CHAPTER 8

POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR THE WESTERN UNITED STATES

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CHAPTER SUMMARY

Regional Context

The West is characterized by variable climate, diverse topography and ecosystems,an increasing human population,and a rapidly growing and changing economy. Western landscapes range from the coastal areas of California,to the deserts of the Southwest,to the alpine tundra of the Rocky and Sierra Nevada Mountains. Since 1950,the region's population has quadrupled,with most people now living in urban areas.The economy of the West has been transformed from one dominated by agriculture and resource extraction to one dominated by government,manufacturing,and services. National parks attract tourists from around the world. The region has a slightly greater share of its economy in sectors that are sensitive to climate than the nation as a whole;these include agriculture,mining,construction,and tourism,which currently represent one-eighth of the region's economy.

As a result of population growth and development, the region faces multiple stresses. Among these are air quality, urban sprawl,and wildfires. Perhaps the greatest challenge,however, is water, which is typically consumed far from where it originates. Competition for water among agriculture,urban, recreation,environmental,and other uses is intense, with water supplies already oversubscribed in many areas.

The combination of continued development of the West and climate change is likely to introduce some new stresses, exacerbate some existing stresses,and ease other stresses.

Climate of the Past Century

- In the 20th century, temperatures in the West rose 2 to 5˚F.
- The region generally became wetter, with some areas having increases in precipitation greater than 50%. A few areas,such as portions of Arizona,became drier and experienced more droughts. The length of the snow season in California and Nevada decreased by about 16 days from 1951 to 1996.

Climate of the Coming Century

- During the 21st century, temperatures are very likely to increase throughout the region,at a rate faster than that observed,with the Hadley and Canadian General Circulation Models (GCMs) projecting increased temperatures of about 3 to over 4˚F by the 2030s and 8 to 11˚F by the 2090s.
- The two climate model scenarios project increased precipitation,particularly during winter, and especially over California. However, parts of the Rocky Mountains are projected to get drier and the Canadian model projects most of the region getting drier by the 2030s. Other changes in climate are possible and there is some chance that that climate over much of the West could become generally drier during the 21st century.
- Under the Hadley and Canadian scenarios, runoff is estimated to double in California by the 2090s, though the climate models also suggest the potential for more extreme wet and dry years in the region.
- This chapter considers the effects of warmer and wetter conditions,based on the climate model scenarios used in this Assessment. It also considers a scenario of generally warmer and drier conditions.

Key Findings

Water Resources

- The potential for flooding is very likely to increase because of earlier and more rapid melting of the snowpack and more intense precipitation. Even if total precipitation increases substantially, snowpacks are likely to be reduced. However, it is possible that more precipitation would also create additional water supplies, reduce demand and ease some of the competition among competing uses.
- In contrast, a drier climate is very likely to decrease water supplies and increase demand for such uses as agriculture, recreation, aquatic habitat, and power, thus increasing competition for scarcer supplies.
- Improved technology, planting of less water-demanding crops, pricing water at replacement cost, and other conservation efforts can help reduce demand and vulnerability to drought. Advanced planning for potentially larger floods is needed to reduce flood risks.

Natural Ecosystems

- Vegetation models estimate that under wetter conditions there is likely to be an increase in biomass, a reduction in desert areas, and a shift toward more woodlands and forests in many parts of the West. However, should the climate become drier, forest productivity would likely be reduced and arid areas would expand. It is possible that fire frequency could increase whether the region gets wetter or drier.
- Human development of the West has resulted in habitat fragmentation, creation of migration barriers such as dams, and introduction of invasive species. The combination of development, presence of invasive species, complex topography, and climate change is likely to lead to a loss of biodiversity in the region. However, it is probable the mountains will enable some species to migrate to higher altitudes. It is also possible that some ecosystems, such as alpine ecosystems, would virtually disappear from the region.
- Human interventions to aid adaptation by species will be challenging, but reducing the pressures of development on ecosystems and removing barriers to migration could be the most effective strategies.

Agriculture and Ranching

- Higher CO_2 concentrations and increased precipitation are likely to increase crop yields and decrease water demands while milder winter temperatures are likely to lengthen the growing season and result in a northward shift in cropping areas. However, there is some chance that higher temperatures will inhibit growth of certain fruits and nuts that require winter chilling, and changes in the rainfall and humidity can harm some crops, such as grapes, by increasing potential for disease.
- It is possible that higher temperatures and increased precipitation will increase forage production and lengthen the growing and grazing season for ranching, but flooding and increased risk of animal disease can adversely affect the industry.
- Increasing crop diversity can improve the likelihood that some crops will fare well under variable conditions, while switching to less water-demanding crops and improving irrigation efficiency would conserve water. Improved weather forecasting could aid farmers in selecting crops, timing harvests, and increasing irrigation efficiency; and aid ranchers in timing cattle sales and breeding.

Tourism and Recreation

- Higher temperatures are very likely to result in a longer season for summer activities such as backpacking, but a shorter season for winter activities, such as skiing. Ski areas at low elevations and in more southern parts of the region are very likely to be at particular risk from a shortening of the snow season and rising snowlines.
- Adaptation strategies for tourism and recreation involve diversification of income sources.

POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR THE WESTERN UNITED STATES

PHYSICAL SETTING AND UNIQUE ATTRIBUTES

The West region spans from California to the Rocky Mountains in Colorado and south to the Mexican border. The region contains 19% of the land area and 17% of the population in the United States. On average,the West has low precipitation,although some parts are quite wet. It also has some of the greatest variance in topography and climate in the lower 48 states. The West includes the lowest point (Death Valley, which is 282 feet below sea level) and the highest point (Mt.Whitney, 14,494 feet above sea level) in the lower 48 states. Among its major mountain ranges are the Sierra Nevada,the Wasatch, and the Rockies. The region also contains the Great Basin in Nevada and Utah;in which most of the rivers do not run to the sea. Especially because of its varied topography, climate zones in the West range from deserts to alpine.

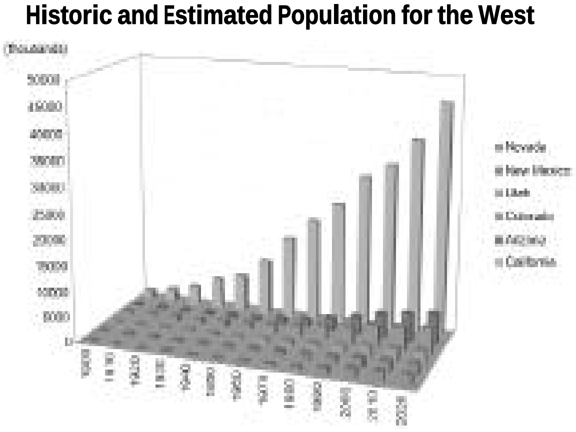

Figure 1: The West's population grew from less than 10 million in 1940 to 46.2 million in 1998 (US Census Bureau, 1998). California's population mushroomed from less than 7 million in 1940 to more than 33 million in 1998 (California Trade and Commerce Agency, 1997; California Department of Finance, 1998). Although more than two-thirds of the West's population lives in California, in recent decades, the intermountain states have become the fastest-growing in the nation. For example, Arizona's population grew from 1.3 million in 1960 to 4.5 million in 1998 (CLIMAS, 1998). Six of the 10 fastest-growing states in the US are projected to be in this region, with Arizona, Nevada, and Utah being the fastest. California's population is projected to rise from its 1998 level of 33 million to about 45 million (NPA Data Services, Inc., 1999). See Color Plate Appendix.

SOCIOECONOMIC CONTEXT

The West underwent a dramatic transformation in the 20th century in its human population,economy, and landscape. Since the middle of the century, the population has increased fourfold (see Figure 1). Although more than two-thirds of the West's 46 million people live in California,more recently the intermountain states have become one of the fastest-growing areas in the nation. Most people in the West live in urban areas. To the large cities of California — San Francisco,Los Angeles,San Diego,and Sacramento — the West has now added Denver, Salt Lake City, Albuquerque,Phoenix,and Las Vegas as major metropolitan areas (see Figure 2). Thus,once predominantly rural states are now among the most urban in the country. The regional population is projected to grow by about one half, reaching 60 to 74 million people, by 2025 (NPA Data Services,Inc.,1999).

The economy of the West has been transformed from one dominated by agriculture and resource extractive industries in the 19th century to one dominated by government,manufacturing,and services such as tourism. Figure 3 displays the relative value of all goods and services produced in the region in 1996. About 11% of the region's output is currently in sectors considered relatively sensitive to climate,including agriculture,mining,construction,and the tourism related sectors of hotels and amusement/recreation. This share of the region's output in these sectors is projected to increase to 12% by 2045,mainly because of increases in tourist related activities,but also because of increases in agricultural services. The share of total output in agriculture is projected to decrease,although the total value of agricultural production is projected to increase (US BEA,1999a).

ECOLOGICAL CONTEXT

Although much of the West is semi-arid grassland or shrubland,the region's diverse ecosystems contain alpine tundra,coniferous and mixed forests, chaparral, wetland,and coastal and estuarine areas (USGS, 1993).

Water and land in the West have been substantially altered by people. In the West, water is typically consumed far from where it originates. For California users, water is extracted from natural systems primarily in the northern part of the state,and from the Colorado River. More than one-third of the water Arizona uses is from the Colorado River (CLIMAS,1998). Western water tends to be subsidized (by the federal government and states) and sold to consumers at prices effectively below what it costs to make supplies available. Irrigation is the major consumer of Western water (see Figure 4).

The federal government owns more than half of the land in the West,including 83% of Nevada. Most of the federally owned land is managed by the Bureau of Land Management, Forest Service, Park Service, and Department of Defense (Riebsame,1997). Indian reservations are scattered throughout the region,and are most concentrated in Arizona,where they comprise about one-third of the state's land area (estimated based on Riebsame,1997). Between two-thirds and three-quarters of the land in the West is used for pasturelands, agriculture,and forests, with ranching using most of that land (USGS,1999). However, the amount of land used for farming (including cultivated and non-cultivated land such as pastureland) in the West decreased by 8% between 1992 and 1997 (USDA,1997).

Continued population and economic growth could result in more demand for water, wood products, and minerals;more roads,and conversion of land to urban uses (which could increase runoff and,in coastal areas,vulnerability to sea-level rise);potentially more automobile emissions (although this depends on future technology and transport practices);and increased demands for recreation. All of these could put more pressure on the remaining undeveloped areas. However, protecting open space could ease the current pressures of development on ecosystems and enhance the ability of species to cope with climate change.

