water sources are largely a thing of the past.

Rising costs and environmental concerns are primarily responsible for the sharp and steady reduction in the pace of dam building since the late 1960s as depicted in Table 4.1. The average annual number of new dams completed declined from 1,909 from 1961-1970 to just 209 from 1991-1995. The decline in new storage was even more precipitous as the average storage per dam declined from 13.2 thousand acre-feet (taf) during the 1960s to 4.5 taf from 1991-1995.

Rising costs, environmental concerns, and diminishing returns in the capacity of dams and reservoirs to increase the “safe yield” of most water systems underlie the decline in dam and reservoir construction. Rising costs of water made available through additional dams and reservoir capacity are inevitable for several reasons. First, there are diminishing returns in the safe yield produced by successive increases in reservoir capacity within a river basin (U.S. Geological Survey, 1984, p. 30). A stream’s maximum possible safe yield is limited by its average annual flow. But at some point well before this maximum is reached, reservoir evaporation losses begin to offset any gains in yield associated with additional surface storage. A study of U.S. river basins suggests that safe yield reaches a maximum when the ratio of storage to average annual renewable supply is in the range of 1.6 to 4.6 (Hardison, 1972). By this criterion the point of negative returns to additional storage may already have been reached in three major river basins: the Lower Colorado, the Upper Colorado, and the Rio Grande.

Second, the best sites for storing water within a basin are the first to be developed. Consequently, subsequent increases in storage generally require ever-larger investments. A study of decadal changes in reservoir storage capacity per unit volume of dam of the 100 largest dams in the United States built between 1920 and 1969 illustrates this point. In the 1920s, a cubic yard of dam produced on average 10.4 acre-feet of reservoir capacity. The average declined in each subsequent decade, and by the 1960s only 0.29 acre-feet of storage was produced per cubic yard of dam (U.S. Geological Survey, 1984).

Third, society’s costs of storing and diverting water also increase as the number of free-flowing streams declines and as society attaches more value to water left in a stream. Projects that control flooding and capture water that would otherwise be lost to human use as a result of evaporation or runoff to the ocean or other unusable sinks, increase society’s usable water supplies. But as the resource becomes scarce, a project to increase supplies for offstream use may add little, if anything, to aggregate supplies. Rather it becomes a means of allocating supplies among alternative uses, usually from instream uses such as fish and wildlife habitat and recreation to withdrawal uses such as domestic supplies and irrigation.

Instream values foregone when water is diverted for use in cities or farms are part of the social costs of a water project. The environmental laws passed in recent decades to protect and restore streamflows, the strong resistance to new dam construction, and the growing movement to restore environmental values by removing dams are evidence of the high values society already attaches to instream uses. These values will continue increasing as demand for instream uses rises with population and incomes and if the supply of free-flowing streams is reduced by additional diversions.

Net additions to the nation’s dams and reservoirs will be much smaller than in the past and will provide only modest improvements in the ability to adapt to climate variability and growing water demands. Nevertheless, additional or enlarged reservoirs will be part of future water management in many regions in spite of their high costs and diminishing returns in contributing to assured supplies. Additional surface storage is an important, but often controversial, option for improving supply reliability under California's water plan. Stored water could be used for environmental or withdrawal purposes while increasing the state's flexibility in operating the Bay-Delta system (California Department of Water Resources, 1998).

With the best dam sites along the rivers already used, new surface storage is more likely to occur offstream (Western Water Policy Review Advisory Commission, 1998). The 800,000 acre-foot, $2 billion Eastside Reservoir in Riverside, Calif., is the largest offstream storage project. The reservoir, which is scheduled to start filling in late 1999, will provide a 6-month emergency supply and a regulated supply to help meet the demands of an additional 1.2 million more people by 2030 in the service area of the Metropolitan Water District of Southern California. While this project adds no new water demands, evaporation losses from such a huge reservoir located in the middle of a desert will be large.

Most new surface storage projects are likely to be much smaller than either the Eastside Reservoir or the large federally constructed facilities of the past. The proposed plan to capture storm runoff from the Los Angeles River to the ocean in an average year is more typical of the size of projects now under consideration. This project would place an inflatable weir across the Los Angeles River near its mouth to direct the flows into intakes along existing levees. The water would then flow by gravity through culverts or tunnels to an offshore reservoir to be constructed in San Pedro Bay. One option under consideration would increase supplies from 71 to 129 taf/year at a cost (depending on the supply gain) of $1,700 to $1,000/af. Expanding the project to capture 172 taf/yr would reduce the cost to $800/af (California Department of Water Resources, 1998).

The limits and rising costs of developing additional supplies with dams and reservoirs are forcing planners and managers to seek alternatives for increasing supplies. The potential and costs of augmenting supplies through wastewater reclamation, desalting brackish and sea water, cloud seeding, vegetation management, and transferring water from water-rich to water-scarce areas will become increasingly important for balancing future water supplies with demands. The costs and potential contributions of these alternatives for expanding water supplies are summarized in Table 4.2 and discussed below.

4.2 Wastewater Reclamation

Wastewater reclamation or recycling involves treating and conveying wastewater to meet the quality required for a specific use. The technology exists to upgrade wastewater to meet the standards for any use, but the costs rise as the quality requirements of the end use increase. Recycled water is commonly used for agricultural and landscape irrigation, groundwater recharge, and some industrial and environmental uses. Public resistance and the high costs of advanced treatment have slowed its use for drinking.

Estimated wastewater reclamation costs for different treatment technologies, plant capacities, and reuse alternatives are summarized in Table 4.3. For a given treatment process, the lower costs are for plant capacities of 50 million gallons per day (Mgal/day). The costs for 1 Mgal/day facilities are generally about 3 times higher than those for the larger plants. The costs of delivering the treated water to the end user are not included.

The least expensive alternative involves a 50 Mgal/day facility using an activated sludge treatment process that provides water suitable for agricultural irrigation at $242/af. At the other extreme, producing water suitable for use in industrial boilers under intermediate pressure in a 1

Mgal/day facility using tertiary lime, carbon absorption, and ion exchange would cost $1,924/af. If the treated water is used for groundwater recharge in spreading basins rather than for direct reuse, treatment costs range from $106/af for a 50 Mgal/day facility to $255/af for a 1 Mgal/day facility (Richard, Takashi, and Tchobanoglous, 1992).

The economics of recycling are driven in large part by environmental and health regulations that dictate how communities collect and treat wastewater and by federal subsidies. Federal regulations require effluent discharged into waterways to undergo at least secondary treatment. Additional treatment to achieve a quality acceptable for unrestricted agricultural use, plus storage and conveyance of the water to a farmer might cost about $125/af. This cost is competitive with alternative sources of supply in many areas. The costs to the local communities may be further reduced by state or federal subsidies. The Reclamation, Recycling, and Water Conservation Act of 1996 authorizes federal cost sharing up to 25 percent of construction costs or a maximum of $20 million dollars (California Department of Water Resources, 1998).

Wastewater is not widely recycled in the United States. Even in areas where wastewater is treated for reuse, recycling accounts for only small fractions of total water supplies. California, the largest user of the technology, recycled an estimated 485 taf (thousand acre-feet) in 1995, only 323 taf of which represented new water supply. Recycling accounted for about 0.4 percent of the state’s average supply (California Department of Water Resources, 1998). Recycling that creates a new demand that would not otherwise exist or treats water that otherwise would have been reapplied downstream or used to recharge groundwater is not considered new supply.

Estimates from California’s Department of Water Resources suggest recycling will only increase to 577 taf/year (407 taf/year of which would be new supply) by the year 2020. If local water agencies implement all the projects identified in a 1995 survey, recycling would grow to more than twice these levels by 2020 (California Department of Water Resources, 1998). But even if all of these projects are completed, recycling would account for only 1.4 percent of the state’s average year supply in the year 2020.

Although recycling is expected to remain a minor source of total water supplies over the next several decades, the combination of the high costs of alternative sources of supply, wastewater disposal regulations, and technological advances that lower treatment costs are likely to make recycling an important source of new water in many areas. Wastewater reclamation will become increasingly common even in the absence of future subsidies.

4.3 Desalination

Seawater is available in unlimited quantities to coastal areas, and brackish waters containing salt levels too high for most uses are available in many aquifers and lakes. The costs of upgrading these waters for use vary depending on the quantity of salts to be removed. While technological advances have reduced desalting costs as much as 50 percent in recent decades, high costs continue to make desalting seawater a supply of last resort and affordable only for domestic and industrial use. California, one of the largest users of desalted seawater, has a desalting capacity of about 8 taf/yr. This capacity, which is currently operated largely as a drought period supply, is expected to grow only modestly over the next 25 years (California Department of Water Resources, 1998).

Seawater desalting costs typically range from $1,000 to $2,000/af depending on factors such as the cost of energy and the extent to which existing infrastructure, such as a brine disposal facility, is already available. The Metropolitan Water District of Southern California is studying a design that would utilize the heat energy of an adjacent power plant in hopes of producing desalted seawater at less than $1,000/af (California Department of Water Resources, 1998). Scientific and technological advances in areas such as membrane technology are likely to result in further reductions in desalting costs. To accelerate such advances, the Water Desalination Act of 1996 authorizes $5 million per year for desalination research and $25 million per year for demonstration and development projects for six years.

Depending on the salinity of the source water, brackish water might be upgraded to drinking water standards for less than half the cost of desalting seawater. Desalting brackish ground and surface waters with salt levels well below the 35,000 ppm found in the oceans is emerging as a competitive water source in some areas. Desalting brackish water is similar to recycling processes that remove salts as well as other contaminants from agricultural, municipal, or industrial returnflows. High-tech industrial plants requiring higher quality water than they can get from public suppliers or groundwater sources may construct their own desalting plants. Although this approach makes for expensive water, water costs may not be a major component of the total production costs of such plants. And if the cost or unreliability of the water supply dictates, affected businesses can relocate to areas where high-quality water is more readily available.

4.4 Weather Modification

Weather modification through cloud seeding has been practiced in a few areas of the West for as long as 50 years. Nevertheless, the practice continues to be controversial because of uncertainties as to its effectiveness and questions about liability and rights to use the augmented supply. Cloud seeding received some scientific support in 1992 when both the American Meteorological Society and the World Meteorological Organization issued policy statements cautiously supportive of its effectiveness for increasing precipitation under the proper circumstances. Increases in precipitation through cloud seeding have been limited to winter orographic clouds formed by encounters with mountain ranges. In 1996, California had 14 active programs to increase water supplies for agricultural and municipal uses and hydroelectric power generation through cloud seeding. Estimates suggest these programs increased annual precipitation in the test areas by 2 to 15 percent, depending on the number and type of storms seeded (California Department of Water Resources, 1998). A 1993 Bureau of Reclamation Report concluded that weather modification might potentially increase seasonal snowpack in California’s Trinity Watershed by about 5 percent at an estimated cost of about $8.40 an acre-foot (Western Water Policy Review Advisory Commission, 1998).

Expanding the conditions under which precipitation can be condensed from clouds would broaden the potential for increasing water supplies through weather modification. But institutional factors limit the use of this technology. Legal and technical disputes over who benefits and who loses from the increased precipitation and over whether and how to compensate the losers are obstacles to wider use of cloud seeding. Potential opponents of cloud seeding are towns with higher snow removal costs, downstream villages with increased flooding from spring snowmelt, and downwind communities that might feel they are deprived of precipitation that would otherwise have fallen on them. If future results support the prospect of augmenting supplies in water-scarce areas at low cost, the institutional barriers to weather modification could also diminish.

4.5 Interbasin Transfers

Transferring supplies from water-surplus to water-deficit areas has helped balance supplies and demands in the past. Laws giving the highest priority rights to the first person to withdraw water from a stream encouraged such transfers. However, the highest priority rights have already been claimed and states are seeking to restrict out-of-state transfers. Currently, few, if any, basins in the conterminous United States are willing to give up more water without compensation, and environmental laws provide them with a powerful tool for blocking or at least stalling transfer proposals. The availability of large quantities of freshwater stored in icebergs or flowing in northern rivers in largely uninhabited areas of Alaska and Canada have fostered bold, environmentally damaging, and costly schemes to divert some of this water to the arid and semiarid West.

While engineers continue to study opportunities for large-scale water transfers, the Western Water Policy Review Advisory Commission (1998, pp. 3-12) concluded that “the political reality ... is that opportunities for new, large importations of water and transbasin diversions are limited for a combination of fiscal, environmental, legal, and political reasons.” As water values rise in the coastal southwest and their options for augmenting supplies locally dwindle, transferring water drawn from the mouths of large northern rivers in tankers or large balloons dragged behind tugs might emerge as a viable means of increasing supplies, especially during drought conditions.

4.6 Vegetation Management

Vegetation management such as removing phreatophytes (high-water-using plants that thrive along streams) and managing forests for increasing water yields can increase water supplies in some areas at financial costs that are competitive with alternative sources of supply. But other factors may limit the use of vegetation management for increasing runoff. Removing phreatophytes from streambanks can adversely affect wildlife habitat, and managing forests for water may conflict with commercial timber production and recreation opportunities.

National forest lands provide about half of the runoff in California. U.S. Forest Service estimates suggest that runoff from their lands might be increased about 360 taf per year (about 1 percent per year) by thinning trees and shrubs. Without new storage facilities, however, only a fraction of this runoff would contribute to water supply. None of the state’s water agencies are currently pursuing forest management as a water supply option. In view of the potential environmental impacts and institutional difficulties, such a forest management program is not likely to be undertaken unless it is part of a multipurpose program in which timber management or fire suppression are the main objectives (California Department of Water Resources, 1998).

4.7 Watershed Management

All water users within a hydrologic unit or watershed become increasingly interdependent as the resource becomes scarcer. One user’s actions can affect the quantity or quality of water available to others. Or where ground and surface waters are interconnected, use of water from one source affects the availability of water from the other. These interdependencies among users and the interchangeability of supplies are likely to be ignored in management decisions when natural hydrologic units are divided into multiple political and administrative units, water-supply facilities are under separate ownership, or ground and surface waters are subject to different laws. Under such circumstances, integrated management of supplies and infrastructure at the river basin level can be an economical way of increasing water supplies.

The agreement among the three principal water agencies servicing the metropolitan Washington, DC area that went into effect in 1982 illustrates the potential benefits of coordinated regional water management. This agreement increased the region's drought-condition water supplies by nearly one-third with relatively little new infrastructure. The yield increases were achieved largely by relying on Potomac River water during periods of high flows and saving the available reservoir storage for low-flow periods. Achieving a comparable yield increase in the absence of such an agreement would have required facilities costing an additional $200 to $1,000 million (Sheer, 1986). On the negative side, relying more on the region's reservoirs to protect against drought sacrificed some capacity to protect against floods.

Sheer (1986) examined the opportunities for and potential benefits of integrated water management in several areas in the United States in the mid-1980s. He concluded that an integrated approach would probably provide the most cost-effective water-supply investments possible over the next decade. A few opportunities have been acted upon to reap such benefits. For example, conjunctive management of ground and surface waters is being employed in a number of areas in the West. Several water districts in California solved a problem stemming from interruptible supplies by using aquifers to store excess wet year supplies, and Arizona uses artificial recharge to store excess surface waters. Well-managed groundwater recharge projects tend to be less expensive than the surface water alternatives. Moreover, they avoid some of the negative environmental impacts and evaporation losses of surface storage (Western Water Policy Review Advisory Commission, 1998).

The Massachusetts Water Resources Authority's (1990) long-range water supply program included opportunities for improving the use of existing supplies. In a few cases the costs of the identified management improvements were competitive with alternative options for augmenting effective supplies. However, the potential yield was small relative to both the need and the potential yield of conservation and demand management measures.

In most areas, the opportunities for increasing water supplies through more efficient integrated management are largely unexplored, perhaps because of the formidable institutional obstacles to their adoption. The obstacles include (1) state water laws that ignore the impacts of use on downstream states, (2) interstate compacts that inhibit reallocation of supplies, (3) legal constraints on collaboration among suppliers, (4) regulations inhibiting the conjunctive management of ground and surface supplies, (5) the multitude of federal and state agencies pursuing narrow and often conflicting objectives, and (6) vested interests that profit from existing inefficiencies and operating criteria that are unresponsive to changing values and supply and demand conditions.

4.8 Conservation

The opportunities for conserving water are in part a legacy of past policies that kept prices low, discouraging development and the adoption of more water-efficient technologies and practices. Water pricing was based on financial rather than efficiency considerations. Prices were and often still are set to recover average costs where the source water is provided free and the distribution and treatment costs are often subsidized. In contrast, efficient pricing reflects marginal costs, including both the financial and environmental costs of using the resource. Moreover, efficient water policy would invest in conservation up to the point where the marginal social cost of saving water is equal to the marginal social cost of developing new supplies. Potential social benefits of conservation that may not be fully reflected in investment decisions are reduced sewage treatment costs and avoidance of adverse environmental impacts associated with developing new supplies.

The disincentives to conservation have often been greatest where the resource is scarcest. Reisner and Bates (1990, p. 7) described the situation in the West as follows: “The whole system encourages inefficient uses. Federal water subsidies, hydropower subsidies, crop subsidies, the doctrine of appropriative rights, constraints on water transfers, fixed or declining block rates—a whole gamut of conservation disincentives has given the American West the most prodigious thirst of any desert civilization on earth.”

Under the prior appropriation doctrine that dominates western water law, rights to use surface water were granted on the basis of “first in time, first in right.” Consequently, farmers hold most of the high priority water rights and irrigation water is often distributed in open dirt canals that result in large infiltration and evaporation losses. Farmers have no incentive to reduce these losses unless they are able to use the conserved water to irrigate more land or sell it. But their appropriative rights were often encumbered with restrictions limiting the ability to transfer water to other uses and locations. As irrigators run out of low cost water, conservation becomes important for maintaining or increasing the land under irrigation. But allowing irrigators to sell water to municipal and industrial users at prices above its marginal value in agriculture may produce even greater incentives to conserve.

Rising costs and growing environmental concerns over traditional water development projects are also encouraging conservation among municipal and industrial water users. Environmental laws requiring secondary treatment before effluent may be discharged into a water body provides added incentive to conserve. Conservation reduces wastewater treatment costs as well as the need for new supplies. Some utilities have adopted increasing block water pricing to encourage conservation by those using large amounts of water.

Efforts to encourage water conservation have not been limited to price incentives. Regulations mandating use of water-conserving items such as toilets and showers, programs to educate users and promote adoption of water conservation opportunities, and drought-induced shortages have been introduced in recent years.