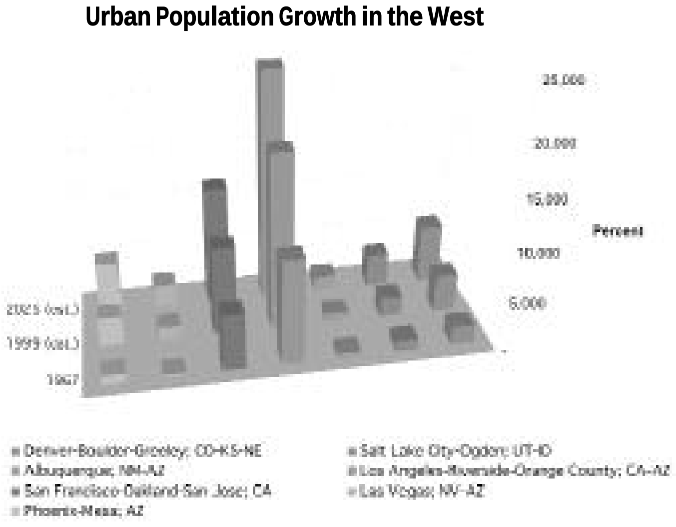
Urban Population Growth in the West

Figure 2: Over 93% of California's residents live in cities, including San Francisco, Los Angeles, San Diego, and Sacramento, and their surrounding metropolitan areas. In intermountain areas, population growth is also largely concentrating in cities, such as Denver, Salt Lake City, Albuquerque, Phoenix, Las Vegas, Santa Fe and Provo. Much of the future population growth is expected to occur in urban areas. Source: NPA Data Services, 1999. See Color Plate Appendix.

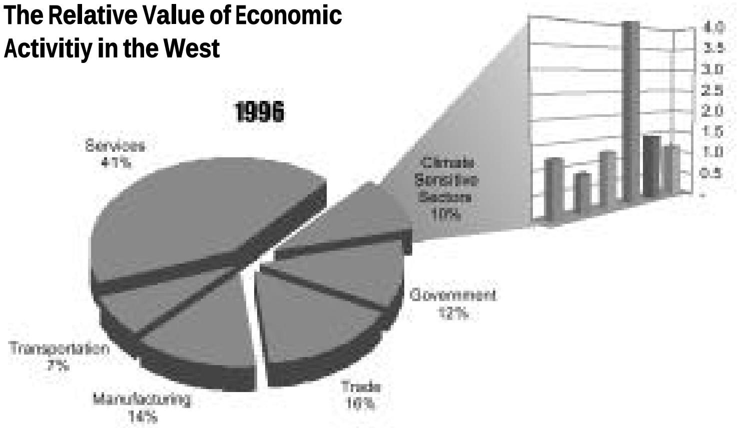
The Relative Value of Economic Activitiy in the West

Figure 3: The West produces 18% of US Gross National Product. The region has a slightly greater share of its economy in relatively climate-sensitive sectors such as agriculture, mining, construction, and tourism, than the nation as a whole. While 1.8% of the nation's economic output is from agriculture (which includes forests and fisheries), 2.0% of the West's economic output is from the agriculture sector. The West has 4.1% of its gross product from hotels, amusement/recreation, restaurants, and museums, which are strongly affected by tourism, while the nation as a whole has 1.6% (US BEA, 1999a). With its Gross State Product of $962 billion, California comprises 72% of the total Regional Product of $1.3 trillion in 1996 (US BEA, 1999a). Ranked as a nation, California would be the seventh largest economy in the world (California Trade and Commerce Agency, 1997). See Color Plate Appendix.

CLIMATE VARIABILITY AND CHANGE

The West experiences great temporal and spatial variation in precipitation and temperature. Temperature regimes range from hot desert environments to cold alpine environments. Precipitation ranges from up to 40 inches per year in northern California to less than 10 inches in the deserts of Nevada,southeastern California,and western Arizona. Although many parts of the region,particularly in the Southwest, receive most of their precipitation from summer monsoons,highly variable winter precipitation provides most of the annual runoff in the rest of the region (Bales and Liverman,1998).

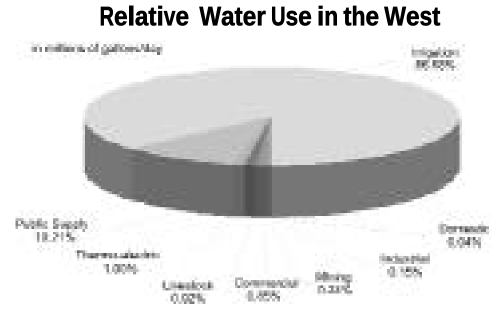

Figure 4: In 1995, 87% of the water consumed in the West was for irrigation (Solley et al., 1998; see Figure 4). However, water use for irrigation has declined slightly since 1980, while municipal uses have grown (Diaz and Anderson, 1995). For example, agriculture accounts for 81% of all water used in Arizona, down from 93% in 1963, while municipal demand currently accounts for 14% of water used, up from 5% in 1963 (CLIMAS, 1998). In addition, irrigated land in the region fell by 8% from 1982 to 1992, although acreage may have increased in recent years (USDA, 1997). Total water use in the region appears to have been declining since 1980 (Templin, 1999). See Color Plate Appendix.

El Niño and Events 1997-1998

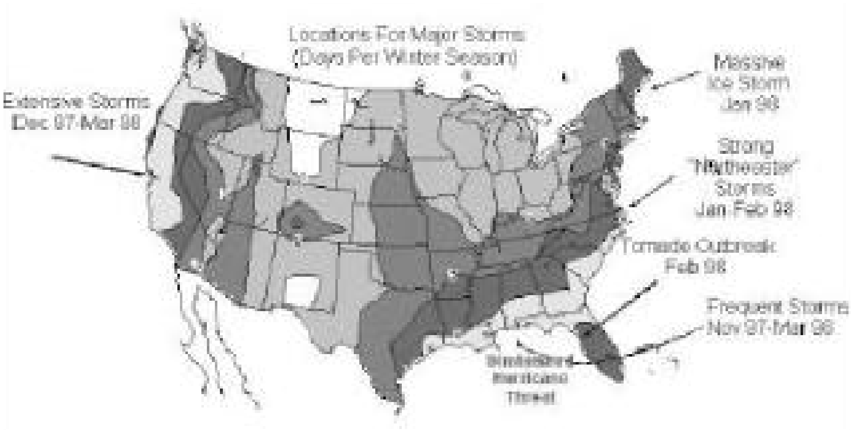

Figure 5: The 1997-1998 El Niño had quite strong effects in the West, with particularly large winter precipitation events. The heavy precipitation lead to such localized consequences as flooding and landslides. See Color Plate Appendix.

In many areas of the West, paleoclimatic data suggest that on some occasions droughts and floods were more extreme over the past few thousand years than was observed during the 20th century (Bales and Liverman, 1998). Since 1900, temperatures in the West have been rising, with increases of 2 to 5˚F per 100 years in all areas except southern Colorado, western New Mexico, and eastern Arizona (See Climate Chapter). Averaged over the region, the number of days with high temperatures over 90˚F increased in the 20th century while days below freezing decreased (David Easterling, National Climatic Data Center, personal communication, 1999).

Over the 20th century, annual precipitation over most of the region generally increased 10 to 40%. However, precipitation in the Central Valley of California, southeastern California, south-central Utah, northeastern Arizona, and western Colorado decreased and some areas have experienced more drought (Karl et al., 1990; USHCN, 1999). The length of the snow season decreased by about 16 days from 1951 to 1996 in California and Nevada, and stayed about the same elsewhere (David Easterling, National Climatic Data Center, personal communication, 2000). Since the late 1940s, snowmelt has come earlier in the year in many northern and central California river basins (Dettinger and Cayan, 1995). The proportion of annual precipitation from heavy storm events has increased in the 20th century (Karl and Knight, 1998).

The region is quite vulnerable to climate variability, as the 1998 El Niño event demonstrated, particularly in California. El Niño storms during February 1998 brought as much as three times the average rainfall for the month, causing numerous deaths in addition to damages to homes, businesses, roads, utilities, and crops (Willman, 1998). On the other hand, an advanced forecast for El Niño resulted in many protective measures being undertaken (see Figure 5).

With its complex topography, developing reliable projections of climate change in the West is particularly difficult. General Circulation Models (GCMs) tend to be least reliable projecting changes in coastal areas and in mountains, two features prevalent in the West. However, it is possible to develop GCM-based scenarios that give an indication of how increased greenhouse gas concentrations could change the climate. The limitations of GCMs are discussed in more detail in Chapter 1.

Average annual outputs from the Hadley and Canadian GCMs are shown in Figure 6. The Hadley model projects a 3.8˚F (2.1˚C) winter warming and a 3.1˚F (1.7˚C) summer warming by the 2030s[1] over 1961-1990 temperatures and an 8.8˚F (4.9˚C) winter and an 8.3˚F (4.6˚C) summer increase by the 2090s. The Canadian model projects more winter warming, with a 4.8˚F (2.7˚C) winter and a 2.5˚F (1.4˚C) increase in summer temperature by the 2030s and a 12.8˚F (7.1˚C) winter and 7.7˚F (4.3˚C) summer increase by the 2090s (NCAR, 1999a).

Both models project a doubling of winter precipitation over California. However, the Hadley and

[1] The results for the 2030s are an average for 2025-2034.

Canadian models also show the potential for decreased precipitation in some parts of the Rocky Mountains. The Canadian model shows no change in summer precipitation, while the Hadley model projects that summer precipitation would decrease.

The models do not project a significant change in interannual variation of precipitation. Should interannual variation of precipitation increase, there would be more extreme wet years and more extreme dry years. It is likely that many areas in the West could have wetter winters and drier summers. It is very unlikely that changes in precipitation will be uniform across the West; some areas will likely be wetter while it is possible that others will be drier. Wet periods will very likely be followed by dry periods because, even with climate change, there will still be variability — seasonally, from year to year, and from place to place.

California has experienced relatively less sea-level rise than the eastern United States because many areas are being uplifted by moving of geological plates (Neumann et al., 2000). The coast south of La Jolla, California has been experiencing a relative sea-level rise of approximately 8 inches (20 cm) per century; the coast from Los Angeles to San Francisco has had a 0 to 6 inches (15 cm) per century of sea-level rise; and the coast in far northern California has experienced a relative reduction in sea level of 2 to 6 inches (5 to 16 cm) per century. The Intergovernmental Panel on Climate Change estimates that sea level will rise 6 to 37 inches (15 to 95 cm) by 2100 (Houghton et al., 1996), which would result in net sea-level rise for the entire California coast.

KEY ISSUES

The key issues in the West involve those systems that are sensitive to climate and, in a number of cases, are already stressed by current development patterns. All of these systems will be affected by climate change.

1. Changes in seasonality and amount of water resources
2. Plant and animal changes in natural ecosystems
3. Changes in agricultural crop productivity
4. Precipitation and forage changes for ranching
5. Sea-level rise effects on coastal resources
6. Changes in tourism and recreation

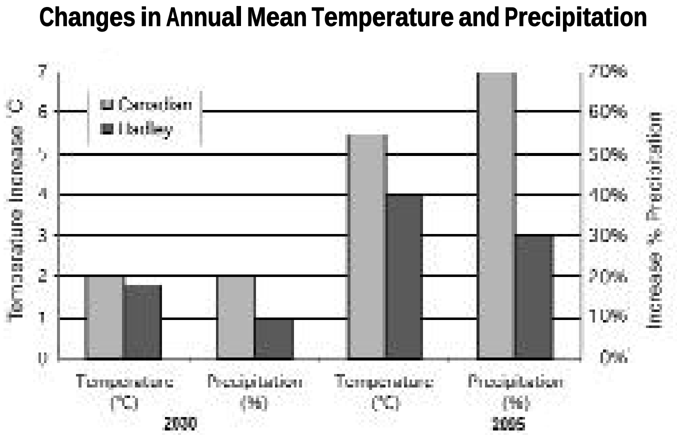

Figure 6: Changes in annual mean temperature and precipitation for the West as projected by the Hadley and Canadian models compared to 1961-90 Base Period.

1. Water Resources

The more than fourfold increase in the population of the West since the middle of the 20th century has dramatically changed the use of natural resources in the West and imposed stresses on these resources. One of the more stressed resources is water. Although agricultural water use is declining,[2] water supplies are tight because of growth in environmental, municipal, and industrial demands and could become tighter as the population and economy continue to grow and unresolved water rights claims are settled. For example, over the last ten years, California consumed more than its normal year apportionment of Colorado River water, but surplus water and water unused by Arizona and Nevada was available to meet California's needs (US Bureau of Reclamation, 1997; US Bureau of Reclamation, 1999).[3] Meanwhile, rapidly growing urban areas such as Las Vegas are demanding more water. In addition, many aquifers are being depleted at rates faster than their recharge, and high-volume groundwater mining has caused land subsidence (sinking) and fissuring (cracking).

[2] Although total water use for irrigation is declining, agricultural production is sensitive to changes in precipitation and subsequent changes in water allocation. For example, in 1991, during the fifth year of a drought, water supplies to California agriculture were severely curtailed. Overall economic losses were approximately $400 million – about 2% of total agricultural revenues. In spite of the drought, agricultural revenues in 1991 reached an all-time high (Gleick and Nash, 1991).

[3] Use of Colorado River water is allocated between the Upper Basin and the Lower Basin. The Lower Division states of California, Arizona, and Nevada are guaranteed a delivery of 75 maf (million acre feet) in each 10 year period. Also, the Upper Division states (Colorado, New Mexico, Utah, and Wyoming) are to supply one-half of the water required to be delivered by treaty to Mexico, that is, 0.75 mafy (million acre feet per year), if waters over and above the quantities of use apportioned to the Upper Basin (7.5 mafy) and the Lower Basin (8.5 mafy) are insufficient. (House Document No. 717, 1948) Nevada's apportionment of Colorado River water is 0.3 mafy plus 4 percent of the surplus water made available. The Upper Basin states receive the following shares: Arizona 0.05 mafy, Colorado 3.855 mafy, Utah 1.713 mafy, Wyoming 1.043 mafy, and New Mexico 0.84 mafy (NYT, 1999).

Brown (2000) forecast that by 2040 net water withdrawals in the region will increase, with withdrawals for domestic and public use increasing most, and irrigation withdrawals declining slightly except in the Upper Colorado Basin. As water use shifts from agriculture to municipal uses, the ability to reduce withdrawals during droughts declines.

It has become increasingly difficult to build any significant new water resources infrastructure because of economic, environmental, and social constraints. In addition, institutional factors such as water rights, local planning and zoning, and regulations influence and can limit the nature and level of response that water managers can make to changes in supply or demand. Reserved and Native American water rights claims are senior to those of many other water consumers, and many of these rights are not currently being exercised (see box on Native American water claims).

Because of its semiarid climate, water supplies in the West are considered to be more vulnerable to climate change than water supplies in other regions (Gleick, 1990; Hurd et al., 1999a). Detailed hydrologic modeling conducted for the western US projects a significant change in snowfall and snowmelt dynamics because of higher temperatures. Rising temperatures are likely to shorten the snowpack season by delaying the autumnal change from rainfall to snow and advancing the spring snowmelt. A larger proportion of winter precipitation in mountainous areas is also very likely to fall as rain rather than snow, even if overall precipitation amounts do not change. McCabe and Wolock (1999) found that under the two GCM scenarios, April 1 snowpack in the major western mountain ranges would be reduced, except that under the Hadley scenario, snowpack in the Rocky Mountains would have little change.[4] Peak runoff is very likely to occur earlier in the year (see Figure 7) (Gleick and Chalecki, 1999). Jeton et al. (1996) found that snowmelt would occur more than two weeks earlier than currently in the East Fork of the Carson River and North Fork of the American River in the Sierra Nevada under a 2.2˚C (4˚F) warming, which the Hadley and Canadian scenarios suggest would occur by the 2030s.[5]

Hypothetical Change in Runoff for a Western Snowmelt Basin

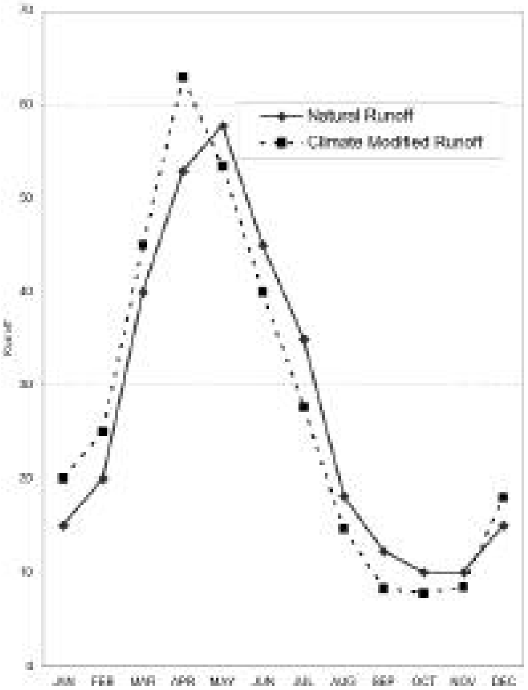

Figure 7: Natural runoff (solid line) peaks in May as winter snow melts. Under conditions of climate change (dashed line), runoff peaks earlier and higher, but is lower in the summer. Source: Gleick and Chalecki, 1999.

Wolock and McCabe (1999) projected changes in runoff for the region using the Hadley and Canadian climate models (see Table 1). They estimate that California runoff will increase by the 2030s by about three-fifths and double by the 2090s.[6] Their study projected small changes in runoff in the rest of the West by the 2030s, and no change to approximately 30% increases in runoff outside of California by the 2090s. The changes in runoff for the areas outside California are not considered to be statistically significant because there is so much variance in year to year runoff. Soil moisture under both scenarios is projected to increase, but in many locations outside of California conditions could be drier during some periods, particularly in the summer (NCAR, 1999b).

These changes in runoff have important consequences for water management. Any changes in runoff timing or variability could possibly cause problems (Gleick, 1987). Earlier spring runoff is likely to increase risk of spring flooding, complicate seasonal allocation schedules, and create problems for matching supply and demand and meeting envi-

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[4] The article does not state at what altitude snowpack is measured.

[5] Jeton et al. (1996) also found that total annual flow was insensitive to changes in temperature and much more sensitive to changes in precipitation.

[6] In contrast, Miller et al. (1999a, 1999b) found that total streamflow in the Russian River in northern California, which is not snowmelt driven, would not change significantly under the Hadley 2090s scenario, but peak runoff may occur one month earlier because of a potential change in winter storms. In contrast, snowmelt driven streamflow in the Sierra Nevada would likely happen earlier and peak streamflow would rise. Miller et al. (2000) found that the American River in the Sierra Nevada, which is snowmelt driven, showed both an increase in magnitude and earlier peak flow (see also Hay et al., 2000).

ronmental in-stream flow requirements in the summer. It is likely to be problematic for the current reservoir system to store earlier spring runoff for use in the summer unless new operating rules and regimes are implemented (Lettenmaier and Sheer, 1991),and it is not clear that such a change would be sufficient to reduce spring flooding and increase summer supplies. This may be especially true in California,where both climate models used in this Assessment show a substantial increase in runoff, particularly in the winter. In addition,more intense precipitation events (such as the extreme event in Las Vegas on July 8,1999 that caused extensive flooding in the city) could increase flooding. The risk of increased flooding is exacerbated by continued urban development,which increases surface runoff during storms. Development in floodplains and expansion of areas that could be flooded because of increased runoff could result in more people and property at risk to the effects of climate change. In addition,higher runoff can increase mudslides.

On the other hand,it is possible that increased runoff would create more water supplies for the West. Presumably, this could contribute to an easing of many current stresses on the water management system because there would be relatively more water available for users. A wetter climate would also likely reduce the demand for surface water and groundwater for such purposes as irrigation and watering lawns.

There is some chance that higher runoff could ease water quality problems although it could also result in more runoff of pollutants from farms and streets, which can degrade water quality. It is likely that hydropower production would increase with more runoff. However, earlier runoff is likely to result in more electricity production in winter time,when demand for heating is very likely to be falling,and less electricity production in summer when demand for cooling is very likely to be rising.