Seattle Public Utilities (1998) analyzed the costs and potential water savings of a wide range of conservation measures that could be introduced into their service area through the year 2020. Seattle’s Water Conservation Potential Assessment (CPA) included only those conservation measures that were not expected to result in a loss of service or customer satisfaction. Although the costs and water savings included in the CPA are based on conditions unique to Seattle, they illustrate the types of conservation opportunities available to many urban areas.

Table 4.4 summarizes the savings and costs of four potential conservation packages examined under Seattle’s CPA. The packages included measures to produce 5 and 10 percent savings, a cost-effective alternative of all measures that could be implemented at a cost less than the marginal cost of increasing peak season supply, and all measures that could be implemented by 2020 regardless of cost without a loss of service or customer satisfaction.

The CPA concluded that water savings up to 31 million gallons per day (mgd) or 16 percent of peak season water use can be achieved over the next 20 years at a marginal cost of $1,050 per acre-foot, the marginal cost of new peak season water supply. Savings beyond this cost-effective level are subject to sharply rising average and marginal costs. The CPA’s cost and savings estimates are considered conservative because they did not consider potential technological improvements, nonwater benefits such as energy savings, or environmental benefits from conservation.

Table 4.5 provides some detail as to where the principal water savings are achieved under the cost-effective conservation package. The residential-domestic category accounts for nearly half of the 31 mgd total saving and has the lowest average cost per acre-foot saved of the five categories. The largest percentage reductions occur in the residential and commercial landscaping categories, but they account for only 22 percent of the total cost-effective savings. Commercial processing accounts for 23 percent of the total cost-effective package and is the highest cost category.

Reducing residential and commercial toilet water use by installing water-efficient toilets and urinals, reducing leaks, and decreasing toilet flushing contributes 34 percent of the total potential savings under the cost-effective package. Installing 1.6 gallon per flush toilets for residential use accounts for nearly 40 percent of the potential toilet-related water savings. But the average cost of $1,041 per acre-foot saved is the highest of all the measures included in the cost-effective package. In contrast, the average cost per unit of conserved water is 45 percent less for installing water-efficient toilets in commercial facilities. Only one-third the amount of water saved from replacing residential toilets would be conserved, however. The other big potential water-saving measure under the cost-effective package involves replacing water-cooled equipment with air-cooled equipment in commercial processes. This measure accounts for 14 percent of the total water savings, but the average cost per unit of water is nearly 50 percent higher than the average cost of the total cost-effective package. Because of their high costs, installing water-efficient toilets in residences and switching to air-cooled equipment in commercial processes are not included in the conservation packages producing 5 and 10 percent savings.

Table 4.6 presents the estimated costs of conserving an acre-foot of water through measures that have been employed or analyzed in three other water districts. The conservation measures are divided into three broad categories: (1) suppliers reducing distribution losses by fixing leaks and lining canals; (2) users employing more efficient technologies that enable them to maintain the same services with less water (e.g., households installing water-conserving toilets, farmers adopting more efficient irrigation systems, and power producers switching from wet to dry cooling); and (3) users adopting less water-using practices (e.g., taking shorter showers or planting crops that use less water).

The costs for reducing distribution losses in California’s Imperial Irrigation District (IID) are based on a water marketing arrangement with the Metropolitan Water District of Southern California (MWD). In exchange for rights to use the conserved water, MWD financed conservation investments in the IID. The costs of reducing an acre-foot of distribution losses in the IID ranged from $22 for constructing spill-interceptor canals to about $175 for lining the All-American canal that carries water from the Colorado River to the irrigation district. MWD’s cost of buying and delivering this water to its service area ranged from $308 to $465 an acre-foot. The total costs of the water to MWD are still less than the estimated costs of developing and importing new supplies from northern California (Wahl and Davis, 1986).

Reducing distribution losses in irrigation and urban supply systems increase total water supplies only to the extent that they save water that otherwise would be evaporated or discharged to an unusable sink. Reducing leaks that recharge useable aquifers or surface supplies or that provide wildlife habitat do not increase total water supplies. They may, however, increase the value of the water by transferring supplies from low to higher value uses. The marketing arrangement between MWD and IID was possible in part because the impacts on the former users of water lost in the distribution system were essentially ignored. Irrigators across the border in Mexico using groundwater recharged from canal leaks lacked a legal claim to the water. And the increased salinity and lower levels of the Salton Sea that resulted from the conservation investments and water transfers to MWD were viewed as minor relative to the benefits of the increased efficiencies.

Many of the water supply systems serving the East's largest cities are old, poorly maintained, and inefficient. Distribution losses of 30 percent or more and increasing rates of water main breaks have been detected in some urban systems where maintenance has failed to keep pace with needs (Wade Miller Associates, 1987). Detecting and repairing such leaks can be an economical means of balancing urban supplies and demands. For instance, the Massachusetts Water Resources Authority's (1990) long-range supply program estimated that leak protection and repair would cost less than one-third of the least expensive option for importing water and would avoid the environmental and political obstacles associated with interbasin transfers.

Industrial and commercial conservation at $18 per acre-foot was the least cost conservation measure identified in the long-range supply program of the Massachusetts Water Resources Authority (1990). But the potential savings of this measure were only about 3 percent of those possible from repairing leaks in the distribution system. Domestic device and low-flow toilet retrofitting together could save nearly as much water as leak repairs but at much higher costs (Table 4.6).

The Marin Municipal Water District (MMWD) in California has estimated the costs of conserving water through various investments and programs (Table 4.6). The conservation measures range from a program to promote 1.6 gallons per flush toilets at a cost of $191 per acre-foot of water to a series of seminars that inform swimming pool owners on how to conserve water at a cost of $781 per acre-foot conserved. The weighted average cost of $357 per acre-foot saved under the MMWD conservation program compares favorably with the $1,241 per acre-foot required to develop additional supplies (Owens-Viani, 1999). Audits designed to motivate and assist MMWD customers in water-conserving adjustments and investments ranged in cost from $543 to $722 per acre-foot saved, depending on the group targeted. Audits costing an estimated $136 per acre-foot conserved are more cost-effective in the Metropolitan Water District of Southern California.

The costs presented in Tables 4.5 and 4.6 indicate considerable regional differences in the costs of saving water through various conservation measures. Many factors may underlie these differences. But an important consideration is evident in a comparison of the marginal and average costs of the conservation measures included in the four conservation packages analyzed in Seattle's CPA. Water conservation is subject to increasing costs. In Seattle, the marginal cost per acre-foot to reduce peak season demand increases from $327 for a 5 percent water saving, to $867 for a 10 percent saving, $1,041 for a 16 percent saving, and $59,242 for a 22 percent saving (Table 4.4).

Several general conclusions can be deduced from the studies underlying the water conservation costs in Tables 4.5 and 4.6. First, fixing distribution losses is likely to be among the more cost-effective conservation measures when the water would otherwise be lost to evaporation or an unusable sink. Second, the opportunities are limited for conserving urban water at costs under $200 per acre-foot, which is well above the marginal value of water in most uses (Frederick, VandenBerg, and Hanson, 1996). In Seattle, for instance, a 5 percent reduction in water use involves conservation measures costing in excess of $300 per acre-foot. And third, a wide range of conservation measures and substantial water savings are profitable at costs that are equal to or less than the costs of developing new supplies.

4.9 Structure of the Economy

Shifts in the nature of its economy during this century tended to make the United States, on balance, less vulnerable to climate-induced changes in water supplies. Technological developments such as steam engines, internal combustion motors, and electricity generation and transmission reduced the significance of onsite water power. Expansion of railroads, highways, and air transport diminished the importance of water-based transport. And most industries have reduced the amount of water required in the production process. The growth of irrigation, which uses large quantities of water, is an exception to this trend. But agriculture, the most water-sensitive sector of the economy, has declined in relative importance.

Irrigated cropland contributes about 40 percent of the value of the nation’s crops on just 15 percent of the total cropland harvested (Economic Research Service, 1997). Irrigation has mixed implications for agriculture’s vulnerability to climate-induced changes in water supplies. In the short-term, drainage and irrigation make crop production less susceptible to the vagaries of precipitation. Without drainage, too much rain floods fields, making it difficult to plant in the spring or to harvest in the fall. And without irrigation, too little rain reduces or even eliminates crop growth.

In the longer term, the future of irrigation depends in part on water costs and scarcity, conditions likely to be affected by climate change. In 1995, irrigation accounted for 81 percent of total consumptive freshwater use and 39 percent of withdrawals (Solley, et al., 1998). As the largest and among the lowest-value water users, irrigators are particularly susceptible to changes in the availability and cost of water. Irrigators hold many of the most senior water rights in the West. Under the prior appropriation doctrine of water law adopted by the 17 western states, owners of the most senior rights are supposedly assured a full supply of water under virtually all conditions. Nevertheless, as the resource becomes scarcer incentives increase to transfer water, either politically or voluntarily, from irrigation to higher value uses. Such transfers are already taking place**.** The Central Valley Project Improvement Act of 1992 amended the purposes of the federal Central Valley Project in California to place fish and wildlife mitigation and restoration on a par with water supply and reallocated 800,000 acre-feet per year from agricultural to environmental uses (California Department of Water Resources, 1998). Voluntary sales of water from agricultural to urban and environmental uses are becoming increasingly common in the West.

Groundwater is the source of about 37 percent of irrigation water withdrawals (Solley, et al., 1998). Although these supplies are less susceptible than surface waters to drought, their use and long-term availability are affected by the climate. Pumping costs rise if more water is extracted during drought, aquifer recharge rates are affected by the climate, and nonrenewable groundwater supplies are mined faster under hotter and drier conditions.

Forestry is another resource-based economic sector susceptible to changes in precipitation. Drought has an adverse impact on forests and the economic interests dependent upon them by increasing the risks of fire, disease, and pest damage. Important changes in the forest products industry during the last century include the growing importance of plantation forestry and the growth of international trade in forest products. Plantation forests with large concentrations of single species of trees may be more vulnerable to disease and pest damage than natural forests containing a wide variety of tree species. On the other hand, globalization may have reduced the industry's sensitivity to regional climate variations.

Water-dependent outdoor recreation activities have become increasingly important as people have become more affluent and have more leisure time. Skiing and freshwater recreation such as boating, swimming, and fishing are particularly vulnerable to temperature and precipitation changes. Unseasonably warm and dry weather can spoil skiing, and drought can convert reservoirs, valued for their recreational opportunities, into unsightly and unusable mudflats.

4.10 Slack in the System

While infrastructure investments, technological advances, and changes in the structure of the economy have generally reduced the nation's vulnerability to hydrologic extremes, there are countervailing forces. Increased development in water-scarce and flood-prone areas have placed more people at risk to droughts and floods. And the rising costs and slowing pace of infrastructure development could limit the ability to respond to hydrologic extremes and water scarcity.

Traditionally, water resource systems have been designed to be "robust" (i.e., capable of responding to the range of uncertainties associated with future variability) and "resilient" (capable of operating under a range of conditions and to return to designed performance levels quickly in the event of failure). However, rising costs and skepticism about new water projects suggest that building large redundancy into water supply and control projects may be a thing of the past.

The decline in dam and reservoir construction since 1970 has reduced the overall robustness of the nation's water supplies. A basic principle of reservoir planning is that the risk of deficiency increases if the storage period (that is, available reservoir storage divided by average daily withdrawals) is not increased as withdrawals increase. The storage period increased for at least six consecutive decades prior to 1970 and rose from 204 days in 1960 to 216 in 1970. But by 1980 it had fallen to 201 days (U.S. Geological Survey, 1984). The 10 percent decline in water withdrawals between 1980 and 1995 may have improved the situation somewhat (Solley, et al., 1998). But the decline in reservoir construction illustrated in Table 4.1 along with the buildup of sedimentation in reservoirs pose a long-term threat to the robustness of some water supply systems and their capacity to control flood flows.

Data on sedimentation rates for most reservoirs are poor or nonexistent. One estimate suggests annual storage losses to sedimentation are about 1.4 to 1.5 million acre-feet (Guldin, 1989). At this rate, the amount of storage lost to sedimentation would have exceeded by 0.5 maf per year the additions to storage from the dams and reservoirs completed from 1991-1995 (Table 4.1). A net loss of storage capacity diminishes the ability to protect against floods and droughts over time.

The loss of wetlands also diminishes the capacity to limit flood flows. Wetlands reduce flooding by dispersing high water flows over time and space. Although the specific extent of the wetland loss is uncertain, there is no doubt that it has been great. A National Research Council (1995) study estimates the loss in total wetland acreage as of the mid-1980s at approximately 117 million acres, half the original endowment in the conterminous 48 states. Most of the federal policies that encouraged draining and developing wetlands and water use and development practices harmful to wetlands have been abandoned. More recent laws and policies designed to protect the remaining wetlands and encourage wetland restoration and creation have slowed net wetland losses. But the United States has not achieved the “no net loss” goal established by President Bush in 1989 (Crosson and Frederick, 1999).

Vulnerability to drought depends in part on the slack between average water use and a system’s safe yield. The ratio of these two values provides a measure of vulnerability to drought; higher ratios indicate greater susceptibility and the possibility of major drought impacts. When supplies are stretched to meet demand under normal hydrologic conditions, even a mild drought requires adjustments in water use.

The National Study of Water Management During Drought (U.S. Army Corps of Engineers, 1991) developed safe yield estimates for eight urban water supply systems. Water use exceeded the safe yield in four of these systems. The most vulnerable areas and their ratios of use: safe yield were Phoenix, Arizona (1.06), Southern California’s Metropolitan Water District (1.12), New York City (1.19), and Merrifield, Virginia (1.46). The locations of these ratios indicate that vulnerability to drought is not limited to and is not necessarily greater in arid regions.

The national drought study concludes that areas relying on surface water generally are inherently more vulnerable to drought than those relying largely on groundwater because precipitation deficits affect streamflows and reservoir storage more rapidly than deep groundwater aquifers. A ranking of the nation’s water resources regions by the percentage of population relying on surface water had the relatively water-rich Great Lakes region with the highest (84 percent) and the relatively water-scarce Rio Grande region with the lowest (24 percent). Other regions with relatively low percentages of their population relying on surface water are California (33 percent), the Great Basin (41 percent), and the Lower Colorado (42 percent) (U.S. Army Corps of Engineers, 1991, p. 35). The high dependence on groundwater in these regions reflects in part the scarcity of surface water supplies relative to current levels of water use. While groundwater may make these regions less vulnerable to short-term fluctuations in precipitation and runoff, dependence on non-renewable supplies for current levels of water use would make them more susceptible to longer-term shifts in water supply and demand conditions that might result from changes in the climate or other factors.

Inefficient and low-value water uses that could be curbed with little pain provide opportunities for mitigating the socioeconomic impacts of drought. Such water uses are found in most areas of the country. As noted above, however, water conservation programs and regulations as well as higher water and sewerage prices have eliminated some inefficiencies and low value uses in recent years and contributed to declines in offstream water use since the mid-1970s.

The greatest efficiency gains were for industrial uses other than thermoelectric power. These “other” industrial withdrawals declined 35 percent between 1980 and 1995 as “the result of new industries and technologies that require less water, improved plant efficiencies, increased water recycling, changes in laws and regulations to reduce the discharge of pollutants, and conservation measures.” (Solley, et al., 1998, p. 62). Withdrawals for thermoelectric power and irrigation, which together accounted for 80 percent of all withdrawals in 1995, declined about 10 percent from 1980 to 1995. Public supplies, which account for 10 percent of total withdrawals, increased 18 percent from 1980 to 1995 but less than 2 percent on a per capita basis. Rural domestic and livestock (which is largely water for livestock, feed lots, dairies, fish farms, and other on-farm needs) is the only category to register significant (i.e., 36 percent) per capita increases in water use over this period. But with only 2 percent of total withdrawals, this increase had little impact on the overall trend toward lower per capita water use (Solley, et al., 1998).

Regional trends in irrigation have had a major impact on aggregate water use. Irrigation withdrawals in the 17 western states declined 9 percent and consumptive use declined 14 percent from 1975 to 1995 due to a combination of factors including a reduction in irrigated acres associated with rising groundwater costs and transfers of surface water rights, more efficient application technologies, and conservation practices. In contrast in the 31 eastern states, irrigated acreage increased nearly 90 percent, withdrawals rose 24 percent, and consumptive use rose 41 percent over these two decades (Solley, et al., 1998). Even with this shift, the West still accounts for 88 percent of the nation's irrigation withdrawals and 86 percent of the consumptive use. However, irrigation water use in the West is likely to continue declining in the coming decades as water becomes scarcer and use of non-renewable groundwater supplies becomes more expensive (National Research Council, 1996).

The implications of increased water-use efficiency for vulnerability to future drought depend on how conserved water is used. If it is used to add more customers to a supply system, vulnerability increases. On the other hand, if the conserved water is stored for use during drought, vulnerability decreases (U.S. Army Corps of Engineers, 1995). With population and income growing faster than new water supplies, vulnerability appears to be increasing.

4.11 Institutional Change

The socioeconomic impacts of extreme events, population growth, climate change, and other factors affecting the supply and demand for water will depend in large part on how society adapts. The social costs of adaptation will be determined in large part by the institutions that allocate supplies among competing uses and provide the opportunities and incentives to use, abuse, conserve, or protect the resource.

Water use and management practices have adjusted in the past in response to changing conditions. But these adjustments tended to be partial, temporary, and introduced only after the social costs of the status quo became too high to ignore. Underpricing, inefficiencies, and restrictions on how water is used and managed continue to result in conflicts and limit the ability to adapt to short- and long-term changes in supply and demand conditions. Obstacles to more efficient adaptation include the following:

- Water is treated as a free resource, some uses are still subsidized, and utility pricing practices tend to price water below its long-term marginal cost. These policies diminish incentives to conserve and enable low-value and inefficient uses to persist when potentially more socially valuable uses are not met.

- Both the nature of the resource and institutional obstacles limit water transfers and increase the costs of the transfers that are made.

- Resolving conflicts between environmental and developmental water uses tends to be contentious, slow, and costly. In some instances environmental values continue to be slighted by institutions rooted in a bygone era when water left in a stream was assumed to have no value. In other cases, environmental values are introduced preemptively through legislation such as the Endangered Species Act or through long and costly judicial or administrative proceedings. Institutions that can expeditiously and fairly balance environmental, social, and developmental values within a basin-wide context (rather than on a project by project basis) are needed to facilitate adaptation to changing supply and demand conditions.

- Current policies for restoring and protecting water quality are encountering high costs and diminishing returns and do little to curb non-point source pollutants, which are now the principal contaminants reaching the nation's waters.
- Natural hydrologic regions are often split into multiple political and administrative units that fail to take account of the interdependencies among water users and the opportunities for integrated management of existing supplies and infrastructure.
- Water management is limited by regulations that fail to take adequate account of changing conditions and information and by managers reluctant to deviate from traditional practices even when better meteorological forecasts and altered circumstances suggest change is warranted.