If there is reduced or even only small increases of precipitation, runoff is very likely to be reduced. In addition,both groundwater recharge and reservoir supplies are very likely to be reduced as higher temperatures increase evaporation (Wilkinson and Rounds,1998a).

Reduced runoff, particularly if combined with higher demands due to hotter and drier conditions, would very likely make allocation of water supplies a more critical issue for the West. It is likely that instream uses such as hydropower and recreation would be among those most affected by a reduction in runoff. It is also likely that urban and industrial users would be less vulnerable to supply reductions. Hurd et al.(1999b) found that urban and industrial users of Colorado River water would have very small reductions in supplies if runoff is reduced. In general,it is very likely that those with more junior water rights claims (those who receive their allocations after the senior claims are met) would be at greatest risk should runoff decline (Miller et al., 1997). In addition it is possible that Native Americans will more fully exercise their rights to water (see box). Furthermore,during droughts there is likely to be increased dependence on groundwater, causing increased overdraft,subsidence,and reduced baseflow of rivers. On the other hand,it is possible that drier conditions would result in a decrease in flood potential and mudslides in California.

With less runoff, water quality is likely to decline if stronger pollution control measures are not undertaken. Higher temperatures alone would decrease dissolved oxygen levels in water while lower streamflow would concentrate pollutants. Lower flows in the Colorado River are likely to result in increased salinity levels,unless additional steps are taken to control the problem (Gleick and Nash, 1991). Lower lake levels could also increase water quality problems. For example,salinity concentrations in the Great Salt Lake are likely to increase with lower lake levels (Grimm et al.,1997).

Table 1: Estimated Changes in Runoff

Current and Estimates Changes in Runoff from the Canadian and Hadley Models (mm)

Region	Historical Runoff 1961-90 (mm/yr)	Change in Annual Runoff 2025-2034 (mm/yr)		Change in Annual Runoff 2090-2099 (mm/yr)	
		Canadian	Hadley	Canadian	Hadley
Upper Colorado	43	-15	3	2	28
Lower Colorado	2	-1	6	0	33
Great Basin	21	-1	4	16	29
California	232	60	63	320	273

Native American Water Claims

Indian water rights remain an unresolved and important issue for water allocation in the West in a number of cases. Under the legal doctrine established by the 1908 Winters case (*Winters v. United States* [207 US 564 (1908)]),Indian tribes have reserved water rights that could amount to 45-60 million acre-feet (Western Water Policy Review Advisory Commission,1998). However, the vast majority of those claims have never been clearly quantified or developed for the benefit of the tribes. In many cases,non-Indian water users have already fully appropriated and used the sources of water potentially available to satisfy tribal rights. Tribal efforts to protect and develop their water rights have encountered resistance from other water users and state water authorities. There is substantial ongoing litigation (approximately 60 pending cases as of 1995) and about 20 ongoing negotiation efforts aimed at achieving settlements of Indian water rights claims. The low availability of financial resources in certain cases makes it difficult for tribes to develop their water rights or to contest competing uses that interfere with Indian water rights,including instream flow rights for fishery purposes.

Historically, tribes often made significant concessions of their reserved water rights to obtain water development on reservations. Yet,many Indian irrigation projects have fallen into disrepair for lack of project funding. Some projects such as the Navajo Irrigation Project remain uncompleted,and others such as the Animas-La Plata Project have yet to be built despite Congressionally approved water settlements. Recently, the Secretary of the Interior promoted a comprehensive dialogue on a government-to-government basis with tribes in an attempt to develop a water rights negotiation process that responds to the concerns of tribes.

Adaptation Options

Although building additional flood controls or storage infrastructure to address the need to store earlier runoff for the summer may bemore attractive under climate change,environmental and cost constraints could serve as impediments. Where both local and imported supplies are available,there will be greater flexibility to deal with changes in water supply availability. If groundwater supplies are maintained as a buffer against drought,local areas are likely to have better coping ability.

Adaptation to potentially increased demand and reduced supply may focus on the demand side of water use. Here too,the development path for the West is critical. Should the increased population continue to use water at the same or an increasing rate, agriculture water allocations could be further reduced.As noted above,this can make it more difficult to reduce demand during droughts.

One source of adaptation lies in changing water pricing structures. Pricing water closer to its replacement cost would discourage wasteful uses. While market-based solutions would increase efficiency, it is possible there will be equity problems: users with limited resources,such as the poor and some farmers,may have to cut back on water use more than others.

Water transfers (between users and across river basins) will almost certainly play some role in addressing future water demand. These transfers include water savings derived from system enhancement measures such as canal lining and other waste reduction measures,and transfer of water currently used in agriculture for use in urban areas. In addition,institutions to manage groundwater quantity and quality may need to be strengthened (Knox, 1991).

The efficiency of municipal and industrial water uses can be significantly improved. Increased application of conservation technologies such as ultra low flush toilets and landscaping practices such as xeriscaping can reduce the growth of urban demand for water and lower the vulnerability of urban areas to drought. Use of treated effluent could be increased (Wong et al.,1999). Municipalities near the ocean can also reduce water demand by desalting seawater, which is an expensive option. For example,Santa Barbara recently built a desalinization plant.

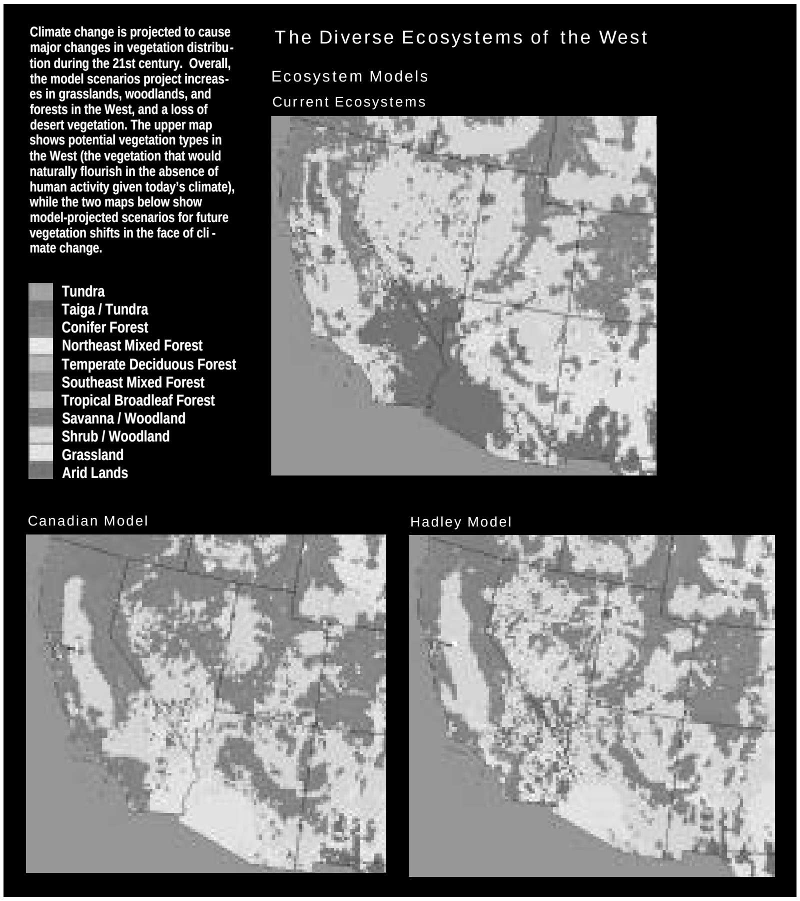
Increasing flood storage or flood control measures is likely to be an adaptation to increased risk of flooding. However, flood control management is shifting away from reliance on physical structures to effective management of floodplains,including restricting development,using wetlands,and trying to re-create the ability of rivers to spread floods to avoid concentrated downstream impacts (Wong et al.,1999). These adaptations may be effective if implemented in response to climate change,but would be more effective if implemented in anticipation of climate change. If annual precipitation increases, but summers become hotter and drier, there is likely to still be a need for additional storage to provide more water in the summer or for demand reduction measures to lessen the need for water in the summer.

2. Natural Ecosystems

The wide diversity of natural ecosystems in the West ranges from low-elevation deserts to alpine tundra (see Figure 8). In addition, productivity varies considerably. Most of the West is grassland, shrubland/grassland, and desert shrubland. The mountains contain coniferous forests, woodlands, deciduous forests (mostly aspen), and mixed forests. California has a wide diversity of ecosystems, including mostly coniferous forests in the north and in the Sierras, oak savanna and chaparral along the central coast, and shrubland and grassland along the southern coast and interior. The central and southern Rocky Mountains are dominated by ecosystems associated with mountains: alpine, coniferous forests interspersed with grasslands, and, at lower elevations, woodlands. The very dry environments in the Great Basin support shrublands, some grasslands, and deserts. The wetter parts of the Great Basin support woodland vegetation (USGS, 1993). Aquatic habitats range from cool mountain to desert streams and rivers, including reservoirs which have substantially altered the aquatic ecology of the West. In addition, wetlands in the west, particularly in arid areas, are important habitat for endangered species, fish rearing, and migratory waterfowl.

With this wide diversity of ecosystems and topography comes a wide diversity of species, many of which are in isolated habitats. California's climate zones, from coastal to desert to alpine regions, support a wide variety of plants and animals, as does the area near the New Mexico-Arizona-Mexico borders and Utah, with its deserts, canyons, and alpine peaks (Wilkinson and Rounds, 1998b; US EPA, 1998a and b).

Development has taken its toll on the natural ecosystems of the region. Dams and reservoirs have altered free-flowing streams, numerous plant and animal species have been eliminated or reduced to low numbers, and agriculture and ranching have transformed lowland ecosystems. By some estimates, 90% of California's wetlands have disappeared (Wilkinson and Rounds, 1998b). All of this alteration has made natural ecosystems vulnerable to invasion by hundreds of non-native species.



The Diverse Ecosystems of the West

Climate change is projected to cause major changes in vegetation distribution during the 21st century. Overall, the model scenarios project increases in grasslands, woodlands, and forests in the West, and a loss of desert vegetation. The upper map shows potential vegetation types in the West (the vegetation that would naturally flourish in the absence of human activity given today's climate), while the two maps below show model-projected scenarios for future vegetation shifts in the face of climate change.

Ecosystem Models

Current Ecosystems

Canadian Model

Hadley Model

Figure 8: Currently the West has a large diversity of ecosystems. Under the two climate change scenarios, the area in arid and grassland ecosystems would decrease and the area in forest ecosystems would increase. See Color Plate Appendix.