5. SOCIOECONOMIC IMPACTS OF CLIMATE VARIABILITY AND CHANGE

Climate influences both the variability and the availability of water, and a change in the climate could affect the magnitude and frequency of floods and droughts and the problems of balancing future water supplies with demands. But climate is only one of many factors that will affect future water conditions; the world in 2030 and 2095 will differ from that of today in the absence of climate change. The following three subsections examine how the socioeconomic costs of floods, droughts, and water scarcity in the years 2030 and 2095 might differ from the 1995 baseline. For each of these water-related events the implications of possible changes in population, incomes, and other non-climate factors are considered first to provide future baselines for examining the potential implications of climate change. The climate change scenarios are based in part on the projections of the Canadian and Hadley models described above.

5.1 Floods

Future flood damages will depend primarily on: (1) the size and frequency of flood events; (2) the number of people and the value of the property at risk; (3) reservoir storage capacity and competing demands for use; (4) changes in wetlands and their capacity to capture flood flows; (5) the ability to anticipate flood events and move people and property out of harms way; and (6) sea level rise and storm surges.

5.1.1 Nonclimate Impacts

In the absence of climate change, it is assumed that future hydrologic variability will be similar to what it was in the past. Changes in non-climate factors, however, will alter the frequency and magnitude of flood events and the ability to anticipate and control flood flows.

On the positive side, scientific and technological advances should improve the ability to forecast future weather events and flood flows. These advances should enable communities to better anticipate flooding and undertake measures to reduce loss of lives and property.

On the negative side, the ability to control floods may decline as: (1) wetlands and their capacity to moderate flood flows continue to be lost; (2) reservoir storage capacity declines as new construction lags behind losses attributable to sedimentation and removal of dams that impose unacceptable environmental damage or risk to occupants of the floodplains below hazardous dams; and (3) rising water scarcity increases incentives to use storage for purposes other than flood control.

Development in the floodplains is likely to continue placing more people and property at risk to floods. Future development would be somewhat less than the 2 percent per annum historic rate if subsidies for floodplain settlement are reduced and more restrictions are placed on new developments. Nevertheless, with more property at risk and less ability to control flood flows, property damages from floods are not likely to decline and might increase somewhat faster than the 1 percent per annum historic rate in spite of improved forecasting and a lower rate of development in the floodplains (Figure 2.1). People are more mobile than property. Advances in the ability to forecast flood events and educational programs that instruct people how to reduce flood risks may be sufficient to reduce or at least prevent any rise in the past 1.5 percent per annum rate of increase in flood-related deaths (Figure 2.2). Increases of 1 to 1.5 percent per year would increase flood-related damages and deaths by 42 to 68 percent after 35 years and by 170 to 343 percent after 100 years.

Projected future flood-related damages and fatalities depend on how the base year levels are calculated as well as on the projected rates of increase. Flood damages in 1995 were $5.1 billion and average annual losses from 1990 to 1997 were $5.3 billion (1995$) (National Weather Service, 1999). Using $5 billion as the base year, and assuming that damages rise annually by 1 to 1.5 percent, future direct annual flood-related property damages would range from $7.1 to $8.4 billion in 2030 and $13.5 to $22.2 billion in 2095. Flood-related deaths were 103 in 1995 and average annual fatalities from 1990 to 1997 were 98. Using 100 as the base year level and a continuation of the 1.5 percent per annum historic rate of increase, annual flood-related deaths would reach 168 by the year 2030 and 443 by 2095.

As noted earlier, indirect costs such as lost wages and business revenues would add to the socioeconomic costs of flooding. Moreover, the cost and fatality projections do not include flood losses attributable to storm surges.

5.1.2 Impacts of climate change

Climate change could have major impacts on the frequency, magnitude, and socioeconomic costs of floods. Precipitation changes could affect the timing and magnitude of runoff, and temperature changes could affect runoff patterns by altering snowfall and snowmelt regimes. The outputs of GCMs say nothing about the potential impacts of a greenhouse warming on climatic and hydrologic variability. However, the changes in average annual streamflows derived from the Canadian and Hadley GCMs (see Tables 3.7 and 3.8) would have important implications for both flood and drought events.

Under the Canadian climate, streamflows in 2030 are lower in all regions except California. In two-thirds of the water resources regions, renewable water supplies decline by more than 20 percent; in one-third of the regions supplies decline by more than 40 percent from the 1995 baseline. Flood damages and fatalities would decline in most of the country under this scenario unless streamflows became more variable and concentrated in brief periods. By 2095 the Canadian climate model presents a more mixed picture regarding water supplies. Most of the East is even drier than in 2030. But the West, with the exception of the Rio Grande basin, is wetter than in the 1995 baseline. Under this scenario, national flood related damages and fatalities might approach those of the baseline period, but they would be more heavily concentrated in the West.

Under the Hadley climate, streamflows are generally higher in both 2030 and 2095 than in 1995. Average annual renewable supplies are 15 percent or more above the 1995 baseline in 7 of the 18 water resources regions by 2030. But by 2095 supplies have increased by at least 28 percent in 16 regions and in half of the regions supplies are 50 percent or more above the baseline. Unless flows become less variable, flood events would likely be both more frequent and severe under the Hadley climate scenarios. In the absence of major efforts to remove property and people from the floodplains, the large increases in streamflows implied by this scenario could increase damages and fatalities several fold by 2095.

Reports of the Intergovernmental Panel on Climate Change (IPCC, 1996a,b) suggest that a greenhouse warming will alter the timing and regional patterns of precipitation, increasing the likelihood of more intense precipitation days in some regions. Although changes in the regional distribution of precipitation are uncertain, precipitation is expected to increase in higher latitudes, particularly in winter. Moreover, both the Canadian and Hadley models indicate a significant winter warming (Doherty and Mearns, 1999) which would reduce the amount of precipitation that falls as snow and alter runoff patterns. For a given level of precipitation, reduced winter snow pack would increase the likelihood of flooding early in the year. The more northern latitudes and mountainous areas in the western United States where runoff is driven largely by snowmelt would be most vulnerable.

Higher sea levels associated with thermal expansion of the oceans and melting of glaciers and land ice are among the more certain implications of a greenhouse warming. The combination of higher seas and increased storm surges would bring more coastal flooding (Frederick and Gleick, 1999).

Past trends in precipitation and runoff have been studied for evidence of the impacts of a greenhouse warming on hydrology. More time and analysis are required to make convincing connections between hydrologic trends and climate changes. Nevertheless, several studies have detected trends that, if continued, would affect future flood events. Karl and Knight (1998) detected an increase in precipitation of about 10 percent since 1910 in the conterminous United States that is attributable largely to an increase in heavy and extreme daily precipitation events. Continuation of this trend could result in more frequent and larger floods.

A study by Lins and Slack (1999) of changes in runoff in areas little affected by human development has different implications for flooding. Their analysis shows streamflow increased across much of the United States during this century in all but the highest quantiles. The study detected no trend in annual maximum streamflow and no continental-scale seasonal shift in peak discharges. Further analysis is needed to reconcile the Lins and Slack finding that the country seems to be getting wetter but subject to fewer extreme events with the Karl and Knight finding that an increase in heavy and extreme precipitation events is largely responsible for a rising trend in average annual precipitation (Frederick and Gleick, 1999).

To summarize, the impacts of climate change on future flood losses are potentially large but highly uncertain as to magnitude, direction, and location. The GCMs give conflicting projections of changes in runoff for much of the United States and are silent as to changes in variability. Precipitation and runoff appear to have been increasing in much of the country during this century. But it is unclear if these trends are likely to produce more flooding, just as it is unclear if they are related to anthropogenic climate change. The most likely climate changes with implications for flooding are reductions in winter snow pack attributable to higher temperatures and storm surges associated with sea level rise.

5.2 Drought

The socioeconomic costs of future droughts will depend largely on: (1) the frequency, magnitude, and duration of droughts; (2) available ground and surface storage; (3) slack in water supply systems such as the ratio of storage to average withdrawals and the availability of low-value water uses that can be curtailed during drought; (4) the institutions that allocate supplies in response to changes in supply and demand; (5) the relative importance of drought-sensitive sectors in the overall economy; and (6) short-term conservation options.

5.2.1 Nonclimate impacts

Vulnerability to drought is changing for several reasons quite apart from climate change. The safe yield of some supply systems is declining as the storage capacity per person served drops. In some cases, urban supply systems will be competing with recreation, environmental protection, hydropower production, and flood control for use of reservoir storage that is gradually being reduced by the combination of increased sediment and little or no new construction. Depletion of groundwater supplies and saltwater intrusion into coastal aquifers diminish the ability to respond to drought. The gradual reallocation of supplies from low- to higher-value uses eliminates some uses that currently provide relatively low-cost opportunities for reducing water use during drought. And conservation that frees up water to serve more people rather than increase a system’s safe yield increases vulnerability to drought.

On the positive side, institutional reforms such as the spread of water banking to facilitate water transfers in response to short-term fluctuations in supplies will help counter some of the factors tending to increase drought impacts. Agriculture, the most water-sensitive sector of the economy, will continue to decline in relative importance, and development of drought-resistant seeds, improved cultivation practices, and better weather forecasting will help mitigate the impacts of drought on farmers. Brown’s (1999) projections of future water use (see section 3 and Table 3.4) suggest irrigators in the arid and semiarid West will be using less water by 2030. Irrigation water will be used more efficiently and concentrated more on higher value crops in the future. Nevertheless, transfers of water from annual crops to municipal and industrial uses during drought periods will continue to be an important means of mitigating the impacts of short-term water shortages.

On balance, it is likely that drought impacts will rise as water resources become increasingly scarce and some water supply systems have less capacity to compensate for shortfalls. But quantifying the impacts of droughts is difficult. With the exception of a few studies of individual droughts there are no estimates of the socioeconomic costs of past droughts. Consequently, there is little basis for quantifying future drought costs.

5.2.2 Impacts of climate change

As noted above, the hydrologic implications of the Canadian and Hadley GCMs differ widely and the models do not provide information as to likely changes in interannual hydrologic variability. Results using the Canadian model suggest that droughts would be more common and severe in the year 2030. Under this scenario average water supplies would be insufficient to provide for both current instream and consumptive uses in much of the United States. Such drastic hydrological changes, especially in areas where current water use exceeds renewable supplies, would require major changes in lifestyles and perhaps a migration from these areas in the southwest, that are projected to be much drier, to California, which both GCMs indicate will be wetter. By 2095, however, people might be returning to areas that dried up earlier in the century as much of the West is projected to have more water than at present.

A very different forecast is implied by results based on the Hadley climate model. Under this scenario most water resources regions have more water in 2030 and a great deal more in

2095. Such an outcome should reduce the frequency and severity of droughts and help mitigate the socioeconomic costs when droughts do occur.

5.3 Water Scarcity in 2030

Even if climate change does not alter the frequency or severity of extreme events, water users would be affected by changes in water availability. Section 3 described the potential consequences of climate and other factors on long-term water scarcity. Section 4 examined the technologies, trends, and other factors likely to affect the costs of adapting to changes in water conditions. This section draws on the results of those earlier sections to examine the socioeconomic implications of changes in average supply and demand conditions between 1995 and 2030 resulting first from non-climate factors and then from the prospect of a greenhouse warming. Four types of costs and benefits of future changes in water supplies and demands are considered: (1) the costs of developing new supplies for offstream use; (2) the costs of reducing offstream demand through conservation; (3) the costs of withdrawal uses foregone because of insufficient or expensive supplies; and (4) the value of changes in streamflows.

Water costs have been rising for much of this century and, in the absence of climate change, are likely to continue rising as more and wealthier people place increasing demands on a limited resource (Frederick, 1991a). The socioeconomic effects of future climate changes will come on top of these non-climate impacts. The first steps in estimating these climate effects on water scarcity are (1) projecting future changes in water use in the absence of climate change and (2) estimating the costs of providing for these changes. The benefits and costs of the climate-induced changes in water supplies based on the Canadian and Hadley climate models are then estimated.

The impacts of the climate changes are calculated as the changes in the costs of maintaining the projected no-climate-change, non-irrigation offstream water uses with the altered water supplies. When renewable supplies decline as a result of change in the climate, these offstream uses are maintained by developing new supplies, investing in conservation, removing land from irrigation, and reducing streamflows. Alternatively, for climate scenarios that provide more water, the benefits of the increased supplies are reflected in higher streamflow values.

The nature of the costs and benefits of climate-induced changes in water will depend in part on institutional factors that provide incentives to use or conserve the resource and opportunities to allocate supplies among competing uses. When water is underpriced for uses such as waste disposal and irrigation, more of society’s costs take the form of deteriorating aquatic ecosystems, loss of instream values, and higher costs and limited supplies for municipal and industrial users. When institutional obstacles restrict use of the resource, more of society’s costs take the form of water-imposed restrictions on development and perhaps more frequent interruptions in service. On the other hand, when the costs are borne by users of the resource with opportunities to conserve and transfer water to higher value uses, improved efficiency reduces the net social costs of adapting to future changes in supplies and demands. The socioeconomic impacts of the climate-induced changes in supplies are estimated for three alternative management scenarios representing a range of constraints that limit society’s ability to adapt to changes in water availability.

5.3.1 Impacts without climate change

Brown’s (1999) projections of changes in consumptive water use by water resources region (see Table 3.4) provide the basis for estimating changes in water use and costs between 1995 and 2030 without climate change. Table 5.1 presents the projected changes in water withdrawals and conservation by type of use, acres irrigated, population, and streamflow in each of the major water resources regions. Changes in streamflows are estimated assuming Brown's offstream water uses are supplied from renewable sources.

Table 5.2 presents an estimate of the annual costs as of 2030 of these changes in water use between 1995 and 2030 in the absence of climate change. The costs are based on estimates of current costs and conservation opportunities with adjustments for future technological and managerial advances and changes in energy prices. The costs are illustrative of the implications of a set of assumptions that are intended to be plausible. However, they are not based on an in-depth analysis of long-term changes in technology and other factors likely to influence future water costs. The rationale for the cost assumptions underlying Table 5.2 are described below.

Developing new supplies. The costs and availability of water will be primary determinants of changes in the location of irrigation. Brown (1999) projects irrigation withdrawals will decline by 1.8 bgd nationally and by 6.8 bgd in the 9 western water resources regions. The projected decline in western irrigation is consistent with recent trends, dependence on nonrenewable groundwater supplies, and the growing pressures to transfer water from agricultural to municipal, industrial, and environmental uses. The largest increases in irrigation withdrawals are projected to be in the Lower Mississippi, the Upper Colorado, and the South-Atlantic-Gulf regions (Table 5.1). With the exception of the Upper Colorado which is not using its full allocation of Colorado River water, increases in irrigation are likely to involve pumping from shallow aquifers or nearby streams. Irrigation water in the East currently costs about $15 to $20/af for capital and another $20 to $25/af in variable costs (Bureau of the Census, 1996; Economic Research Service, 1997; N. Gollehon, economist, Economic Research Service, U.S. Department of Agriculture, personal communication, July1999). Developing new water for irrigation is assumed to cost $50/af [$153/million gallons (mg)] in the year 2030. This assumption makes allowance for some increase in future energy costs.

Thermoelectric cooling is second only to irrigation in its use of freshwater in the United States. In 1995, thermoelectric power production accounted for 39 percent of all freshwater withdrawals and nearly half of all surface water withdrawals (Solley, et al., 1998). Power plants relying on freshwater for cooling are located next to streams where water can be extracted at low cost. Initially, most plants adopted once-through cooling systems that withdraw large quantities of water. The cooling process heats the water before it is returned to the stream; only about 2.5 percent of the water is consumed through evaporation.

Concerns over the environmental impacts of the large withdrawals and the heated returnflows associated with once-through cooling have resulted in a shift to wet tower cooling in recent decades. Wet tower systems are about 2.4 times more expensive to build and operate than once-through systems but reduce withdrawals from about 47 to 3 gallons per kilowatt hour produced (Miller, 1990). However, there is little difference between the two systems in consumptive water use. With a wet tower or cooling pond the losses occur on site; in a once-through system the losses occur when the water is returned to the river. Cooling systems constructed to meet the no-climate-change increases in water use are assumed to be wet towers and cost $125/af ($384/mg) withdrawn (Miller, 1990).

The costs of developing new supplies for all other uses (i.e., domestic, public supply, industrial, and commercial) are likely to be higher than those for irrigation and thermoelectric cooling for several reasons. Unlike irrigation and thermoelectric power plants, access to low cost water has not been a primary factor in the location of most municipal and industrial sites. Water for these other uses is already more expensive than agricultural water, and augmenting renewable supplies is likely to require additional storage and transport costs. Moreover, the higher water quality requirements of domestic, industrial, and commercial uses may limit their sources of supply. The costs of developing water for these other uses are assumed to vary with the water scarcity index (i.e., desired water use as a percent of mean renewable supply in Table 3.5) as of 2030 in each region. Based on the discussion and cost data presented in section 4, the assumed relation between costs and water scarcity is:

1995 $	scarcity index
300/af (921/mg)	<80
400/af (1,228/mg)	≥80 & <90
500/af (1,534/mg)	≥90 & <100
1,000/af (3,069/mg)	≥100

Conservation costs. There are wide differences among irrigation practices in the efficiencies with which water gets delivered to crops and in the use of water by the plants. Gravity flow systems (i.e., flood and furrow irrigation), which are used on about 63 percent of the irrigated acreage in the 17 western states, are generally less efficient than a sprinkler or drip system in delivering water to the plants. On average 38 percent more water is applied per irrigated acre with gravity flow than with sprinkler systems in the West (Bureau of the Census, 1996). Switching to a more efficient delivery system or recycling water that runs off the field reduces the amount withdrawn from a stream or aquifer. Irrigation scheduling to deliver water when the plants can use it most effectively and switching to crops and varieties that require less water or provide higher returns per unit of water are other alternatives for reducing a farmer's water use (Frederick and Hanson, 1982). The cost of reducing irrigation withdrawals through conservation in the 2030 baseline is assumed to be $25/af ($77/mg) based on the cost of tailwater recovery in Table 4.6.

Tables 4.4 to 4.6 indicate the costs and potential water savings of measures that might be employed by residential, commercial, and industrial users. Seattle Public Utilities' (1998) Conservation Potential Assessment indicates that water savings are subject to sharply rising costs. Marginal costs per acre-foot conserved increase from $327 ($1,003mg) for a 5 percent saving, to $867 ($2,660/mg) for a 10 percent saving, $1,041 ($3,194/mg) for a 16 percent saving, and $59,242 ($181,754/mg) for a 22 percent saving (Table 4.4). These costs are modified to allow for the benefits of lower wastewater treatment costs associated with conservation and future technological and managerial advances. Conservation saves about $190/af ($583/mg) that otherwise would be spent on secondary wastewater treatment to comply with environmental legislation (McConnell and Schwarz, 1992). In addition, technological and managerial progress is assumed to reduce conservation costs (after including the benefits of lower wastewater treatment) by 20 percent. With these adjustments, it is assumed that the first 7.5 percent reduction in withdrawals from conservation is achieved at no cost. Savings from 7.5 to 13 percent cost on average $148/af ($454/mg) and higher savings cost $378/af ($1,160/mg).