California contains more threatened and endangered species (257) than any of the other lower-48 states (US Fish and Wildlife Service, 1999) and is second highest in rate of species extinction (The Nature Conservancy, 1999). Myers et al. (2000) consider the California Floristic Province as one of the 25 "hotspots" in the world that have exceptional diversity of species and are experiencing exceptional loss of habitat.

The rise in population has resulted in more urban development and development into wooded areas which among other things has exposed human settlements to wildfires (see box on fires). Fire is a natural part of the ecology of the West. However, fire suppression has resulted in an unnatural increase in the density of vegetation, thereby making the landscape more susceptible to severe fires. In addition, some invasive species, such as cheatgrass, have increased fire frequency, while species such as star thistle and *Tamarix* have reduced water supplies and increased flooding (Chapin et al., 2000).

Vegetation

Under both the Canadian and Hadley climate scenarios, using the VEMAP biogeography and biochemistry models, biomass is projected to increase and vegetation to shift from deserts and grasslands to woodlands and forests in many parts of the region. Forests are projected to expand in California, Utah, and Colorado, mostly in the mountains. Nevada, northern Arizona, and western New Mexico are projected to see a shift toward shrub woodland and savanna woodland, while southwestern Arizona and southeastern California are projected to shift from arid lands to grasslands (see Chapter 2: Vegetation and Biogeochemical Scenarios: Future Vegetation). Across the West, a wetter climate is likely to increase forest productivity, including shifting some conifer forests to broadleaf forests, although there could still

Fire in the West

The rise in population in the West has resulted in more development into wooded areas and increased exposure to fire risk, which was already high (see Figure 9). For example, there were major fires in recent years in urban areas, including Oakland, Santa Barbara, Malibu, and Los Alamos. The Oakland fire destroyed or damaged about six thousand structures. In addition, fire suppression, which has resulted in dense growth and invasion of non-native species such as cheat grass, have made many Western forests more vulnerable to major fires. Continued development into forested areas, along with continued suppression of fires and spread of non-native species, is likely to increase risks of severe fires.

Studies suggest there is a good chance that climate change will increase the risk of fire frequency, whether precipitation increases or decreases in the region. Lower precipitation renders montane forests more fire-prone. These forests are already at risk because of the massive fuel buildup and predisposition to uncontrollable crown fires. Torn et al. (1998) found that warmer and drier conditions could lead to a “dramatic” increase in land area burned and potentially catastrophic fires in California. Higher precipitation increases the fuel loads of sparse vegetation in arid areas. If interannual variability of precipitation does not decrease, wet periods will be followed by dry periods and there is a good chance fires would increase. Modeling with a dynamic global vegetation model (MC1) found that fires across the West could increase under such conditions. As temperatures continue to rise, so would evapotranspiration, which can lead to more drying and more fires (Neilson and Drapek, 1998). Under the Hadley and Canadian scenarios, the fire severity rating in the West increases 10%.

Increased fire could reduce the indigenous vegetation in some cases and promote conversion to nonnative weeds. More fire could degrade water quality because of increased runoff of sediments. Fires also add to air pollution. Should fire increase, there could be increased risks for human settlements within or close to forests and grasslands.

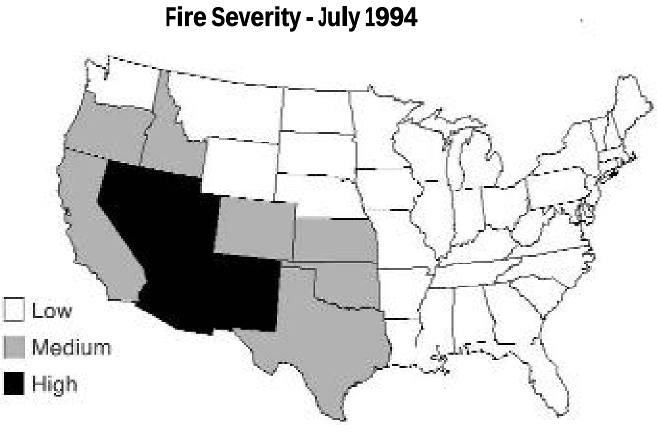


Figure 9: Relative fire severity across the United States in July, 1994. All of the states with high fire severity were in the West. Source: Liverman, 1998. (see http://udallcenter.arizona.edu/publications/pdfs/swclimatereport-final.pdf, page 22.)

The risk of fire in urban areas and in heavily forested areas could be reduced through a number of measures. Restrictions can be placed on development in fire-prone areas. Building and landscape design criteria have been developed for fire-prone areas. Construction with nonflammable materials and installation of “firescape” landscape designs are also being used in high-risk areas. Controlled burns may also need to be used as part of a vegetation management strategy in urban areas. Many of these adaptations have been implemented in response to urban fires such as those in Oakland. Fires in natural areas should not be suppressed to the degree that a large amount of fuel buildup is allowed. These adaptations should be implemented in anticipation of climate change.

be a net increase in conifer forest cover (Neilson and Drapek,1998). The higher temperatures,however, are likely to result in many alpine areas virtually disappearing from the West and being replaced by temperate forests (see Chapter 2: Vegetation and Biogeochemical Scenarios).Note that the projected changes do not show steady increases in biomass in all places at all times. Under the Hadley model, vegetation productivity declines in New Mexico and Arizona by the 2030s. One model result shows that in Colorado, forests first decrease in area by 2030, but expand by 2095 to cover an area larger than today.

There are a number of reasons for caution about these projections. First the CO_2 fertilization effect on plant growth and water use efficiency may not be as positive as assumed in the models (Walker and Steffen,1997). Under the Canadian model,assuming no CO_2 fertilization effect,biomass is projected to decline in some parts of the West (Aber et.al., 2001). Modeling conducted for this Assessment and other studies discussed in the box on fire show an increased risk of fire in the West. Climate change could also make conditions more favorable for pest outbreaks and introduction and spread of invasive alien species (Dale et al.,2001). Should high levels of air pollution continue and wind storms increase, these would be additional stresses on forests. It is also uncertain whether transitions from one type of ecosystem to another would be smooth or involve disruptions.

Furthermore,as climate continues to change,the CO_2 fertilization effect (which increases growth and water use efficiency) becomes saturated and declines,and higher temperatures would impose more moisture stress on vegetation.

If conditions become drier, productivity of vegetation is likely to decrease (Neilson and Drapek, 1998). There could be a shift from forests, woodlands,and shrublands,to grasslands and deserts.

Biodiversity

As noted above,development has resulted in fragmentation of habitats,creation of barriers to migration,such as urban areas and dams,and introduction of invasive species. This,in combination with the complex topography and varied climate of the region,is likely to make it difficult for many species to adapt to climate change through migration. It is also likely that development would favor the spread of invasive and non-indigenous species because invasive species are generally better suited to changing conditions. Without development,the adverse impacts of climate change on biodiversity would likely be substantially reduced.

While the mountains of the West can serve as barrier to species migration,they also provide higher altitude and northern routes for migration as well as many microclimates that can create refugia for some species. But,migration upslope also means migrating to smaller and smaller areas of habitat,which would only support smaller and smaller populations. As climate change continues,species migrating upslope are very likely to be threatened as their habitats figuratively disappear off the tops of mountains.

The faster the rate of climate change,the greater the stress will be on many species and populations.

Terrestrial Species

Hansen et al.(2001) found there is a slight chance that Quaking Aspen and Engleman Spruce will not survive under projected climate change (however, this study did not account for the positive effects of CO_2 fertilization). Interestingly, paper birch is projected to expand southward in the Rocky Mountains. Hansen et al.(2001) also found that animal populations could change. It is possible that higher temperatures lead to a decrease in bird and mammal populations that are currently found in the region because they cannot tolerate higher temperatures. It is possible that higher temperatures could increase reptiles and amphibians in the southern Rocky Mountains because of their greater tolerance for heat.

Murphy and Weiss (1992) projected that a 5˚F (3˚C) warming would result in a substantial reduction in the area of the Great Basin suitable for boreal species. They estimated that plant species would be reduced from 305 to 254, four of nine mammals would be lost,and 23 to 30% of butterflies living in boreal areas in the Great Basin would become extinct. On the other hand,there is some chance that higher temperatures would enable some southwestern desert plants to invade the Great Basin (Neilson and Drapek,1998),although such a large-scale change could take thousands of years to be realized.[7]

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[7] In warm periods in the past,some species migrated to new locations, while others remained in the same general location (Tausch et al., 1995).

Observed Shift in Range of Edith's Checkerspot Butterfly: 1900 to 1990s

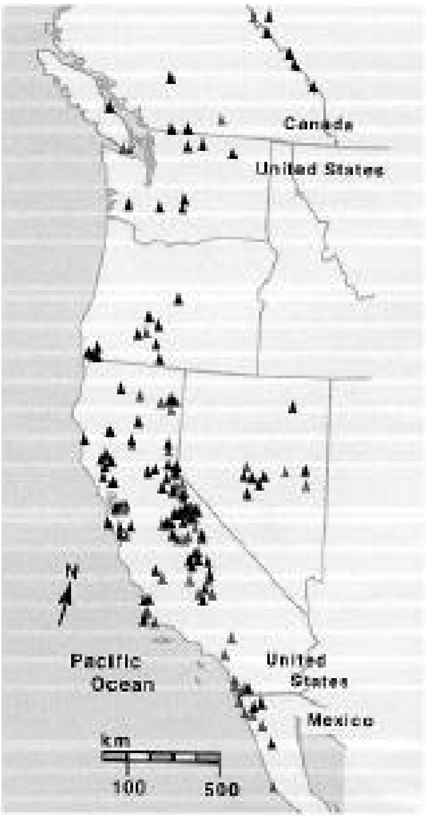

Figure 10: On this map of studied sites, the lighter triangles represent extinct populations of Edith's Checkerspot butterfly, while the darker triangles represent present populations. The mean location of populations of this butterfly has shifted northward by 57 miles (92 kilometers) and upward in altitude by 407 feet (124 meters) since 1900. This is an indication that climate change is already having an affect on the some species ranges. Source: Parmesan, 1996. See Color Plate Appendix.