Costs of foregone water uses. Brown's projections suggest irrigated acreage declines from 3 to 15 percent in six western water resources regions because of increasing water scarcity. The foregone cost of the projected reductions in irrigation is assumed to be $50 per acre. This cost is within the range of estimates of the average value of water in the production of some lower value crops (Frederick, et al., 1996). As water becomes scarcer and more expensive, the lower value crops are likely to be eliminated first.

Value of changes in streamflows. The benefits of increased flows and the costs of decreased flows are assumed to depend on the relation between mean streamflow and the desired and critical flows in each water resources region. Three categories of streamflow scarcity are considered: mean flow greater than or equal to that desired; mean flow less than desired but greater than or equal to critical flow; and mean flow less than critical flow. The assumed benefits and costs of changes in streamflows are an average of all the estimated values for fish and wildlife habitat and recreation use within each of these three categories presented in Frederick, et al. (1996). The values for the first category, when the mean exceeds the desired flow, differentiates between the instream values in the nine eastern and the nine western water resources regions. Streamflows may shift from one scarcity category to another as a result of the projected changes in water use from 1995 to 2030. Since these are marginal water values, the cost or benefit of a change in streamflow reported in Table 5.2 reflects the portion of the change in flow that falls within each category. The assumed values are:

water scarcity	value of water (1995 $)
mean flow ≥ desired flow	4/af (12/mg) in the East; 21/af (64/mg) in the West
desired flow > mean ≥ critical flow	205/af (629/mg)
mean flow < critical flow	597/af (1,832/mg)

Net impacts. The annual costs of the water use changes implied by Brown's (1999) projections are estimated at $13.8 billion (Table 5.2). Developing new water supplies for offstream use accounts for 51 percent, conservation 26 percent, and the loss of instream values for 22 percent of the total costs. The reduction of irrigation in the West accounts for the remaining 1 percent. Geographically, the 9 western water resources regions account for 52 percent of the costs. The South Atlantic-Gulf with 15 percent of the total incurs the highest costs of any region.

5.3.2 Impacts with climate change

The climate-induced changes in the availability of water implied by the projections of annual mean renewable water supplies in the year 2030 based on the Canadian and Hadley general circulation models (Table 3.7) would have significant socioeconomic impacts. The increases in supplies suggested by the Hadley climate conditions might reduce the costs of providing municipal and industrial water for a growing population and provide more water for irrigation and instream use. On the other hand, the sharp decline in supplies over most of the country suggested by the Canadian climate conditions would increase the competition among instream and withdrawal uses and might require additional investments to conserve and develop new supplies. The nature of the changes and the magnitude of the costs and benefits associated with climate change would depend in part on the institutions that allocate the resource among competing uses.

The economic implications of these climate-induced changes in water supplies are estimated for three alternative management scenarios that differ as to the protection provided for streamflows and irrigation. The scenarios are: ***environmental management*** that does not let streamflows fall below the lower of desired flow or the 2030 no-climate-change flow; ***efficient***

management that allows streamflows to fall to the smaller of the critical level or the 2030 no-climate-change flow; and ***institutional management*** that limits both the reduction in streamflows and irrigation. Under this scenario streamflows may not fall below the lower of 75 percent of desired flow or the 2030 no-climate-change flow; irrigated acreage may not fall below 75 percent of the 2030 no-climate-change level.

The estimated net benefits and costs of the climate-induced changes in water supplies are calculated as changes in the annual costs of maintaining non-irrigation offstream water uses in the 2030 no-climate-change scenario. The demand for water is assumed to be unchanged by the climate. These offstream uses can be maintained through withdrawals and conservation investments that reduce the amount of water required to provide a given service. Conservation costs are converted from withdrawal to consumptive use units using the conversion ratios for each water use and resource region from Brown (1999). Subject to the constraints of the institutional scenarios, each region is assumed to employ the least-cost alternatives for maintaining these offstream uses. The regional optimization does not result in the least-cost national solution because the impacts on downstream regions are not incorporated into the optimization process.

The options and costs for adapting to the changes in renewable water supplies are (a) removing land from irrigation, (b) investing in conservation, (c) developing new supplies, and (d) changing instream flow. The assumptions for the costs and potential savings of these adaptation alternatives are described below.

Removing land from irrigation. It is assumed that as much as 50 percent of a region's 1995 baseline irrigated acreage can be removed at an opportunity cost of $50 per acre and another 30 percent can be removed at a cost of $100/ac. These assumptions are roughly consistent with water values in Frederick, et al. (1996) and the acreage devoted to various crops (Bureau of the Census, 1996). Removing the last 20 percent of irrigated acreage in a water resources region is assumed to cost $500/ac. Two factors contribute to the assumed sharp rise in the value of water—the highest value crops are the last to be eliminated and crop prices rise as irrigation declines. Higher crop prices increase the value of water in irrigation. The implications of a change in irrigated acreage on consumptive water use within each region are based on data in Brown (1999). Average consumptive use per acre varies from about 0.4 to 1.3/af in the more humid regions and from 2.2 to 4.2/af in the more arid regions.

Investing in conservation. The opportunities for curtailing consumptive use of irrigation water through conservation measures are small because most irrigation runoff gets reused downstream. Consequently, irrigation water use may be relatively efficient at the basin level even though water is applied inefficiently at the farm level. The maximum saving in consumptive use through irrigation conservation measures is in the range of 5 percent of the 1995 irrigation baseline (N. Gollehon, personal communication, July 1999). It is assumed that all feasible irrigation conservation was accomplished in the no-climate-change case and that climate change does not result in additional conservation of irrigation water.

Dry tower cooling virtually eliminates both withdrawal and consumptive water uses in the production of thermoelectric power. But this system is about twice as expensive as wet tower cooling, and it results in a loss of thermal efficiency (Miller, 1990). Taking these factors into account, reducing consumptive use through dry tower systems is assumed to cost $440/af ($1,350/mg).

The opportunities and costs of conserving domestic, industrial, and commercial water in the climate change scenarios depend on how much the region has already invested in conservation. For a region that conserved only 5 percent in the no-climate-change case, it is assumed that an additional 5 percent can be saved at an average cost of $110/af ($337/mg). And regions can go from 10 to 16 percent reductions at an average cost of $542/af ($1,663/mg). These cost assumptions allow for the benefits discussed above of reduced water treatment associated with conservation and technological and managerial progress. The costs of reducing an acre-foot of consumptive use through conservation may be 2 to 10 times higher than the withdrawal costs, depending on the conversion factors in Brown (1999).

Developing new supplies. Recycling municipal and industrial wastewater is assumed to be the lowest cost source of new supply. It is assumed that up to 10 percent of these uses can be recycled at an average cost of $400/af ($1,228/mg) (see Table 4.3). Only part of the water that is recycled would represent new supply. About 70 percent of the water that is recycled in California is new supply (California Department of Water Resources, 1998). Using this percentage, recycling produces new supplies at $570/af ($1,774/mg).

If supplies and demand are still not in balance, it is assumed that an unlimited quantity of new water can be developed at $1,000/af ($3,069/mg). In coastal areas and in areas with abundant supplies of brackish water, desalination is a likely source of new supplies. In other areas, water storage projects or imports might be alternative sources of supply.

Changing instream flow. Streamflows are valued as a function of water scarcity using the same values for the no-climate-change case described above.

Net impacts. Table 5.3 reports the unit values of the above cost assumptions accounting for regional variations in consumptive use factors and water applied per acre irrigated. The regional adaptations under the three management scenarios to the changes in water supplies derived from the climate projections of the Canadian model are presented in Tables 5.4 to 5.6. Positive numbers indicate an increase in costs and negative numbers a decrease from the $13.8 billion estimated annual cost of the water use changes projected for the 2030 no-climate-change case. The increased annual costs for the conterminous United States attributable to the sharp reduction in water supplies under the Canadian model range from $105 billion ($308 per person) under the efficient management scenario (Table 5.5) to $251 billion ($736 per person) under the environmental management scenario (Table 5.4). The difference between the two is largely attributable to the need to develop more new supply under the environmental scenario in order to maintain streamflows at desired levels. The more modest protection of streamflows and the limits on reductions in irrigation under the institutional management scenario result in annual cost increases of $171 billion (Table 5.6).

With the Canadian climate and the efficient management scenario, 7 regions incur annual climate-related costs in excess of $2.5 billion each (Table 5.5). These regions combined account for 98 percent of the total increase in annual water costs in the conterminous United States. The 9 eastern water resources regions account for 79 percent of the total cost increase under this management scenario. The South Atlantic-Gulf region alone incurs 50 percent of the cost increase, and the Lower Mississippi accounts for another 17 percent. On a per capita basis, the change in annual water costs associated with this climate and management scenario ranges from a $54 saving in the Great Basin to an increase of $1,991 in the Lower Mississippi.

California and the Great Basin have lower water costs under the Canadian climate and the efficient management scenario. Both regions benefit by transferring some water out of relatively low value irrigation use to higher value instream use. California also benefits from increased water supplies under the Canadian climate scenario.

The higher costs of the environmental and institutional management scenarios result from the need to develop new water supplies in order to satisfy the restrictions placed on supporting instream flows and irrigation levels. For instance, the annual cost of new supplies rises from $45 billion with efficient management to $123 billion with institutional management to $246 billion with the environmental management. In the environmental scenario, 98 percent of the total climate-related increase in water costs is for developing new supplies.

In contrast to the scenarios based on the Canadian climate, water supplies increase and adaptation costs decline relative to the no-climate-change scenario under the Hadley climate (Table 5.7). For the conterminous United States, streamflows increase by nearly 172 bgd and annual water costs decline by nearly $5 billion relative to the no-climate-change case under the Hadley climate and the environmental and efficient management scenarios. The benefits are attributable entirely to the value of increased streamflows. The higher flows result from both the wetter climate projected by the Hadley model and a transfer of water from irrigation to instream use in the Rio Grande, Lower Colorado, and Great Basin water resources regions. The largest transfers of water out of irrigation and consequently the largest reductions in water costs occur in the Lower Colorado. Under the institutional management scenario, the benefits are slightly less because the restriction limiting the amount of water transferred from irrigation to 25 percent of the 1995 baseline becomes effective in the Lower Colorado basin. Otherwise the results for the institutional case are identical to those of the other two scenarios. Consequently, a separate table for this management scenario is not provided.

5.4 Water Scarcity in 2095

This section considers changes in average supply and demand conditions for water between 2030 and 2095 and their socioeconomic implications. The analytical approach is similar to that used above for the period from 1995 to 2030. However, additional simplifying assumptions are introduced reflecting added uncertainties and reduced data to support projections further into the future.

5.4.1 Impacts without climate change

Table 5.8 presents the projected changes between 2030 and 2095 in water withdrawals, irrigated acreage, and streamflows by water resources region. The projections of offstream water use and irrigated acreage to 2095 assume that consumptive water use and irrigated acreage in each region change at the same rates as Brown's projected changes between the years 2030 and 2040 (Table 3.4). The conversion from consumptive use to withdrawals and the breakdown between irrigation and livestock and all other offstream uses as of 2095 assume the regional ratios among these uses are the same as those for 2040 in Brown (1999). Thermoelectric cooling is not treated separately for these longer-term projections. Cooling is not a large consumptive user of water, and as water costs and environmental concerns rise, greater reliance on saline and brackish water and dry cooling technologies are likely to further limit withdrawals and consumption of freshwater for cooling. These assumptions imply a 14 percent increase in total offstream water use over the 65-year period. Renewable water supplies are unchanged in the no-climate-change case. Consequently, increases (decreases) in consumptive use result in corresponding decreases (increases) in streamflow. In the absence of population projections by water resources region for 2095, the projected changes in water use are not differentiated into the effects of conservation measures that would alter per capita use and changes attributable to population growth.

Table 5.9 presents an estimate of the change in annual costs associated with the projected changes in water use, irrigation, and streamflows from 2030 to 2095 presented in Table 5.8. The unit costs of withdrawals and developing new supplies and the values of water for irrigation and instream flows discussed in section 5.3 are assumed to be unchanged between 2030 and 2095. Total annual water costs increase by $23.8 billion over the 65 years, 97 percent of which is for increases in withdrawals. Regionally, the nine eastern water resources regions account for 74 percent and the South Atlantic-Gulf alone accounts for 25 percent of the total cost increase.

The projected increase in annual water costs over the 100 years from 1995 to 2095 without any change in the climate is $37.6 billion in the conterminous United States. Nearly two-thirds of the higher costs are in the nine eastern water resources regions.

5.4.2 Impacts with climate change

The climate-induced changes in renewable water supplies as of 2095 are based on projections from the Canadian and Hadley general circulation models (Table 3.9). The Canadian model indicates that seven of the nine eastern water resources regions will be even drier in 2095 than in 2030 (Table 3.9). The exceptions are the Great Lakes region, which is slightly wetter, and Upper Mississippi, which is projected to become significantly wetter. In contrast to the general picture in the East, all nine western water resources regions are projected to be wetter in 2095 than in 2030. Moreover, with the exception of the Rio Grande, the Canadian model suggests that the West will be even wetter in 2095 than in the 1995 base year.

Under the Hadley model, renewable water supplies increase between 2030 and 2095 in all regions except the Texas-Gulf and the Pacific Northwest. The Texas-Gulf is the only region where renewable supplies are projected to decline over the 100 years.

The economic implications of these climate-induced changes in supplies are estimated for the environmental, efficient, and institutional management scenarios described above. The options for adapting to changes in renewable supplies are removing land from irrigation, developing new supplies, and changing instream flows. The costs per unit of water of these options are assumed to be unchanged between 2030 and 2095 and are described in section 5.3.2.

The changes in annual water costs for 2095 that are attributable to climate change are presented in tables 5.10 to 5.12 for the Canadian climate and in Table 5.13 for the Hadley climate. Under the Canadian climate, annual water costs for the conterminous 48 states increase under all three management scenarios. The annual cost increases range from $97 billion under the efficient management to $211 billion under the environmental management scenario. Regionally, the climate-related cost impacts vary widely. Under the efficient management scenario, for instance, annual costs are $103 billion higher in the nine eastern water resources regions but $7 billion lower in the nine western regions as a result of the Canadian climate. The South Atlantic-Gulf region is again the big loser with climate-related increases in annual water costs of nearly $86 billion (Table 5.11).

The increase in water supplies projected by the Hadley model reduces the costs from the no-climate-change levels of adapting to changing supply and demand conditions. Under both the environmental and efficient management scenarios, annual water costs as of 2095 are nearly $11 billion less under the Hadley climate. All of the benefits are attributable to the increase in streamflows. The constraint on reducing irrigation under the institutional management scenario limits the ability of the Texas-Gulf region to adapt, resulting in slightly higher regional and national water costs than under the other two management scenarios.

6. SUMMARY AND CONCLUSIONS

The large investments in dams, reservoirs, and other water-related infrastructure help protect against floods and droughts and meet growing water demands. Nevertheless, floods and droughts continue to impose progressively higher costs on the country and water is becoming increasingly scarce and expensive.

The prospect of an anthropogenically induced climate change introduces new uncertainties and potential stresses. Climate influences both the variability and availability of water. A change in the climate could alter the magnitude and frequency of floods and droughts and the costs of balancing future water supplies and demands. The socioeconomic costs of floods, droughts, and water scarcity in the years 2030 and 2095 are examined under three climate scenarios: continuation of the current climate and two climate-change scenarios based on projections from the respective results of the Canadian and the Hadley general circulation models. The implications of these models on future renewable water supplies are strikingly different. Streamflow projections based on the Canadian model show most of the country becoming drier while those based on the Hadley model show most of the country becoming wetter. The GCMs do not project how a greenhouse warming might alter climatic and hydrologic variability.

Flood damages have been rising over time and are likely to continue rising in spite of improved forecasting as floodplain development places more people and property at risk. A continuation of past growth rates suggests average annual direct flood damages might increase from about $5 billion in 1995 to $8 billion by 2030 to $18 billion by 2095. The changes in average annual streamflows derived from the Canadian and Hadley models would likely have very different implications for future floods even in the absence of any change in the frequency and severity of extreme hydrologic events. Damages would likely decline under the Canadian and rise under the Hadley projections.

Drought damages are likely to rise as water resources become increasingly scarce and some water supply systems have less capacity to compensate for shortfalls. Lacking comprehensive estimates of past drought costs, there is no good basis for estimating future drought impacts with or without climate change. However, hydrologic projections based on the Canadian model suggest droughts would become more frequent and severe while projections based on the Hadley model suggest droughts might be less frequent and communities might have more capacity to deal with short-term reductions in supply.

The Second National Water Assessment’s framework for assessing the adequacy of water supplies to meet both withdrawal and instream uses is used to develop measures of current and future water scarcity under alternative conditions in the 18 major water resources regions and 99 assessment subregions in the conterminous United States. That framework is initially used to examine water scarcity in the 1995 base year and subsequently to assess the adequacy of supplies to meet consumptive and instream uses on a sustainable basis in the years 2030 and 2095 with and without climate change.

Climate is only one of many factors affecting future water conditions. Changes in population, incomes, technology, and numerous other non-climate factors will make the world in 2030 and 2095 different from that of today. Thus, developing future baselines against which the climate impacts can be measured is the first step in assessing the impacts of climate change. Projections of water use in the year 2030 in the absence of climate change are based on a U.S. Forest Service study of past and future freshwater use in the United States (Brown, 1999). Projections for the year 2095 assume a continuation of the growth rates between 2030 and 2040 in the Forest Service study.

The socioeconomic impacts of hydrologic extremes and water scarcity depend in part on the infrastructure available to control and distribute water, the costs of nontraditional sources of supply, water management practices, conservation opportunities, the nature of the economy, slack in the system, and institutions influencing water use. Past and likely future changes in these factors are examined and provide the basis for evaluating the impacts of changes in both climate and non-climate factors on U.S. water resources. Providing for these future water uses involves developing new supplies, introducing conservation measures, foregoing some water uses, and changing streamflows. Estimates of the costs of meeting these future water uses are based on current costs and conservation opportunities with adjustments for future changes in technology, management practices, and energy prices.