Aquatic Species

Aquatic and riparian ecosystems in the West are also vulnerable to changing precipitation and runoff regimes. Wetlands may have some resiliency to climate change because they currently cope with highly variable climate conditions (Grimm et al.,1997). While wetter conditions are likely to alleviate some existing stresses,higher temperatures are likely to exceed the thermal tolerances of many fish species and lead to increased fragmentation of many cold water fish habitats particularly in mountains (Meyer et al.,1999). It is probable that some alpine and cold water fish species will not survive in the region (Grimm et al.,1997). In addition,higher temperatures are likely to allow for invasions by non-native fish species (Wagner and Barron,1998). It is also possible that higher water temperatures would be a problem for salmonid populations,since these fish are near the southern end of their range now in California and show signs of stress in the warmer years (Wilkinson and Rounds,1998a). Drier conditions are likely to result in the loss of many small water bodies and aquatic ecosystems (Grimm et al., 1997).

In addition,the change in seasonality of runoff is likely to have adverse effects on many species. It is difficult to anticipate exactly how these changes in flow magnitude and timing would affect particular species or flow-dependent habitats. However, some general predictions can be made based on knowledge of species life history strategies in relation to hydrology. In general, climate-related hydrologic changes are very likely to favor some species more than others, resulting in decreased species diversity and altered composition of native biological communities. For example,it is possible that alterations to the timing and magnitude of spring flows will favor non-native riparian plants that would otherwise be suppressed by high runoff in spring (Kattelmann and Embury, 1996). Modified flow regimes are also very likely to affect populations of native fish species. For example,the distribution and abundance of the four seasonal runs of chinook salmon native to the Sacramento River drainage that are already in jeopardy are likely to be further altered by seasonal changes in the availability of spawning flows (Yoshiyama et al.,1996).

Observed Effects on Species

The effects of climate change on species are already being observed. Parmesan (1996) found that the mean location of populations of Edith's Checkerspot butterfly shifted northward and upward in elevation since the beginning of the century (Figure 10). She found that the southern boundary moved northward but was unable to determine if the northern boundary moved further northward (Camille Parmesan,University of Texas,personal communication.) These butterflies do not migrate;in fact,it is their relatively sedentary nature that makes them a good choice for tracking long term trends in wildlife range shifts in response to climatic warming. A range shift northward is a process which takes decades. In theory, as climate change makes the most southern regions less suitable and the far northern regions more suitable,populations at the southern end of the range go extinct while new populations are established northward of the previous boundary. However fragmentation of habitat and barriers to migration are likely to impede northward migration of many species, resulting in decreases in their total range.

Sagarin et al.(1999) found that in the past 50 years, the southern invertebrates have become more common and northern invertebrates have become less common in the rocky intertidal community in Pacific Grove,California. Both of these changes appear to be the result of higher temperatures.

Adaptation Options

A number of steps could be taken to at least help reduce some of the pressures of development on ecosystems and biodiversity and even anticipate the need for species to migrate in response to climate change. Urban development could be managed to better protect riparian areas and reduce habitat fragmentation. There could be concerted efforts to link habitats and even create migration corridors for species to migrate northward or upslope in response to climate change. The current trend toward reduced land for agriculture could present some opportunities if abandoned lands are used for habitat. Reducing offstream water use will also help improve aquatic habitats. These measures would need to be implemented in anticipation of climate change. It is not clear how effective many of these measures,particularly migration corridors, would be in averting negative effects of a warmer and wetter climate on natural systems. In addition,implementing these measures may be challenging,while continued urban and suburban development could result in increased stress on ecosystems and species diversity.

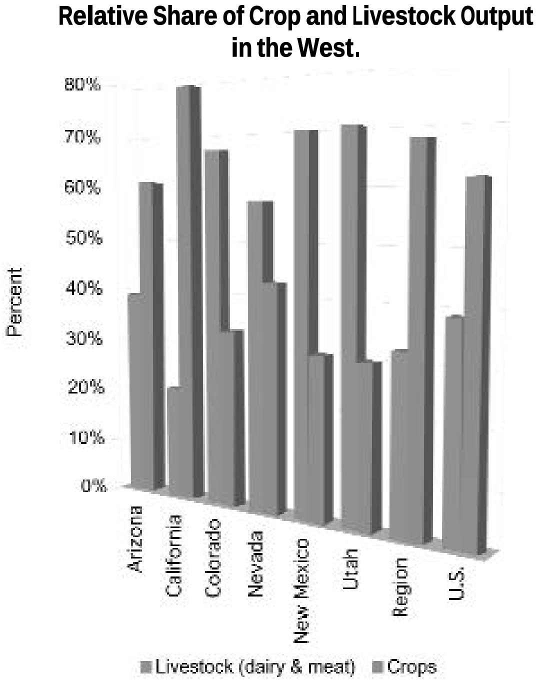

Figure 11: For most of the states in the West, the majority of value-added agriculture production comes from livestock and dairy production. However, because California's agricultural production is dominated by crops (75% of total agricultural output for the state), and because California dominates regional agricultural output (84% of regional crop production, 51% of regional livestock and dairy production), the majority of the region's total agricultural production comes from crops. This difference between the dominant types of agricultural production on a state level and on a regional level highlights the heterogeneity of agriculture in the West. Source: USDA Economic Research Service State Farm Sector Value-Added Data; (http://www.econ.ag.gov/briefing/fbe/fi/fivadmu.htm). August 30, 1999. See Color Plate Appendix.

Table 2. Relative Share of Crop and Livestock Output in the West

State	Output	Percentage of Combined Crop and Animal Output
Arizona	Crop	60.94%
	Livestock and Dairy	39.06%
California	Crop	79.02%
	Livestock and Dairy	20.98%
Colorado	Crop	33.14%
	Livestock and Dairy	66.86%
Nevada	Crop	42.66%
	Livestock and Dairy	57.34%
New Mexico	Crop	30.22%
	Livestock and Dairy	39.78%
Utah	Crop	29.75%
	Livestock and Dairy	70.25%
Region	Crop	67.74%
	Livestock and Dairy	32.26%

3. Agriculture

The total value of crop and livestock production in the West in 1997 was $32 billion (US BEA, 1999a;see Figure 11. About two-thirds of the value of western agriculture is from crops,with the rest from livestock (Figure 11 and Table 2). Fruits,tree nuts,and vegetables comprise about two-thirds of the value of crop production,while seven-eighths of livestock production is from meat animals and dairy products. The West produces 17% of the nation's agricultural output,but three-fifths of the country's fruits and tree nuts, almost half of the vegetables,and almost one-quarter of the dairy products.

Higher CO_2 concentrations are likely to help increase crop yields and decrease water demand, although higher temperatures are also likely to hasten phenological development of crops (resulting in reduced yields) and increase demand for water. Higher precipitation can increase yields but can also cause flooding and waterlogging of crops.The net effect on yield will depend on relative changes in CO_2 concentrations,temperature, and precipitation.

Milder winter temperatures are likely to lengthen the growing season and result in a northward shift of where some crops are planted,assuming the land and infrastructure are available for such geographic shifts.In addition,there is some chance that frost-sensitive plants once grown primarily in areas such as the Imperial Valley of California will be grown in the state's Central Valley.

Conversely, it is possible that crops that prefer cold winters such as winter wheat and potatoes could be limited to more northern areas (although other wheat varieties could be grown). It is very likely to be more difficult to relocate perennial crops such as vineyards,fruits and nuts, than to relocate annual crops,because perennials can take many years to decades to get established. In addition, warmer temperatures can inhibit growth of certain fruit and nut crops that require chilling during the winter. It is also possible that warmer temperatures will increase heat stress, weeds,pests,and pathogens that affect plants,animals,and farm workers.

Changes in the seasonality of precipitation could cause some problems. There is some chance that vineyards, for example,could experience losses if rains increase near harvest time — unseasonable rain can cause molds, ruining the grapes. Higher air temperatures and humidity can increase risk of diseases that can harm vineyards. However, higher temperatures in the Sonoma and Napa Valleys since 1951,which is mainly the result of nighttime warming,improved the quality and yield of wines (Nemani et al.,2001).Cotton yields can also be reduced by rain at critical stages of growth.

Should the climate become hotter and drier, agriculture would be at particular risk. It is probable that the amount of water available for irrigation will be reduced substantially (Hurd et al.,1999b). Thus, agriculture could be squeezed between an increased need for water and less available water. If additional irrigation water is applied,there would be increased salinity in soils and rivers. Rural communities would be sensitive to declines in agriculture or ranching.

Estimated changes in irrigated crop yields using scenarios derived from the Hadley and Canadian climate models in the 2030s and 2090s for the "Pacific"and "Mountain" regions are displayed in Table 3. The Pacific region includes California, Oregon,and Washington,and the Mountain region contains all of the Rocky Mountain states. The 2030 results assume a CO_2 concentration of 445 parts per million (ppm),and the 2095 results assume CO_2 levels of 660 ppm (Francesco Tubiello,Goddard Institute for Space Studies,personal communication, 1999). The specific numerical results should be treated with caution since they include states outside the West as it is defined here and include optimistic assumptions about the CO_2 fertilization effect while not considering other effects such as pests and disease. The results show increases in yields for many crops,but decreases for some crops such as tomatoes in the Pacific and hard red spring wheat in the mountain states. Although not shown,the results tend to show small changes in demand for irrigation water for the major western crops,but in a few cases,significant decreases in demand. Crop production in the Pacific and Mountain states is projected to increase (see Chapter 13:Agriculture).