The impacts of the climate changes are calculated as the changes in the costs of maintaining the projected no-climate-change, non-irrigation offstream water uses with the climate-altered supplies. When renewable supplies decline as a result of a change in the climate, these offstream uses are maintained by developing new supplies, investing more in water conservation, removing land from irrigation, and reducing streamflows. Increases in supplies are reflected in higher streamflow values. The costs and benefits of the climate-induced changes in water supplies are estimated under three alternative management strategies that differ in the protection provided for streamflows and irrigation.

The estimated changes in annual water costs from the 1995 baseline for the nine eastern and nine western water resources regions and the conterminous 48 states under the three climate scenarios and the efficient management strategy are summarized in Table 6.1. This table highlights the sensitivity of the costs to the various climate scenarios and the large regional differences in the projected changes. The increases in water costs are notably higher in the eastern United States under both climate-change scenarios. But the cost increases in both the East and West under the Canadian climate from 1995 to 2030 and 2095 are about an order of magnitude higher than under the Hadley climate.

The projections of future water scarcity and costs involve multiple uncertainties (Frederick, et al., 1997). First is the problem of developing a baseline of what the future would be in the absence of any change in the climate. Changes in population, incomes and other economic factors, technologies influencing both the supply and demand for water, social values regarding the environment and alternative water uses, and institutions that provide the incentives and opportunities to use the resource will make future water conditions different from the present.

Second, there are uncertainties as to how the climate might change and how these changes might affect the supply and demand for water at geographic scales relevant for water planners and managers. GCM predictions of large-scale regional atmospheric and surface variables such as temperature and precipitation are scaled down to water resources regions and subregions. Hydrologic models are then used to estimate the impacts of the climate variables on streamflows. And renewable water supplies are then adjusted for estimated evaporation losses from dams and reservoirs under the alternative climates.

Third, there are uncertainties as to how society can and will adapt to changes in the climate and hydrology. The projections of future water costs associated with alternative climate scenarios allow for technological advances and illustrate the potential role of alternative management strategies, but the uncertainties 30 and 100 years in the future are enormous.

The various steps underlying the projections of water supplies, use, and costs are based on a multitude of assumptions with varying degrees of uncertainty. In addition, the analysis and projections leave out some potentially important factors that could affect the socioeconomic costs of climate change on water resources. For example, there is no allowance for the impacts of the climate on water demands, intra-annual changes in supplies and demands, and water quality. On balance, omitting these factors probably understates the costs of the reduction in supplies predicted for the Canadian climate model. On the other hand, the analysis likely understates the ability of society to adapt to changes in hydrologic conditions. For instance, the projections do not allow for the use of non-renewable water supplies and migration among water resources regions as means of adapting to climate-induced changes. And technological and managerial developments yet to be imagined are likely to facilitate adaptation to changing hydrologic conditions over the next century.

These shortcomings of the analysis and the uncertainties surrounding the long-term projections of future climate conditions, the impacts of the climate on the supply and demand for water, and how society adapts suggest that the specific cost projections presented in section 5 and Table 6.1 should be viewed cautiously. Nevertheless, the results support several general conclusions. First, a greenhouse warming could have major impacts on the future costs of floods, droughts, and balancing water demands and supplies. Second, the contrasting hydrologic implications of the Canadian and Hadley climate models indicate that the magnitude as well as the direction of these impacts are uncertain and likely to vary significantly among water resources regions. Third, there are many opportunities to adapt to changing hydrological conditions, and the net costs are particularly sensitive to the institutions that determine how the resource is managed and allocated among users.

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Table 3.1 Mean and Dry Condition Renewable Water Supplies for the 1995 Baseline (in millions of gallons per day)

Region	Mean renewable supply	Dry condition renewable supply
New England	78,661	63,116
Mid-Atlantic	81,001	62,739
South Atlantic-Gulf	211,638	152,352
Great Lakes	75,281	59,309
Ohio	180,111	142,672
Tennessee	41,113	36,175
Upper Mississippi	134,219	101,026
Lower Mississippi	453,702	293,157
Souris-Red-Rainy	6,763	4,056
Missouri	56,180	36,370
Arkansas-White-Red	64,356	37,106
Texas-Gulf	33,555	13,387
Rio Grande	4,549	406
Upper Colorado	12,138	7,979
Lower Colorado	8,884	6,944
Great Basin	5,782	3,646
Pacific Northwest	266,403	222,289
California	71,201	45,908

Sources: mean and dry condition (80 percent exceedance) renewable supply in 1975 (U.S. Water Resources Council, 1978) with reservoir evaporation modified according to the change in storage in large reservoirs (volume greater than 5,000 acre feet) between 1975 and 1995 (U.S. Army Corps of Engineers, 1996).

Table 3.2 Cumulative Consumptive Use, Desired Instream Use, Desired Water Use, and Critical Water Use for the 1995 Baseline (in millions of gallons per day)

Region	Cumulative consumptive use[1]	Desired instream use	Desired water use	Critical water use
New England	407	69,001	69,408	34,908
Mid-Atlantic	1,152	68,840	69,992	35,572
South Atlantic-Gulf	5,569	188,655	194,224	99,897
Great Lakes	1,580	63,951	65,531	33,556
Ohio	2,156	160,520	162,676	82,416
Tennessee	289	38,480	38,769	19,529
Upper Mississippi	15,858	110,750	126,608	71,233
Lower Mississippi	33,941	359,033	392,974	213,458
Souris-Red-Rainy	122	3,673	3,795	1,959
Missouri	14,193	33,958	48,151	31,172
Arkansas-White-Red	8,187	46,169	54,356	31,272
Texas-Gulf	7,341	22,917	30,258	18,799
Rio Grande	2,959	2,287	5,246	4,102
Upper Colorado	2,517	7,947	10,464	6,491
Lower Colorado	7,039	6,864	13,903	10,471
Great Basin	3,256	3,389	6,645	4,950
Pacific Northwest	10,571	214,004	224,575	117,573
California	25,270	32,607	57,877	41,574

[1] Value includes consumptive use within the region and all upstream regions.

Sources: 1995 consumptive use (Solley et al., 1998); desired water use is the sum of 1995 consumptive use and 1975 desired instream flow (U.S. Water Resources Council, 1978); critical water use is the sum of 1995 consumptive use and 50 percent of 1975 desired instream flow.

Table 3.3 Water Scarcity Indices for Mean and Dry Condition Renewable Supply for the 1995 Baseline (in percent)

Region	Ratio of desired use to mean renewable supply	Ratio of critical use to mean renewable supply	Ratio of critical use to dry condition renewable supply
New England	88	44	55
Mid-Atlantic	86	44	57
South Atlantic-Gulf	92	47	66
Great Lakes	87	45	57
Ohio	90	46	58
Tennessee	94	48	54
Upper Mississippi	94	53	71
Lower Mississippi	87	47	73
Souris-Red-Rainy	56	29	48
Missouri	86	55	86
Arkansas-White-Red	84	49	84
Texas-Gulf	90	56	140
Rio Grande	115	90	1,011
Upper Colorado	86	53	81
Lower Colorado	156	118	151
Great Basin	115	86	136
Pacific Northwest	84	44	53
California	81	58	91

Source: see text and Tables 3.1 and 3.2.

Table 3.4 Projected Changes in Consumptive Water Use from 1995 to 2030 and 2095 (in percent)

Region	Change in consumptive use 1995-2030	Change in consumptive use 1995-2095
New England	6	44
Mid-Atlantic	3	27
South Atlantic-Gulf	22	63
Great Lakes	3	26
Ohio	4	27
Tennessee	18	71
Upper Mississippi	14	50
Lower Mississippi	40	92
Souris-Red-Rainy	39	102
Missouri	-1	1
Arkansas-White-Red	-12	-18
Texas-Gulf	-9	-6
Rio Grande	-23	-32
Upper Colorado	27	43
Lower Colorado	2	14
Great Basin	7	1
Pacific Northwest	-10	-19
California	-3	-4

Source: changes to 2030 are from Brown (1999); changes to 2095 are extrapolated from trends reported by Brown (1999) for the period 2030 to 2040.

Table 3.5 Water Scarcity Indices for Mean and Dry Conditions for the Year 2030 without Climate Change (in percent)

Region	Ratio of desired use to mean renewable supply	Ratio of critical use to mean renewable supply	Ratio of critical use to dry condition renewable supply
New England	88	44	55
Mid-Atlantic	86	44	57
South Atlantic-Gulf	92	48	66
Great Lakes	87	45	57
Ohio	90	46	58
Tennessee	94	48	54
Upper Mississippi	94	53	71
Lower Mississippi	87	48	74
Souris-Red-Rainy	57	30	49
Missouri	86	55	85
Arkansas-White-Red	83	47	82
Texas-Gulf	88	54	135
Rio Grande	100	75	841
Upper Colorado	92	59	90
Lower Colorado	165	127	162
Great Basin	119	90	142
Pacific Northwest	84	44	52
California	80	57	89

Source: see text and Tables 3.1-3.4.

Table 3.6 Water Scarcity Indices for Mean and Dry Conditions for the Year 2095 without Climate Change (in percent)

Region	Ratio of desired use to mean renewable supply	Ratio of critical use to mean renewable supply	Ratio of critical use to dry condition renewable supply
New England	88	45	56
Mid-Atlantic	87	44	57
South Atlantic-Gulf	93	49	68
Great Lakes	88	45	57
Ohio	91	46	58
Tennessee	95	48	55
Upper Mississippi	95	54	71
Lower Mississippi	88	49	75
Souris-Red-Rainy	58	31	51
Missouri	86	56	86
Arkansas-White-Red	82	46	80
Texas-Gulf	89	55	137
Rio Grande	95	70	780
Upper Colorado	95	62	95
Lower Colorado	176	138	176
Great Basin	116	86	137
Pacific Northwest	84	43	52
California	80	57	88

Source: see text and Tables 3.1-3.5.

Table 3.7 Projected Changes in Natural Streamflows, Evaporation Losses, and Renewable Water Supplies under Alternative Climate Scenarios, 1995-2030 (in percent)

	Canadian Climate Model			Hadley Climate Model		
Region	Change in natural streamflow	Change in reservoir net evaporation	Change in renewable supply	Change in natural streamflow	Change in reservoir net evaporation	Change in renewable supply
New England	-8	0	-8	9	0	9
Mid-Atlantic	-13	0	-13	9	0	9
South Atlantic-Gulf	-67	0	-67	0	0	0
Great Lakes	-12	0	-12	20	0	20
Ohio	-21	0	-21	6	0	6
Tennessee	-33	0	-33	4	0	4
Upper Mississippi	-23	2	-23	20	0	21
Lower Mississippi	-33	3	-34	5	0	5
Souris-Red-Rainy	-24	3	-22	-18	2	-17
Missouri	-25	2	-27	18	0	20
Arkansas-White-Red	-40	4	-42	-1	1	-1
Texas-Gulf	-92	6	-98	-3	2	-3
Rio Grande	-63	1	-73	-3	1	-4
Upper Colorado	-36	3	-41	7	0	8
Lower Colorado	-38	2	-68	23	0	40
Great Basin	-9	1	-9	14	-1	15
Pacific Northwest	-2	5	-2	16	-6	16
California	28	-16	27	28	-14	27

Sources: natural streamflow and reservoir evaporation modified from 1995 values (see Table 3.1) according to changes in runoff and net evaporation under the Canadian and Hadley climate models (Wolock and McCabe, 1999).

Table 3.8 Projected Changes in Natural Streamflows, Evaporation Losses, and Renewable Water Supplies under Alternative Climate Scenarios, 1995-2095 (in percent)

	Canadian Climate Model			Hadley Climate Model		
Region	Change in natural streamflow	Change in reservoir net evaporation	Change in renewable supply	Change in natural streamflow	Change in reservoir net evaporation	Change in renewable supply
New England	-19	0	-19	28	0	28
Mid-Atlantic	-25	0	-25	33	0	33
South Atlantic-Gulf	-80	0	-80	33	0	33
Great Lakes	-9	0	-9	56	0	56
Ohio	-23	0	-23	42	0	42
Tennessee	-37	0	-37	40	0	40
Upper Mississippi	17	-1	17	60	-1	62
Lower Mississippi	-17	-1	-18	41	-1	42
Souris-Red-Rainy	-80	7	-73	79	-4	72
Missouri	48	-1	53	45	-1	50
Arkansas-White-Red	6	-1	7	44	-3	46
Texas-Gulf	1	2	1	-19	2	-20
Rio Grande	-56	1	-66	60	1	69
Upper Colorado	5	1	5	66	-4	76
Lower Colorado	3	1	4	151	-7	270
Great Basin	59	-9	61	187	-13	194
Pacific Northwest	20	-7	20	14	-4	14
California	150	-106	144	126	-81	122

Sources: natural streamflow and reservoir evaporation modified from 1995 values (see Table 3.1) according to changes in runoff and net evaporation under the Canadian and Hadley climate models (Wolock and McCabe, 1999).

Table 3.9 Water Scarcity Indices for the Year 2030 With Projections from the Canadian Climate Model (in percent)

Region	Ratio of desired use to mean renewable supply	Ratio of critical use to mean renewable supply	Ratio of critical use to dry condition renewable supply
New England	96	48	60
Mid-Atlantic	99	51	65
South Atlantic-Gulf	280	145	201
Great Lakes	98	50	64
Ohio	114	58	73
Tennessee	140	71	80
Upper Mississippi	123	69	92
Lower Mississippi	132	72	112
Souris-Red-Rainy	73	38	62
Missouri	117	76	120
Arkansas-White-Red	143	81	145
Texas-Gulf	4,140	2,537	-1,933
Rio Grande	374	280	-1,022
Upper Colorado	156	101	161
Lower Colorado	511	392	675
Great Basin	131	99	157
Pacific Northwest	86	45	54
California	63	45	71

Sources: see text and Tables 3.4 and 3.7.

Table 3.10 Water Scarcity Indices for the Year 2030 with Projections from the Hadley Climate Model (in percent)

Region	Ratio of desired use to mean renewable supply	Ratio of critical use to mean renewable supply	Ratio of critical use to dry condition renewable supply
New England	81	41	51
Mid-Atlantic	79	40	52
South Atlantic-Gulf	92	48	66
Great Lakes	72	37	47
Ohio	85	43	54
Tennessee	91	46	52
Upper Mississippi	78	44	58
Lower Mississippi	83	45	70
Souris-Red-Rainy	68	36	59
Missouri	71	46	71
Arkansas-White-Red	84	47	82
Texas-Gulf	91	56	141
Rio Grande	104	78	948
Upper Colorado	85	55	83
Lower Colorado	118	90	112
Great Basin	104	78	124
Pacific Northwest	72	38	45
California	63	45	71

Sources: see text and Tables 3.4 and 3.7.

Table 3.11 Water Scarcity Indices for the Year 2095 with Projections from the Canadian Climate Model (in percent)

Region	Ratio of desired use to mean renewable supply	Ratio of critical use to mean renewable supply	Ratio of critical use to dry condition renewable supply
New England	110	55	69
Mid-Atlantic	115	59	76
South Atlantic-Gulf	470	246	341
Great Lakes	96	49	63
Ohio	118	60	76
Tennessee	150	76	86
Upper Mississippi	81	46	61
Lower Mississippi	107	59	91
Souris-Red-Rainy	214	114	160
Missouri	56	37	56
Arkansas-White-Red	77	43	75
Texas-Gulf	88	54	136
Rio Grande	280	205	-1,200
Upper Colorado	90	59	90
Lower Colorado	169	132	168
Great Basin	72	53	84
Pacific Northwest	69	36	43
California	33	23	37

Sources: see text and Tables 3.4 and 3.8.

Table 3.12 Water Scarcity Indices for the Year 2095 with Projections from the Hadley Climate Model (in percent)

Region	Ratio of desired use to mean renewable supply	Ratio of critical use to mean renewable supply	Ratio of critical use to dry condition renewable supply
New England	69	35	43
Mid-Atlantic	66	33	43
South Atlantic-Gulf	70	37	51
Great Lakes	56	29	37
Ohio	64	32	41
Tennessee	68	34	39
Upper Mississippi	59	33	44
Lower Mississippi	62	34	53
Souris-Red-Rainy	34	18	31
Missouri	57	37	57
Arkansas-White-Red	56	32	54
Texas-Gulf	111	68	175
Rio Grande	56	41	290
Upper Colorado	54	35	52
Lower Colorado	48	37	44
Great Basin	39	29	46
Pacific Northwest	73	38	46
California	36	26	40

Sources: see text and Tables 3.4 and 3.8.

Table 4.1 Dams and Reservoirs Completed in the United States, 1961-1995

Period of completion	Number of dams	Storage (maf)	Average annual number of dams	Average annual storage (maf)
1961-1965	9,687	105.8	1,937	21.1
1966-1970	9,401	146.1	1,880	29.2
1971-1975	6,628	54.0	1,326	10.8
1976-1980	3,957	41.4	791	8.3
1981-1985	2,269	17.5	453	3.5
1986-1990	2,139	14.2	428	2.8
1991-1995	1,044	4.7	209	0.9

Source: Calculated from data in U.S. Army Corps of Engineers, 1996.

Note: Includes dams at least 6 feet high with at least 25 acre-feet of storage, or at least 25 feet in height with at least 15 acre-feet of storage.

Table 4.2 Alternatives for Increasing Potable Water Supplies: Costs and Potential

Supply Alternative	Costs (1995$/acre-foot)	Potential contribution to water supplies
Dams & reservoirs	vary widely $500 - $1,000+	Large economies of scale but environmental and political factors limit new large projects. Offstream storage and small-scale projects competitive in some regions. Sedimentation reduces storage of existing reservoirs
Recycling	$240-$2,000 ~$125 to go from secondary to advanced treatment	Costs vary with treatment process, intended reuse, and plant capacity. Competitive source of supply for some uses, especially for water that has undergone secondary treatment to meet environmental regulations. Expected to add ~1% to California's water supplies by 2020. Federal cost sharing available.
Desalination	$1,000 - $2,000 for seawater $750+ for brackish water	Seawater unlimited in coastal areas but high costs and environmental concerns over siting of plants and deposition of brine make this a source of last resort. Desalting brackish water becoming competitive in some areas for high value uses.
Weather modification	$8 - $15	2 – 15% increase in precipitation in test areas. Limited geographic application with current scientific knowledge. Institutional obstacles could also limit use.
Interbasin transfers	West $600+ East $300+	Transfers water among areas without adding to total supplies. Environmental and political obstacles add to costs and limit opportunities.
Vegetation management	?	Potential limited to few areas. Environmental concerns and conflicts with other land uses are potential conflicts.
Integrated basin management	potentially low where current management is inefficient	Opportunities unstudied but potentially large. Existing laws, regulations, and vested interests are barriers to improved management.

Note: These costs are estimates based on current technologies and management practices.

Source: See the text.

Table 4.3. Estimated Water Reclamation Treatment Costs

Treatment Process	Cost (1995 $ per acre-foot)	Recommended Reuse Alternative
Activated sludge	242 - 670	Agricultural irrigation
Trickling filter	263 - 699	Livestock and wildlife watering Power plant and industrial once-through cooling
Rotating biological contactors	373 - 715	Urban irrigation landscape Industrial supply - primary metals, petroleum and coal products
Activated sludge, filtration of secondary effluent	286 - 888	Recreation -secondary contact Power plant and industrial cooling - recirculation Industrial supply - paper and allied products
Tertiary lime treatment	397 - 1,311	Recreation - primary contact
Tertiary lime, nitrified effluent	405 - 1,449	Industrial boiler make-up - low pressure
Tertiary lime plus ion exchange	515 - 1,498	Fisheries Industrial supply - chemicals and allied products
Activated sludge, filtered secondary effluent, carbon adsorption	382 - 1,180	Industrial supply - food and kindred products
Tertiary lime, carbon adsorption, ion exchange	613 - 1,924	Industrial boiler make-up - intermediate pressure

Source: Adapted from Richard et al., 1992.

Notes: Costs include amortized capital costs based on a facility life of 20 years and a return of 7 percent plus operation and maintenance costs. The lower cost estimates within each treatment process are for 50 Mgal/day plants and the higher costs are for 1 Mgal/day plants. Costs have been converted to 1995 dollars using the construction cost index.

Table 4.4 Seattle's Conservation Potential Assessment Packages

Package	Savings in mgd	Savings as % of projected peak season demand	Average annual cost (millions 1997$)	Average cost ($/acre-foot)	Marginal cost ($/acre-foot)
5% savings	9	5	0.3	152	327
10% savings	19	10	2	375	867
Cost- effective savings	31	16	5	662	1,041
Technical potential	43	22	19	1,681	59,242

Source: Seattle Public Utilities, 1998.

Table 4.5 Water Savings under Seattle's Cost-Effective Conservation Package - Selected Measures

Conservation measure	Peak season Savings (mgd)	Savings as % of projected program area demand	Average cost ($/acre-foot)
Improve irrigation scheduling	1.42		305
Improve irrigation system performance	2.27		984
Allow lawn to go dormant	0.62		109
Install auto rain shut off	0.68		871
Install low water use plantings	0.26		575
Install soil moisture sensor	0.54		836
TOTAL: Residential Landscape	5.79	33	680
Decrease toilet flushes	1.57		388
Decrease faucet use	1.93		318
Decrease shower use	2.69		227
Eliminate partial cloths washer loads	0.87		449
Install redesigned toilet flappers	2.71		462
Install 1.6 gallon per flush toilets	4.13		1,041
Switch to recirculating car wash	0.33		462
Dry sidewalk cleaning	0.26		645
Improve swimming pool & hot tub use	0.22		241
TOTAL: Residential Domestic	14.70	12	553
TOTAL: Commercial Landscape	1.00	22	640
Install 1 gallon per flush urinals	0.41		775
Install 1.6 gallon per flush toilets	1.35		571
Install waterless urinals	0.33		1,028
Improve swimming pool & hot tub use	0.13		83
TOTAL: Commercial Domestic	2.21	17	649
Improve control of process water	0.94		971
Improve cooling tower performance	1.15		436
Switch to air cooling	4.30		984
Recycle laundry washwater	0.39		841
Water efficient clothes washers	0.29		719
Eliminate single pass decorative use	0.02		30
TOTAL: Commercial Process	7.09	18	871
TOTAL EFFICIENT PACKAGE	30.79	16	662

Source: Seattle Public Utilities, 1998

Table 4.6 Costs of Conserving Water in Selected Areas

Conservation Projects	1995 $ per acre-foot
(1) Reducing Distribution Losses	
Imperial Irrigation District projects[1]	
Spill interceptor canals	22
Lining main canals	48-105
Lining All-American canal	174-178
Reducing canal spills	42-155
Massachusetts Water Resources Authority[2]	
Leak detection and repair	53
(2) Adopting water-efficient technologies	
Imperial Irrigation District projects[1]	
Tailwater recovery	12-39
Massachusetts Water Resources Authority[2]	
Industrial and commercial conservation	18
Domestic device retrofit	86-210
Low-flow toilet retrofit	1,237
Marin Municipal Water District[3]	
Low-flow flush toilets	191
Horizontal-axis washing machines	702
(3) Adopting less water-using practices	
Metropolitan Water District of Southern California[4]	
Commercial, industrial, and institutional audits	136
Marin Municipal Water District[3]	
Irrigation scheduling reminders	206
Landscape personnel training	440
Multifamily audits	543
Cooling tower workshops	577
Single-family audits	592
Commercial, industrial, and institutional audits	649
Large landscape audits	722
Swimming pool seminars	781

Sources:
1. Wahl and Davis, 1986.
2. Massachusetts Water Resources Authority, 1990.
3. Owens-Viani, 1999.
4. Wilkinson and Wong, 1999.

Note: Cost estimates are converted to 1995 dollars using the construction cost index.

Table 5.1 Change in Water Withdrawals and Conservation by Use, Acres Irrigated, Population, and Streamflow, 1995-2030

	Withdrawals (MGD)			Conservation[1] (MGD)				
Region	Irrigation and livestock	Thermo-electric	Other[2]	Irrigation	Other[2]	Acres irrigated (thousands)	Population (millions)	Streamflow (MGD)
New England	-8	123	285	-14	-249	0	3.8	-3
Mid-Atlantic	25	62	577	-40	-1,279	40	9.3	-217
South Atlantic-Gulf	831	3,002	2,505	-442	-1,352	856	15.3	-3,252
Great Lakes	73	132	-35	-5	-1,909	114	4.6	-106
Ohio	93	311	-635	-18	-2,277	169	4.8	-134
Tennessee	81	1,007	163	-18	-382	33	1.3	-51
Upper Mississippi	166	542	259	-25	-600	277	5.7	-1,728
Lower Mississippi	3,496	201	160	579	-863	1,879	1.8	-12,915
Souris-Red-Rainy	42	2	13	14	-8	44	0.1	-48
Missouri	-449	837	466	-576	-181	0	3.1	-1,493
Arkansas-White-Red	-1,289	254	375	-374	-251	-677	2.4	-3,184
Texas-Gulf	-949	691	988	-405	-410	-474	5.2	-3,653
Rio Grande	-1,548	2	173	-650	-36	-191	1.1	134
Upper Colorado	1,562	26	60	312	-20	299	0.3	-683
Lower Colorado	-281	19	624	-843	-115	106	2.7	-1,197
Great Basin	47	5	370	200	-72	-63	1.3	-1,010
Pacific Northwest	-2,253	1,050	825	1,040	-902	-1,063	3.9	-4
California	-1,423	74	1,994	-688	-599	-298	12.4	1
Conterminous U.S.	-1,783	8,339	9,167	-1,954	-11,503	1,051	79	-29,541

[1] Irrigation conservation is the change in irrigation withdrawals per acre, 1995 to 2030, times irrigated acreage in 2030; other conservation is the change in other withdrawals per capita, 1995 to 2030 times population in 2030. A negative value denotes improved conservation.

[2] Other includes domestic, public, industrial, and commercial uses.

Sources: Solley et al. (1998) and Brown (1999).

Table 5.2 Estimated Annual Costs of Changes in Water Use, 1995 to 2030, without Climate Change (in millions of 1995 dollars)

	Cost of Increased Withdrawals			Cost of Conservation				
Region	Irrigation and livestock	Thermo-electric	Other	Irrigation	Other	Cost of irrigation foregone use	Cost of change in streamflow	Total cost
New England	0	17	128	0	41	0	0	187
Mid-Atlantic	1	9	259	1	212	0	1	483
South Atlantic-Gulf	47	420	1,403	12	224	0	15	2,122
Great Lakes	4	19	0	0	808	0	0	832
Ohio	5	43	0	1	965	0	1	1,014
Tennessee	5	141	91	1	162	0	0	399
Upper Mississippi	9	76	145	1	254	0	396	882
Lower Mississippi	196	28	72	0	366	0	59	720
Souris-Red-Rainy	2	0	4	0	0	0	1	8
Missouri	0	117	209	16	0	0	342	684
Arkansas-White-Red	0	36	168	10	42	34	74	364
Texas-Gulf	0	97	443	11	0	24	646	1,220
Rio Grande	0	0	194	18	0	10	-90	132
Upper Colorado	88	4	34	0	0	0	157	281
Lower Colorado	0	3	699	24	0	0	800	1,526
Great Basin	3	1	415	0	0	3	676	1,097
Pacific Northwest	0	147	370	0	382	53	0	952
California	0	10	894	19	0	15	0	938
Conterminous U.S.	359	1,168	5,527	115	3,456	138	3,078	13,841

Source: see text.

Table 5.3 Unit Costs of Foregone Irrigation Water Use, the Conservation of Thermoelectric and Other Uses, and the Production of New Supply (in 1995 dollars per million gallons consumption saved)

	Foregone Irrigation				Conservation of Other		New Supply	
Region	Reductions of 0 to 50 percent	Reductions of 50 to 80 percent	Reductions of 80 to 100 percent	Thermoelectric conservation	Reductions of 0 to 10 percent	Reductions of 10 to 16 percent	Recycle	Desalination
New England	110	220	1,100	1,351	2,821	13,898	1,750	3,070
Mid-Atlantic	250	500	2,498	1,351	4,411	21,733	1,750	3,070
South Atlantic-Gulf	169	337	1,686	1,351	2,017	9,936	1,750	3,070
Great Lakes	260	521	2,604	1,351	4,145	20,422	1,750	3,070
Ohio	349	698	3,490	1,351	2,835	13,968	1,750	3,070
Tennessee	163	326	1,628	1,351	3,116	15,354	1,750	3,070
Upper Mississippi	334	669	3,343	1,351	1,847	9,103	1,750	3,070
Lower Mississippi	127	255	1,273	1,351	1,531	7,546	1,750	3,070
Souris-Red-Rainy	260	520	2,600	1,351	1,468	7,235	1,750	3,070
Missouri	142	283	1,416	1,351	1,154	5,686	1,750	3,070
Arkansas-White-Red	125	250	1,249	1,351	1,325	6,527	1,750	3,070
Texas-Gulf	122	243	1,216	1,351	922	4,541	1,750	3,070
Rio Grande	75	150	749	1,351	751	3,702	1,750	3,070
Upper Colorado	97	194	972	1,351	1,101	5,424	1,750	3,070
Lower Colorado	54	107	536	1,351	700	3,448	1,750	3,070
Great Basin	74	148	739	1,351	880	4,336	1,750	3,070
Pacific Northwest	92	183	917	1,351	3,365	16,579	1,750	3,070
California	58	117	583	1,351	1,375	6,775	1,750	3,070

Source: see text.

Table 5.4 Year 2030 Changes in Water Use and Supply and Associated Annual Costs Attributable to Climate Change Predicted by the Canadian Climate Model under the Environmental Management Scenario

	Change in Water Quantity (millions of gallons per day)				Change in Cost (millions of 1995 dollars)				
Region	Foregone irrigation	Conser-vation[1]	New supply	Streamflow	Foregone irrigation	Conser-vation[1]	New supply	Streamflow	Total
New England	0	0	0	-6,013	0	0	0	27	27
Mid-Atlantic	0	0	0	-10,521	0	0	0	48	48
South Atlantic-Gulf	3,581	412	121,605	-16,213	683	203	136,167	74	137,127
Great Lakes	0	0	0	-8,686	0	0	0	39	39
Ohio	123	916	7,991	-17,301	22	452	8,916	78	9,468
Tennessee	64	0	11,025	-2,293	12	0	12,344	10	12,367
Upper Mississippi	436	393	15,958	-7,469	73	194	17,849	34	18,150
Lower Mississippi	8,190	278	26,452	-58,329	1,179	137	29,596	265	31,177
Souris-Red-Rainy	0	0	0	-1,502	0	0	0	35	35
Missouri	7,126	0	0	-8,122	408	0	0	190	597
Arkansas-White-Red	5,967	187	9,929	-10,957	843	92	11,094	256	12,285
Texas-Gulf	4,287	305	24,290	-3,958	590	142	27,126	92	27,950
Rio Grande	1,962	35	1,334	0	166	13	1,478	0	1,657
Upper Colorado	2,828	153	1,035	-991	311	75	1,156	23	1,566
Lower Colorado	3,482	123	100	1,712	211	49	64	-1,145	-821
Great Basin	1,637	0	0	1,097	50	0	0	-251	-202
Pacific Northwest	0	0	0	-5,542	0	0	0	129	129
California	10,864	0	0	29,999	231	0	0	-701	-470
Conterminous U.S.	50,547	2,801	219,719	-125,090	4,779	1,357	245,789	-796	251,129

[1] Conservation of thermoelectric, domestic, public, industrial, and commercial uses.

Source: see text.

Table 5.5 Year 2030 Changes in Water Use and Supply and Associated Annual Costs Attributable to Climate Change Predicted by the Canadian Climate Model under the Efficient Management Scenario

	Change in Water Quantity (millions of gallons per day)				Change in Cost (millions of 1995 dollars)				
Region	Foregone irrigation	Conservation[1]	New supply	Streamflow	Foregone irrigation	Conservation[1]	New supply	Streamflow	Total
New England	0	0	0	-6,013	0	0	0	27	27
Mid-Atlantic	0	0	0	-10,521	0	0	0	48	48
South Atlantic-Gulf	3,581	412	27,277	-110,541	683	203	30,469	21,696	53,052
Great Lakes	0	0	0	-8,686	0	0	0	39	39
Ohio	77	0	0	-37,292	10	0	0	4,661	4,671
Tennessee	52	0	0	-13,331	4	0	0	2,541	2,545
Upper Mississippi	273	0	0	-23,984	33	0	0	3,820	3,853
Lower Mississippi	6,552	0	0	-134,512	418	0	0	17,728	18,147
Souris-Red-Rainy	0	0	0	-1,502	0	0	0	35	35
Missouri	7,126	0	0	-8,122	408	0	0	190	597
Arkansas-White-Red	4,774	0	0	-22,267	299	0	0	2,848	3,148
Texas-Gulf	4,287	305	12,832	-15,417	590	142	14,286	2,719	17,737
Rio Grande	1,962	35	198	-1,136	166	13	205	260	645
Upper Colorado	2,262	0	0	-2,745	110	0	0	425	536
Lower Colorado	3,482	123	142	0	211	49	111	0	371
Great Basin	1,637	0	0	1,097	50	0	0	-251	-202
Pacific Northwest	0	0	0	-5,542	0	0	0	129	129
California	10,864	0	0	29,999	231	0	0	-701	-470
Conterminous U.S.	46,928	874	40,449	-370,513	3,214	407	45,070	56,216	104,907

[1] Conservation of thermoelectric, domestic, public, industrial, and commercial uses.

Source: see text.

Table 5.6 Year 2030 Changes in Water Use and Supply and Associated Annual Costs Attributable to Climate Change Predicted by the Canadian Climate Model under the Institutional Management Scenario

	Change in Water Quantity (millions of gallons per day)				Change in Cost (millions of 1995 dollars)				
Region	Foregone irrigation	Conser-vation[1]	New supply	Streamflow	Foregone irrigation	Conser-vation[1]	New supply	Streamflow	Total
New England	0	0	0	-6,013	0	0	0	27	27
Mid-Atlantic	0	0	0	-10,521	0	0	0	48	48
South Atlantic-Gulf	895	412	77,127	-63,377	55	203	86,328	10,885	97,471
Great Lakes	0	0	0	-8,686	0	0	0	39	39
Ohio	38	0	0	-35,912	5	0	0	4,345	4,350
Tennessee	16	0	1,454	-11,913	1	0	1,619	2,216	3,835
Upper Mississippi	136	0	0	-28,062	17	0	0	4,755	4,771
Lower Mississippi	2,047	0	0	-141,948	95	0	0	19,433	19,528
Souris-Red-Rainy	0	0	0	-1,502	0	0	0	35	35
Missouri	3,183	0	0	-12,065	165	0	0	1,093	1,258
Arkansas-White-Red	1,492	187	2,862	-22,500	68	92	3,175	2,902	6,237
Texas-Gulf	1,072	305	21,776	-9,687	48	142	24,309	1,406	25,904
Rio Grande	491	35	2,241	-564	13	13	2,495	129	2,651
Upper Colorado	707	153	1,169	-2,978	25	75	1,307	479	1,886
Lower Colorado	871	123	2,986	0	17	49	3,298	0	3,364
Great Basin	715	0	0	176	19	0	0	-40	-21
Pacific Northwest	0	0	0	-5,542	0	0	0	129	129
California	5,432	0	0	24,567	116	0	0	-574	-458
Conterminous U.S.	17,096	1,214	109,616	-336,527	643	575	122,530	47,307	171,054

[1] Conservation of thermoelectric, domestic, public, industrial, and commercial uses.

Source: see text.

Table 5.7 Year 2030 Changes in Water Use and Supply and Associated Annual Costs Attributable to Climate Change Predicted by the Hadley Climate Model under the Environmental and Efficient Management Scenarios

	Change in Water Quantity (millions of gallons per day)				Change in Cost (millions of 1995 dollars)				
Region	Foregone irrigation	Conservation[1]	New supply	Streamflow	Foregone irrigation	Conservation[1]	New supply	Streamflow	Total
New England	0	0	0	7,109	0	0	0	-32	-32
Mid-Atlantic	0	0	0	7,644	0	0	0	-35	-35
South Atlantic-Gulf	0	0	0	-337	0	0	0	2	2
Great Lakes	0	0	0	15,225	0	0	0	-69	-69
Ohio	0	0	0	11,333	0	0	0	-51	-51
Tennessee	0	0	0	1,617	0	0	0	-7	-7
Upper Mississippi	0	0	0	27,925	0	0	0	-127	-127
Lower Mississippi	0	0	0	23,789	0	0	0	-108	-108
Souris-Red-Rainy	0	0	0	-1,135	0	0	0	27	27
Missouri	0	0	0	11,188	0	0	0	-261	-261
Arkansas-White-Red	0	0	0	-482	0	0	0	11	11
Texas-Gulf	0	0	0	-1,166	0	0	0	27	27
Rio Grande	180	0	0	8	5	0	0	-2	3
Upper Colorado	0	0	0	974	0	0	0	-23	-23
Lower Colorado	2,246	0	0	5,810	54	0	0	-2,378	-2,324
Great Basin	258	0	0	1,097	7	0	0	-251	-244
Pacific Northwest	0	0	0	42,768	0	0	0	-999	-999
California	0	0	0	18,881	0	0	0	-441	-441
Conterminous U.S.	2,683	0	0	172,247	66	0	0	-4,718	-4,652

[1] Conservation of thermoelectric, domestic, public, industrial, and commercial uses.