Adaptation Options

One strategy to adapt to the effects of climate change is to maintain and increase the diversity of crop types and varieties,because diversity increases the likelihood of having some crops that fare well under variable climate conditions. For example,in California,the artichoke crop was good in 1998,but the orange crop was devastated by freezing conditions. Farmers may also plant low-chill varieties of certain tree crops in anticipation of higher average temperatures. This adaptation is already under way

Table 3: Estimated Changes in Crop Production in the West

Estimated Percent Changes in Dryland Crop Production for the Mountain Region from the Canadian and Hadley Models (%)

	2030s		2090s	
Crop	Canadian	Hadley	Canadian	Hadley
Cotton	4.86	16.73	50.41	38.55
Hard Red Spring Wheat	12.92	16.90	-10.54	27.47
Hay	9.57	11.14	16.77	30.50
Tomatoes (processed)	21.92	23.59	-22.99	35.19
Oranges (processed)	66.90	69.90	114.60	111.60
Pasture	20.90	19.50	51.49	49.27

Estimated Percent Changes in Irrigated Crop Production for the Mountain Region from the Canadian and Hadley Models (%)

	2030s		2090s	
Crop	Canadian	Hadley	Canadian	Hadley
Cotton	74.22	92.11	188.24	170.36
Hard Red Spring Wheat	-16.98	-1.22	-29.62	-1.41
Hay	17.29	30.58	16.32	33.00
Tomatoes (processed)	21.92	23.59	-22.99	35.19
Oranges (processed)	66.90	69.90	114.60	111.60

Estimated Percent Changes in Dryland Crop Production for the Pacific Region from the Canadian and Hadley Models (%)

	2030s		2090s	
Crop	Canadian	Hadley	Canadian	Hadley
Cotton	6.58	22.63	68.22	52.17
Hard Red Spring Wheat	16.25	65.75	137.90	131.10
Rice	6.49	6.27	1.76	5.77
Hay	26.76	28.38	62.24	50.29
Tomatoes (processed)	-19.95	-9.14	-7.62	-19.54
Oranges (processed)	36.87	42.77	77.90	73.03
Pasture	47.53	58.83	102.12	92.55

Estimated Percent Changes in Irrigated Crop Production for the Pacific Region from the Canadian and Hadley Models (%)

	2030s		2090s	
Crop	Canadian	Hadley	Canadian	Hadley
Cotton	41.66	51.70	105.66	95.62
Hard Red Spring Wheat	0.25	4.60	4.80	11.75
Rice	6.49	6.27	1.76	5.77
Hay	38.26	61.06	52.94	70.33
Tomatoes (processed)	-19.95	-9.14	-7.62	-19.54
Oranges (processed)	36.87	42.77	77.90	73.03

and can be enhanced in response to climate change. Breeding crops better suited to take advantage of higher CO_2 levels and more heat may also make sense.

Development of drought- and heat-resistant crops will help reduce the vulnerability of the agriculture sector. Bioengineering could be helpful in this regard,but this is a complicated issue with advantages and disadvantages.

There is substantial potential to reduce current and future water use through less water demanding technologies and better water management practices. Agriculture could switch from high water use crops such as irrigated pasture,alfalfa, cotton,and rice,to less water demanding crops such as soybeans,wheat,barley, corn for grain,and sorghum (USDA,1997;Gleick et al.,1995). Water-intensive crops grown in desert areas could possibly become uneconomic if water prices increase. More efficient irrigation technologies such as sprinklers or drip irrigation can reduce water demand. Crops may need to be planted earlier to take better advantage of earlier runoff (higher temperatures may also favor earlier planting of crops).

4. Ranching

Ranching is quite sensitive to climate variability. The cattle industry in Arizona reduced herd size by about 80,000 head during the 1994 to 1996 drought,but an increase in precipitation in New Mexico in the same period resulted in an increase of 100,000 head of cattle (McClaren and Patterson, 1998)

It is possible that an increase in temperature and precipitation could have the benefit of increasing forage production in many locations,and lengthening the growing and grazing season on native rangelands. Moreover, increased water supplies and longer growing seasons would make it possible to harvest more alfalfa crops per year (now typically two to three),increase hay supplies,and reduce prices.

A warmer and wetter climate can pose problems for dairy cattle. There is some chance that flooding could wash out holding ponds. If winters become wetter, it is possible dairy cattle will suffer. In the Chino,California area,which produces 25% of the state's milk,some 6,500 head of cattle died during El Niño conditions in February 1998. Cows and calves became mired in mud and weakened by the cold,succumbing to bacterial infections that breed in the muck. However, should conditions become generally wetter, it is likely vegetation will get more dense,which may reduce winter mud.

Ranching is extremely vulnerable to drought (Liverman,1998) and should the climate become drier, vegetation productivity, water supplies,and the carrying capacity of land and,hence,livestock production, would be reduced. In addition,higher temperatures can increase livestock diseases and calving problems (Wagner and Baron 1998). The economic impact would be felt most strongly in the rural and intermountain areas.

Adaptation Options
Stakeholders identified improvement in weather forecasting to be the most important adaptation for ranching. The timing of cattle sales and breeding, and the range of management strategies that ranchers employ, depend on knowledge of anticipated and observed range conditions and long-term water availability. Consideration may be given to raising different species or breeds more suitable for hotter conditions (Wagner and Barron,1998). Management practices should be adjusted to changes in conditions to reduce stress on ecosystems when appropriate.

5. Coastal Resources

Although a large portion of California's coast is made up of cliffs,many of the state's most populous coastal areas are vulnerable to sea-level rise,including the San Francisco Bay area and the coast south of Santa Barbara. If no protective measures are taken,sea-level rise will inundate hundreds of square miles of low-lying land in California (Gleick, 1988). Unless protected,coastal structures from harbors to houses could succumb to the ocean,as numerous California beachfront homes did in February 1998. Also,beaches will be flooded unless defensive actions are taken. Agricultural lands in the Sacramento-San Joaquin delta,some already as much as 25 feet below sea level,are threatened with inundation. As the ocean encroaches,some aquifers near the coast will become contaminated by saltwater intrusion. Rising sea level could inundate many coastal wetlands and unprotected development (see Figure 12). Should sea walls be used to protect coastal areas downslope, wetlands are likely to be blocked from migrating inland with the sea and could thus be lost.

A study of the costs of protecting the margins of San Francisco Bay from a 3.3-foot (1-meter) sea-level

[8] Gleick and Maurer (1990) also noted that many costs were not,or could not be,quantified.

rise concluded that more than $1 billion (1990$) would be needed for new or upgraded levees to protect existing industrial and commercial developments, with an additional annual maintenance cost exceeding $100 million (Gleick and Maurer, 1990).[8]

Adaptations Options

Strategies for protecting developed coastal areas include defending with engineered fortifications any assets of high economic value such as cities, airports, ports, and delta levees (for water supply security); relocating vital assets to higher ground (or engineering alternative solutions); and, for less economically valued areas of the developed coast (housing on coastal bluffs), retreating. Building coastal defenses can block inland migration of wetlands and result in loss of beaches. Advance planning can prevent new developments from being built in areas likely to be at risk in the future. Avoiding new construction is likely to prove far less costly than trying to protect such development in the future. For new development of any kind, local government agencies such as the Coastal Commission could be authorized to consider "risk of harm" from impacts of climate change. After consideration of risk of harm, developments would be approved only with no assured warranty of safety or loss, and private insurance would underwrite the risk or self-insurance would bear any costs or losses.

6. Tourism and Recreation

The spectacular scenery, favorable climate, and large amounts of public land, especially in national parks, have made the West a major destination for tourists from around the world. Billions of dollars have been invested in ski resorts in all of the region's states, with Colorado, Utah, and California having particularly extensive facilities which attract many visitors. Tourist expenditures in the West are growing. Hotels, lodging, amusement, and recreation provided $32 billion in revenues in 1996 and are projected to provide $52 billion in 2045 (US BEA, 1999a).

Since the tourism industry in the West is so strongly outdoors oriented, it is particularly sensitive to climate. The period for winter activities is likely to shrink, while the period for summer activities is likely to increase. Natural vegetation provides part of the aesthetic attraction, and significant climate-change effects on western ecosystems are very likely to change the distribution and abundance of vegetation and animals. Much of the attraction for tourists is associated with water: its inherent aesthetic appeal, and the growing water-related sports of fishing, whitewater rafting, kayaking, and canoeing. Some of this recreation is on the many artificial lakes such as Lake Powell and Lake Mead. Increases in runoff could possibly enhance these sports while decreases could possibly reduce their attractiveness.

The skiing industry is at particular risk from higher temperatures. With rising temperatures, snowpack seasons are very likely to shorten. Moreover, snow-

Current and Projected Wetlands in South San Francisco Bay

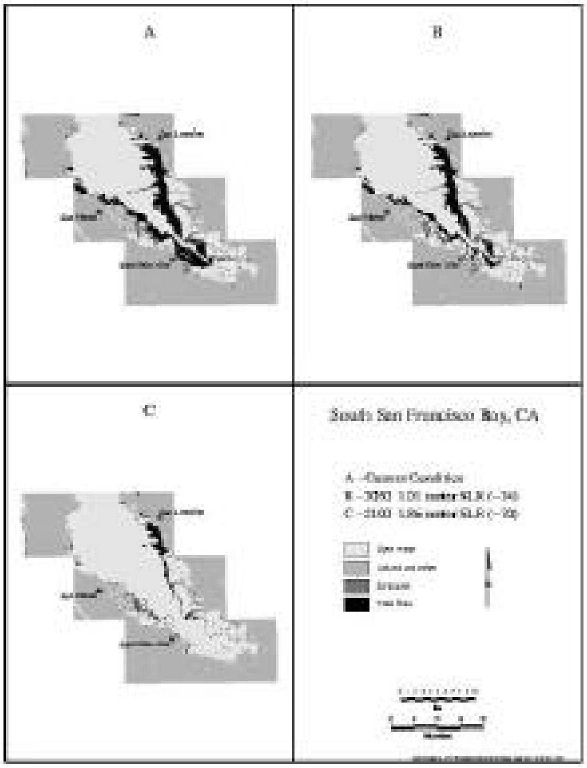

Figure 12: This figure shows the spatial extent and distribution of current and projected wetland habitat types in southern San Francisco Bay (derived from US Fish and Wildlife, National Wetlands Inventory data) following sea-level rise as calculated using the Sea Level Affecting Marshes Model (SLAMM4) (Galbraith et al., In prep.). The sea-level rise scenarios use historic rates that include local subsidence (obtained from tide gages at or close to each of the sites), superimposed on the median estimate of the likely rate of sea-level change due to climate change (Titus and Narayanan, 1996). The historic rate of sea-level rise in the southern part of San Francisco Bay is estimated to be 3.0 feet (0.9 meter) by 2050 and 5.3 feet (1.6 meter) by 2100. This could be due to tectonic movements resulting in land subsidence and/or crustal subsidence due to the depletion of subterranean aquifers. When combined with the projected median estimate of 13.4 inches (34 cm) eustatic (global) sea-level rise by 2100 from climate change, sea-level rise is estimated to be 3.3 feet (1.0 meter) by 2050 and 6.1 feet (1.9 meters) by 2100. The numbers shown in parenthesis on the figure indicate that approximately 57.7% of tidal flat habitat will be lost by 2050 and 62.1% by 2100, compared to the current condition. Using only the historic rate of local sea level rise, approximately 58.9% (2050) and 61.1% (2100) of tidal flat habit. See Color Plate Appendix.

line elevations will rise. Lower-elevation and more southern ski areas are likely to be at greatest risk.