Table 5.8 Change in Water Withdrawals by Use, Acres Irrigated and Streamflow, 2030-2095

Region	Withdrawals (MGD) Irrigation and livestock	Withdrawals (MGD) Other[1]	Acres irrigated (thousands)	Streamflow (MGD)
New England	57	1,102	37	-149
Mid-Atlantic	107	4,020	87	-285
South Atlantic-Gulf	1,971	10,411	1,489	-2,287
Great Lakes	99	5,022	145	-354
Ohio	74	4,268	85	-578
Tennessee	150	2,665	34	-153
Upper Mississippi	278	3,163	409	-846
Lower Mississippi	4,706	2,091	2,834	-4,949
Souris-Red-Rainy	67	88	95	-76
Missouri	457	1,674	245	-262
Arkansas-White-Red	-583	977	-380	504
Texas-Gulf	142	2,474	112	-197
Rio Grande	-492	-65	-117	248
Upper Colorado	1,110	51	258	-411
Lower Colorado	727	298	161	-956
Great Basin	-286	157	-84	190
Pacific Northwest	-2,448	3,838	-585	934
California	-370	2,773	-122	323
Conterminous U.S.	5,766	45,006	4,705	-9,303

[1] Other includes domestic, public, industrial, commercial and thermoelectric

Source: see text.

Table 5.9 Estimated Annual Costs of Changes in Water Use, 2030 to 2095, without Climate Change (in millions of 1995 dollars)

Region	Cost of Increased Withdrawals				
	Irrigation and livestock	Other	Cost of irrigation foregone use	Cost of change in streamflow	Total cost
New England	3	494	0	1	498
Mid-Atlantic	6	1,802	0	1	1,809
South Atlantic-Gulf	110	5,833	0	10	5,954
Great Lakes	6	2,251	0	2	2,258
Ohio	4	2,392	0	3	2,398
Tennessee	8	1,493	0	1	1,502
Upper Mississippi	16	1,772	0	194	1,982
Lower Mississippi	264	937	0	22	1,223
Souris-Red-Rainy	4	30	0	2	35
Missouri	26	750	0	60	836
Arkansas-White-Red	0	438	19	-12	445
Texas-Gulf	8	1,109	0	45	1,162
Rio Grande	0	0	6	-166	-160
Upper Colorado	62	29	0	94	185
Lower Colorado	41	334	0	640	1,014
Great Basin	0	176	4	-127	53
Pacific Northwest	0	1,720	29	-22	1,728
California	0	932	6	-74	864
Conterminous U.S.	557	22,490	64	674	23,786

Source: see text.

Table 5.10 Year 2095 Changes in Water Use and Supply and Associated Annual Costs Attributable to Climate Change Predicted by the Canadian Climate Model under the Environmental Management Scenario

	Change in Water Quantity (millions of gallons per day)			Change in Cost (millions of 1995 dollars)			
Region	Foregone irrigation	New supply	Streamflow	Foregone irrigation	New supply	Streamflow	Total
New England	175	6,036	-9,101	22	6,747	41	6,810
Mid-Atlantic	250	9,024	-10,676	71	10,059	48	10,178
South Atlantic-Gulf	4,791	150,833	-13,926	914	168,844	63	169,821
Great Lakes	0	0	-6,542	0	0	30	30
Ohio	149	11,870	-16,723	26	13,203	76	13,306
Tennessee	93	12,817	-2,140	17	14,347	10	14,374
Upper Mississippi	0	0	23,441	0	0	-106	-106
Lower Mississippi	1,128	0	-53,380	52	0	242	294
Souris-Red-Rainy	162	1,928	-2,843	48	2,158	66	2,272
Missouri	0	0	29,557	0	0	-690	-690
Arkansas-White-Red	0	0	4,402	0	0	-103	-103
Texas-Gulf	0	0	308	0	0	-7	-7
Rio Grande	1,748	1,021	-240	148	1,132	6	1,286
Upper Colorado	0	0	659	0	0	-15	-15
Lower Colorado	3,892	0	4,271	236	0	-2,445	-2,209
Great Basin	0	0	3,555	0	0	-270	-270
Pacific Northwest	0	0	54,335	0	0	-1,269	-1,269
California	0	0	102,804	0	0	-2,401	-2,401
Conterminous U.S.	12,389	193,527	107,760	1,534	216,490	-6,725	211,299

Source: see text.

Table 5.11 Year 2095 Changes in Water Use and Supply and Associated Annual Costs Attributable to Climate Change Predicted by the Canadian Climate Model under the Efficient Management Scenario

	Change in Water Quantity (millions of gallons per day)			Change in Cost (millions of 1995 dollars)			
Region	Foregone irrigation	New supply	Streamflow	Foregone irrigation	New supply	Streamflow	Total
New England	140	0	-15,172	8	0	1,433	1,441
Mid-Atlantic	200	0	-19,750	25	0	2,128	2,153
South Atlantic-Gulf	4,791	56,505	-108,254	914	63,145	21,686	85,746
Great Lakes	0	0	-6,542	0	0	30	30
Ohio	93	0	-41,485	12	0	5,752	5,764
Tennessee	75	0	-14,976	6	0	2,952	2,958
Upper Mississippi	0	0	23,441	0	0	-106	-106
Lower Mississippi	8,992	0	-70,277	574	0	4,116	4,690
Souris-Red-Rainy	162	91	-4,680	48	100	487	635
Missouri	0	0	29,557	0	0	-690	-690
Arkansas-White-Red	0	0	4,402	0	0	-103	-103
Texas-Gulf	0	0	308	0	0	-7	-7
Rio Grande	1,625	0	-1,384	115	0	268	382
Upper Colorado	0	0	659	0	0	-15	-15
Lower Colorado	3,892	0	4,271	236	0	-2,445	-2,209
Great Basin	0	0	3,555	0	0	-270	-270
Pacific Northwest	0	0	54,335	0	0	-1,269	-1,269
California	0	0	102,804	0	0	-2,401	-2,401
Conterminous U.S.	19,970	56,596	-59,187	1,938	63,245	31,544	96,727

Source: see text.

Table 5.12 Year 2095 Changes in Water Use and Supply and Associated Annual Costs Attributable to Climate Change Predicted by the Canadian Climate Model under the Institutional Management Scenario

	Change in Water Quantity (millions of gallons per day)			Change in Cost (millions of 1995 dollars)			
Region	Foregone irrigation	New supply	Streamflow	Foregone irrigation	New supply	Streamflow	Total
New England	44	0	-15,269	2	0	1,455	1,457
Mid-Atlantic	62	0	-19,887	6	0	2,160	2,166
South Atlantic-Gulf	1,198	107,262	-61,090	74	120,021	10,875	130,969
Great Lakes	0	0	-6,542	0	0	30	30
Ohio	47	0	-38,316	6	0	5,026	5,031
Tennessee	23	3,267	-11,760	1	3,646	2,215	5,862
Upper Mississippi	0	0	23,441	0	0	-106	-106
Lower Mississippi	2,810	0	-73,290	131	0	4,806	4,937
Souris-Red-Rainy	41	1,131	-3,761	4	1,265	277	1,546
Missouri	0	0	29,557	0	0	-690	-690
Arkansas-White-Red	0	0	4,402	0	0	-103	-103
Texas-Gulf	0	0	308	0	0	-7	-7
Rio Grande	437	1,760	-812	12	1,961	137	2,109
Upper Colorado	0	0	659	0	0	-15	-15
Lower Colorado	973	122	1,474	19	78	-986	-889
Great Basin	0	0	3,555	0	0	-270	-270
Pacific Northwest	0	0	54,335	0	0	-1,269	-1,269
California	0	0	102,804	0	0	-2,401	-2,401
Conterminous U.S.	5,634	113,542	-10,193	254	126,970	21,132	148,355

Source: see text.

Table 5.13 Year 2095 Changes in Water Use and Supply and Associated Annual Costs Attributable to Climate Change Predicted by the Hadley Climate Model under the Environmental and Efficient Management Scenarios

	Change in Water Quantity (millions of gallons per day)			Change in Cost (millions of 1995 dollars)			
Region	Foregone irrigation	New supply	Streamflow	Foregone irrigation	New supply	Streamflow	Total
New England	0	0	21,874	0	0	-99	-99
Mid-Atlantic	0	0	26,350	0	0	-120	-120
South Atlantic-Gulf	0	0	69,215	0	0	-314	-314
Great Lakes	0	0	42,445	0	0	-193	-193
Ohio	0	0	75,671	0	0	-343	-343
Tennessee	0	0	16,274	0	0	-74	-74
Upper Mississippi	0	0	82,697	0	0	-375	-375
Lower Mississippi	0	0	188,859	0	0	-857	-857
Souris-Red-Rainy	0	0	4,880	0	0	-114	-114
Missouri	0	0	27,897	0	0	-652	-652
Arkansas-White-Red	0	0	29,713	0	0	-694	-694
Texas-Gulf	2,877	0	-3,761	157	0	88	245
Rio Grande	0	0	3,159	0	0	-74	-74
Upper Colorado	0	0	9,242	0	0	-216	-216
Lower Colorado	0	0	24,003	0	0	-3,420	-3,420
Great Basin	0	0	11,223	0	0	-449	-449
Pacific Northwest	0	0	37,815	0	0	-883	-883
California	0	0	86,650	0	0	-2,024	-2,024
Conterminous U.S.	2,877	0	754,205	157	0	-10,811	-10,654

Source: see text.

Table 6.1 Estimated Changes in Annual Water Costs in the Eastern and Western Water Resources Regions under Alternative Climate Scenarios and the Efficient Management Scenario (in billions of 1995 dollars)

	Current Climate[1]			Canadian Climate[2]			Hadley Climate[2]		
	1995-2030	2030-2095	1995-2095	1995-2030	2030-2095	1995-2095	1995-2030	2030-2095	1995-2095
9 Eastern regions[3]	6.6	17.7	24.3	89.0	121.0	210.0	6.2	15.2	21.4
9 Western regions[4]	7.2	6.1	13.3	29.7	-0.5	29.2	2.9	-2.1	0.8
Conterminous 48 states	13.8	23.8	37.6	118.7	120.5	239.2	9.1	13.1	22.2

1. The efficient management scenario is used to calculate costs only for the climate change scenarios.

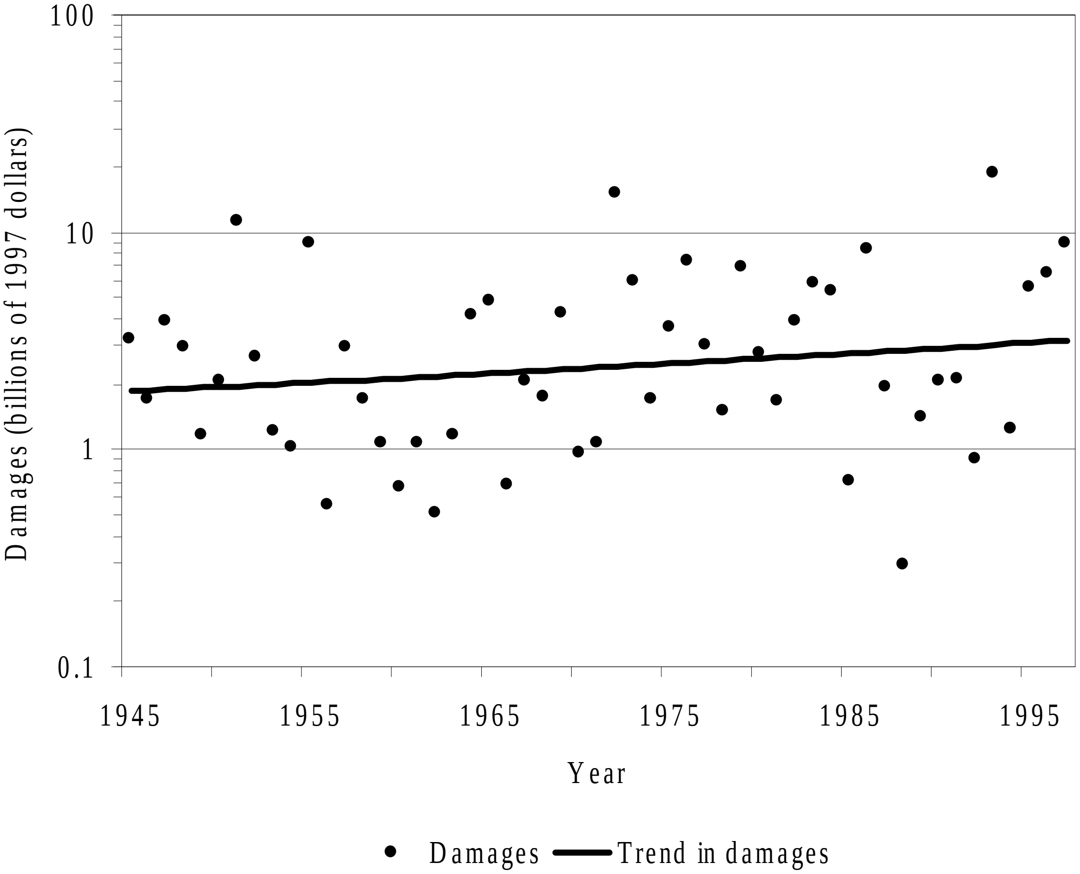
2. The figures are the sum of the costs attributable to both climate and non-climate factors.

3. Includes the following water resource regions: New England, Mid-Atlantic, South Atlantic-Gulf, Great Lakes, Ohio, Tennessee, Upper Mississippi, Lower Mississippi, and Souri-Red-Rainy.

4. Includes the following water resource regions: Missouri, Arkansas-White-Red, Texas-Gulf, Rio Grande, Upper Colorado, Lower Colorado, Great Basin, Pacific Northwest, and California.

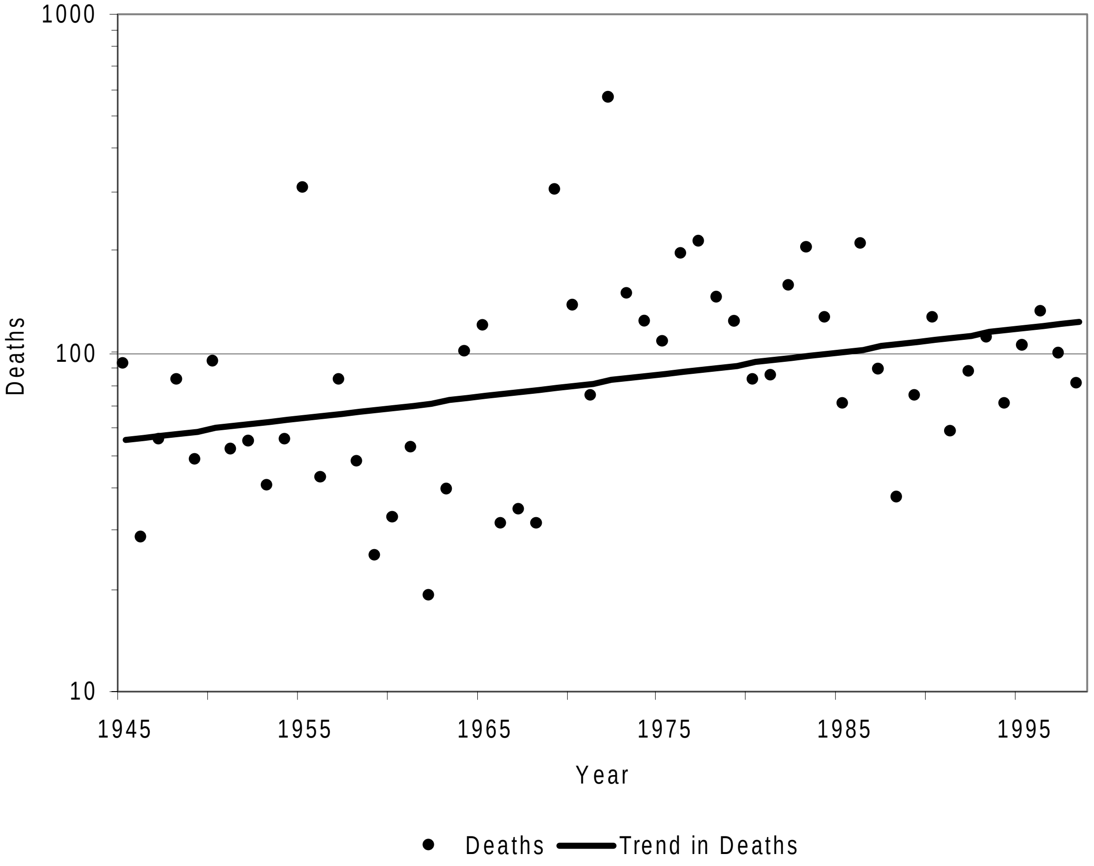
Sources: Tables 5.2, 5.5, 5.7, 5.9, 5.11, and 5.13.

Figure 2.1 Flood Damages, 1945-1997 (in billions of 1997 dollars)



Source: National Weather Service, 1999.

Figure 2.2 Flood Related Deaths, 1945-1998

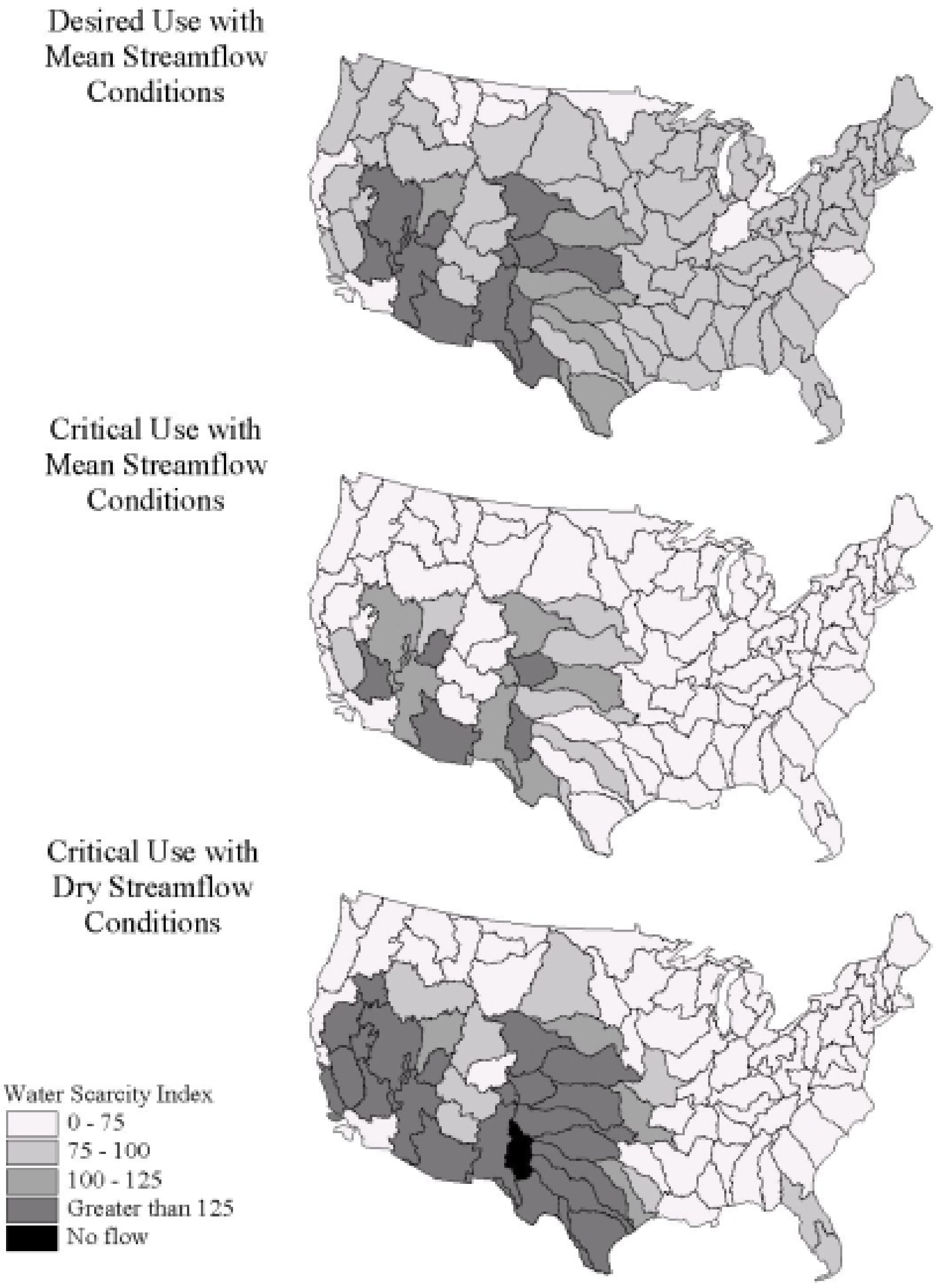


Source: National Weather Service, 1999.

Figure 3.1 The 18 Water Resources Regions and 99 Assessment Subregions within the Conterminous United States

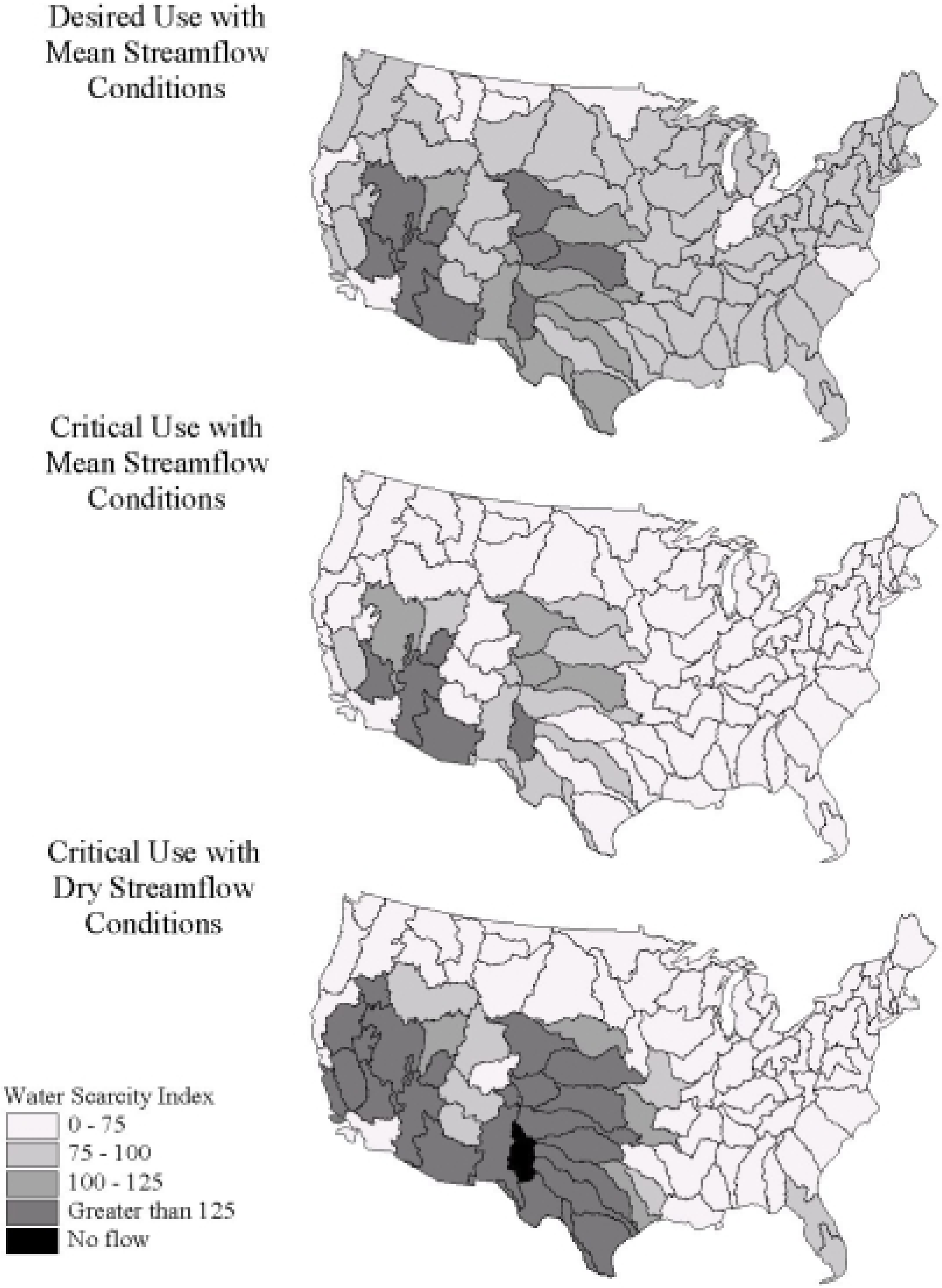
Source: U.S. Water Resources Council, 1978.

Figure 3.2 Water Scarcity Indices for the 99 Assessment Subregions for the 1995 Baseline Climate



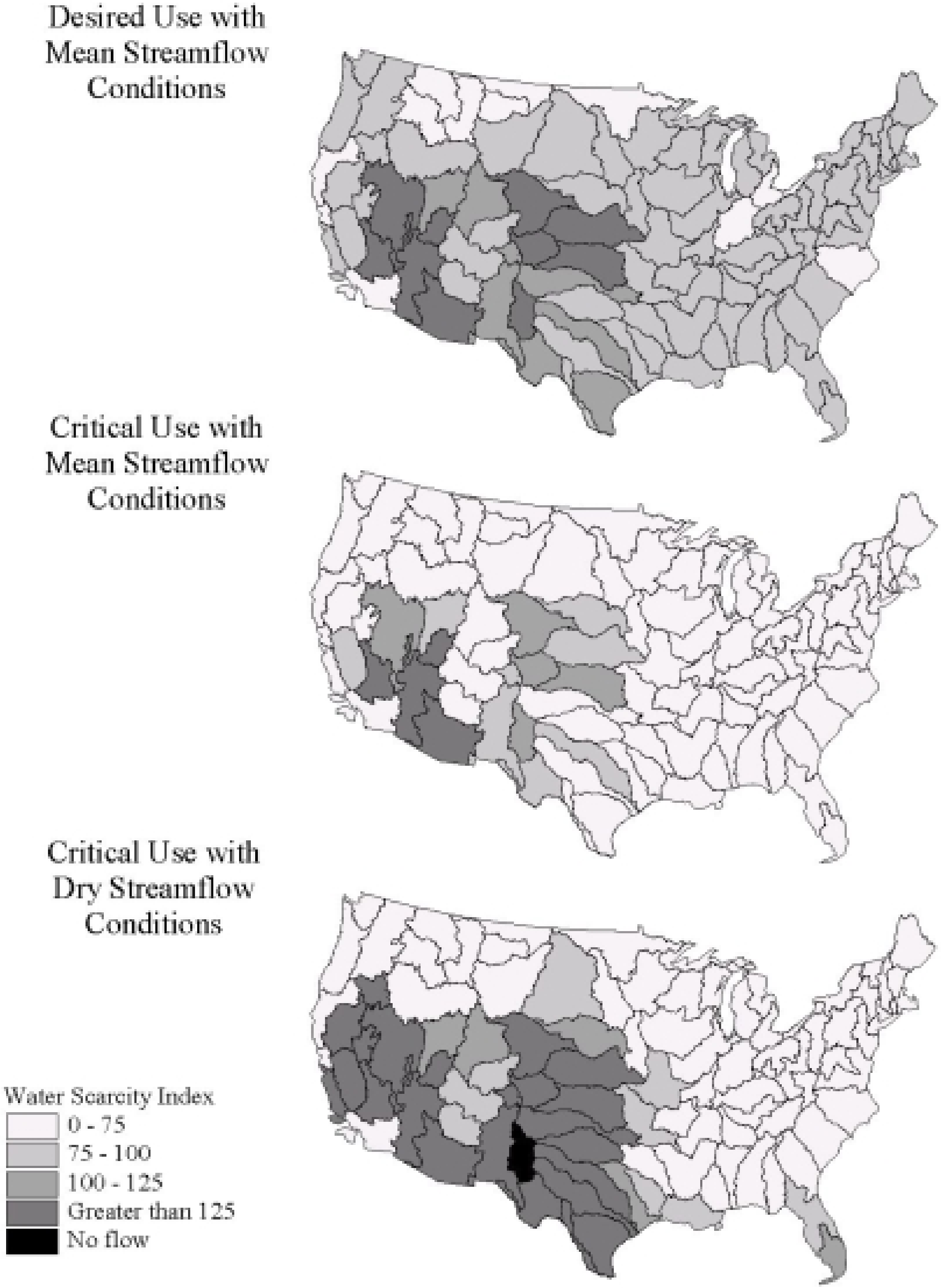
Source: see Table 3.3.

Figure 3.3 Water Scarcity Indices for the 99 Assessment Subregions for the Year 2030 without Climate Change



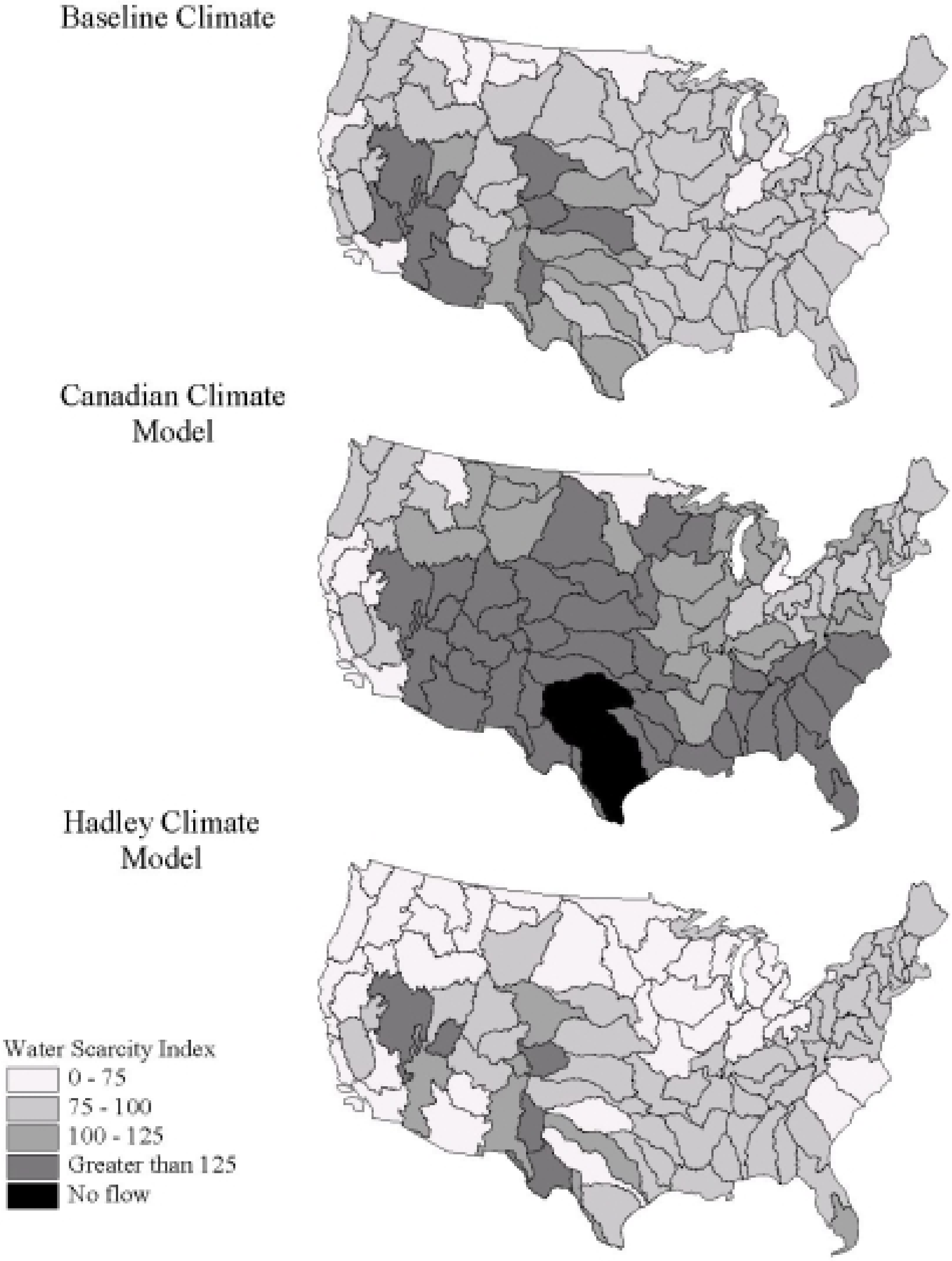
Source: see Table 3.5.

Figure 3.4 Water Scarcity Indices for the 99 Assessment Subregions for the Year 2095 without Climate Change



Source: see Table 3.6.

Figure 3.5 Water Scarcity Indices of Desired Use Relative to Mean Flow for the 99 Assessment Subregions in the Year 2030 under Alternative Climate Scenarios



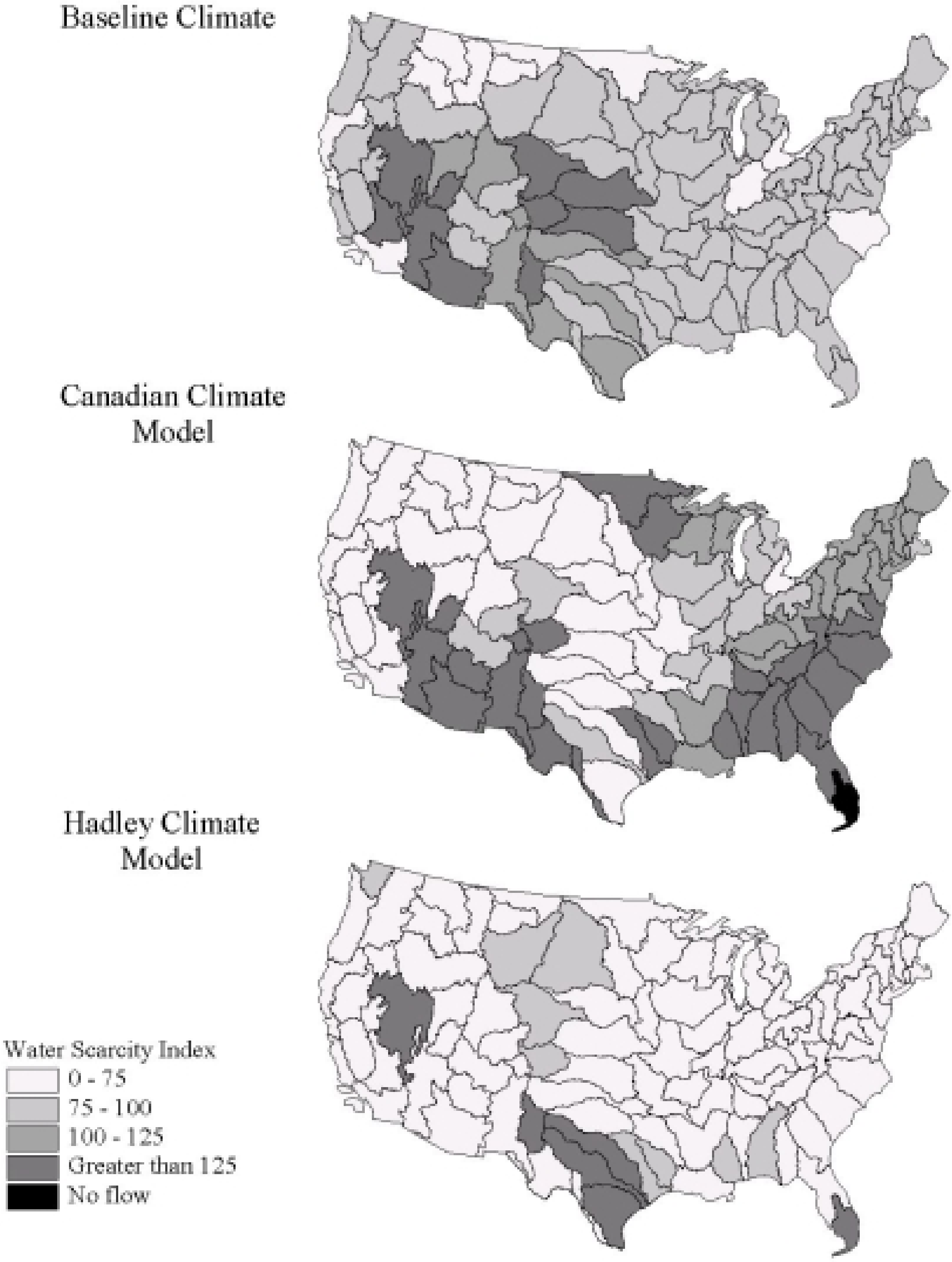
Baseline Climate

Canadian Climate Model

Hadley Climate Model

Source: see Tables 3.5, 3.9 and 3.10.

Figure 3.6 Water Scarcity Indices of Desired Use Relative to Mean Flow for the 99 Assessment Subregions in the Year 2095 under Alternative Climate Scenarios



Source: see Tables 3.6, 3.11 and 3.12.