On the other hand, rising temperatures are likely to result in a longer summer season for warm weather recreation activities. Backpacking,biking,mountain climbing,and rock climbing have been growing in popularity. For example,the number of backpackers in the Canyonlands of Utah rose sevenfold from the early 1970s to the mid-1990s (Riebsame,1997). But there is some chance that increased precipitation could decrease the number of days desirable for summer recreation activities. Whether warmer and wetter conditions would result in a net increase or decrease in summer recreation is unclear.

Adaptations Options

Adaptations for tourism and recreation generally involve diversification of income sources. The larger, better-capitalized resorts such as Aspen and Vail have already adapted their facilities to serve as summer destination resorts with a range of warm-season recreational activities,conference facilities,and music and dance programs;those with private land have extensive,high-priced real estate development. The smaller areas may not be sufficiently capitalized or have the private land to achieve these forms of diversification. This strategy can be taken in response to climate change and can be done in anticipation of climate change only to the extent that current recreation patterns support it.

ADDITIONAL ISSUES

Mining

The mining industry is quite sensitive to climate variability and change because of the importance of water to its production processes,and the fact that environmental laws hold mines liable for the quality of effluent water. Water is needed for the concentration step of processing. In addition,a typical mining operation is required to collect and use or process all precipitation that falls within the limits of the facility or otherwise comes in contact with unnaturally exposed material. There is some chance that increased precipitation can result in more runoff of pollutants,while decreased precipitation could result in reductions in water supplies for processing. The mining industry is likely to adapt to climate variability by relying on short-term forecasts of precipitation in day-to-day operations,interannual forecasts of precipitation for temporary enhancement of water treatment facilities,and long-term climate outlooks to decide on capital improvements in water holding areas,mechanical pumps,and water treatment facilities.

Air Quality

Air quality is a significant problem in many parts of the West. For example,with 17 million inhabitants occupying a basin subject to many temperature inversions,the greater Los Angeles area has a particularly serious problem with ground-level ozone levels and particulate matter. In addition,San Francisco,Las Vegas,Phoenix,Reno,and Salt Lake City have problems meeting federal government standards for ozone levels,and many western cities have particulate matter concentrations close to or exceeding federal standards.

If precursors are not reduced and temperatures increase,it is possible that ozone levels,which are at their peak in the summer, will increase. Higher temperatures increase ozone formation when precursors are available. Should wetter conditions increase biomass,which emits ozone precursors,air quality could further decline. Fine particulate matter concentrations could also increase. This could lead to more health problems. On the other hand, increased El Niño conditions,which would result in more storms and precipitation in the winter, would be likely to reduce levels of winter air pollutants, such as carbon monoxide and particulates. Reducing emissions of air pollutants,which is needed anyway in many Western cities,may be even more necessary because of climate change.

Health Effects

Since the West is generally dry, it is likely to be at lower risk of increase in vector-borne infectious diseases than more humid regions. Should the West become warmer and significantly wetter, there is some chance that there could be an increase in the potential presence of disease vectors. In recent years, wetter conditions contributed to the outbreak of cases of Hantavirus in the region,particularly in the Four Corners area (Engelthaler et al.,1999). It is possible that wetter conditions would increase the potential for a Hantavirus outbreak and other climate sensitive diseases such as plague (Parmenter et al.,1999),assuming other control measures are not taken. But,because of the capability of the public health system,it is unlikely that there will be large outbreaks of infectious diseases in the West. It is more likely that if climate gets warmer and wetter, the potential for small outbreaks from people carrying the diseases from other countries into the region would increase. To keep health risks low, it is critical that the public health system be maintained.

The region currently has lower risk of heat stress mortality than Midwest and Northeastern cities. Kalkstein and Greene,1997 found in San Francisco and Los Angeles, winter mortality would decrease, while in Los Angeles summer mortality would increase. The estimated net change in mortality across the nine large western cities studied is close to zero.

ADAPTATION STRATEGIES

For managed systems in the West, there appears to be significant potential to reduce negative consequences of climate change and take advantage of positive impacts. For example, wise water management can reduce the risks from droughts and floods. The potential for adaptation appears to be high in many of the other potentially affected sectors of the economy. And many of the measures mentioned above would have significant benefits regardless of climate change. Clearly though, these adaptations will involve costs, are not necessarily easy to implement, and can result in both winners and losers. The costs and feasibility of these adaptations were not assessed. Should there be sudden or extreme climate changes, it is not clear how effective adaptations would be in ameliorating adverse impacts.

Risks from climate change are likely to be greatest for those affected sectors or subsectors that lack the resources or capacity to adapt. For example, it is uncertain how effective the adaptations discussed above would be in reducing the vulnerability of natural ecosystems and biodiversity to climate change. Reducing current stresses on natural systems may help, but adverse impacts are still likely to occur. Poor or immobile people are likely to bear particular risks from climate change. In addition, activities that are fixed in place, such as national parks and Indian reservations, are at particular risk because they are unable to relocate in response to climate change. The development of adaptation strategies may need to pay particular attention to these types of situations.

Many development trends can increase vulnerability to climate change. But the development of the West also presents many opportunities to prepare for and thereby reduce the risks of climate variability and change in development plans and projects. For example, development can attempt to minimize water use and degradation of water and air quality. Coastal structures can be designed to minimize the risks of sea-level rise and harm to natural ecosystems. Development in flood plains can be reduced. The tourist industry can further diversify into both winter and summer recreation. The public health system can be maintained and improved. Riparian areas can be protected, fragmentation of ecosystems reduced, and migration corridors developed or maintained. The capability of the poor and immobile to adapt can be enhanced. The effectiveness of these strategies in reducing the risks of climate change has not been assessed.

One strategy that should help virtually all affected sectors is improved forecasting of climate. In particular, improved seasonal and annual forecasting of climate would help water supply managers, farmers, ranchers, miners, health care professionals, and others plan for wet or dry seasons and extreme heat and cold episodes. Improved multidecadal forecasts of climate change would help infrastructure designers, land use planners, and others in identifying future directions of climate change.

CRUCIAL UNKNOWNS AND RESEARCH NEEDS

Clearly there are many uncertainties about how climate in the West will change and what the impacts of such changes will be, and there are many research needs that should be addressed to help resolve uncertainties. Improved research is a coping strategy itself, and many of the research areas will help improve the effectiveness of adaptations identified above. A number of general research needs cut across all sectors sensitive to climate change:

- Improve climate forecasts for the West: improve predictions of the sign, magnitude, and seasonality of change of important climate variables such as precipitation, and improve the estimation of probabilities.
- Seek a better understanding of the interrelationships between climate impacts and the institutional structures that facilitate or constrain effective action.
- Improve methods for involving the public in research and communicating research results to the public and decision makers.
- Conduct more research on adaptation, specifically to improve understanding of the potential effectiveness, costs, and impediments to adaptations.

Water

- Develop a better understanding of the human and ecological impacts of climate variability and change on water resources, particularly at the local and regional levels.
- Analyze all water resource options, including full

efficiency potential in all sectors, water transfer options, impacts of pricing changes on all sectors (including the impacts of different water price levels on the types of crops grown in different locations).
- Develop methodologies, analytical tools, and design criteria for incorporating increased climatic variability and change into hydraulic design and water resources planning and management.
- Develop effective long-term strategies for conservation.
- Study improvements in flood forecasting and response, improvements in reservoir management, and enhancement of other infrastructure that may be vulnerable to climate impacts.
- Improve understanding of groundwater resources in terms of amounts, locations, water quality, relationship to surface water, and potential for recharge, including effects of climate variability and altered precipitation. Develop an accurate and complete inventory of groundwater, ascertain the rates of use and potential for natural recharge, examine the extent to which it can be recharged by technology, and understand how all of these parameters would be affected by an increase or decrease in precipitation.
- Examine how to effectively transfer knowledge and technology from the research community to the public, particularly with regard to improving long-term planning and developing more realistic supply/demand water budgets.

Agriculture

Many of the research topics that apply to water resources are critical for agriculture. Additional research topics include the following:

- Improve understanding of the effect of climate change on plant yield and health.
- Enhance knowledge of how climate change and variability may affect pest and disease problems.
- Improve understanding of the effects of ENSO on agriculture.
- Examine the impact of climate change on the competitiveness of agriculture with other regions in the US and globally.
- Analyze the institutional obstacles to adaptation to climate change in agriculture (water laws, endangered species, etc.)

Ranching
- Examine how ranchers cope with climate variability and how their experience can be used to enhance their ability to adapt to climate change. Examine the interactions between urban development, climate change, and loss of land for ranching.
- Examine the impact of climate change on the competitiveness of ranching with other regions in the US and globally.

Coastal Issues
- Develop a statewide (California) map identifying the extent of sea-level rise. Certain areas have been mapped using a simple 1-meter demarcation, but the maps have not been based on the best available mapping technology, such as that used by NOAA and NASA.
- Analyze the impacts of sea-level rise and accelerated cliff erosion on buildings, energy, transportation, coastal infrastructure, and other features. The impacts of altered sediment flows along the coast may also have important implications for harbors and navigation.

Ecosystem Management
- Conduct extensive interdisciplinary ecosystem research, monitoring, and modeling in the region to provide an understanding of ecosystem structure and function on which sound land-management practices can be based.
- Improve understanding of CO_2 fertilization on natural ecosystems.
- Improve understanding of the effectiveness of possible adaptations for preserving biodiversity.

Fire
- Improve modeling and predictive capacity to allow fire personnel to deploy resources as needed.
- Link the remote sensing and GIS-based images being used with models to better understand fire risk and the dynamics of fire to increase ground-truthing. Additional work on the dynamics of fire and ecological communities would improve the modeling efforts.

Health
- Improve understanding of the vulnerability of the region to the spread of infectious diseases and heat waves.
- Improve understanding of the relationships between emissions of air pollutants, climate change, and resulting air pollution.

Landscape Processes
- Conduct more research on how climatic change will affect the land surface, in terms of erosion by wind and water, sediment discharge, and landslide potential.

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