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CHAPTER 14
CALIFORNIA

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FINDINGS

Global warming could cause higher winter runoff and lower spring runoff in California and increase the difficulty of meeting water supply needs. It could also increase salinity in the San Francisco Bay and the Sacramento-San Joaquin Delta and increase the relative abundance of marine species in the bay; degrade water quality in subalpine lakes; raise ambient ozone levels; increase electricity demand; and raise the demand for water for irrigation.

Water Resources

- Higher temperatures would lead to higher winter runoff from the mountains surrounding the Central Valley, because less precipitation would fall as snow, and the snowpack would melt earlier. Runoff in the late spring and summer consequently would be reduced.

- As a result, the amount and reliability of the water supply from reservoirs in the Central Valley Basin would decrease. Annual water deliveries from the State Water Project (SWP) could be reduced by 200,000 to 400,000 acre-feet or 7 to 16%. In comparison, the statewide increase for water from the SWP, due to nonclimate factors such as population growth, may total 1.4 million acre-feet by 2010. Even if operating rules were changed, current reservoirs would not have the capacity to store the heavier winter runoff and at the same time retain flood control capabilities.

- Rising sea level could increase the possibility of levee failure. If the delta and bay levees failed and sea level rose 1 meter (40 inches) by 2100, agriculture in the delta region would be almost eliminated, the pumping of freshwater out of the delta to users to the south could be jeopardized by increasing salinity, and the area and volume of the estuary could triple and double, respectively. Even if the levees were maintained, the estuary could still increase in area and volume by 30 and 15%, respectively, as a result of a 1-meter sea level rise alone.

- Sea level rise of 1 meter could cause saline (brackish) water to migrate inland between 4 and 10 kilometers (2.5 and 6 miles, respectively) if the levees fail and if tidal channels do not erode. Freshwater releases into the delta might have to be doubled to repel saline water near the major freshwater pumping facilities.

Wetlands and Fisheries

- The wetlands in the San Francisco Bay estuary would be gradually inundated as sea level rises faster than the wetlands accrete sediments. The amount of wetlands lost would be a function of the rate of sea level rise and of whether shorelines are protected. If sea level rises 1 meter by 2100, the rate of rise will be greater than wetland vertical accretion by the middle of the next century. If sea level rises 2 to 3 meters by 2100, wetland inundation will begin early in the 21st century.

- If salinity increases within the San Francisco Bay estuary, wetland vegetation will shift from brackish and freshwater species to more salt tolerant plants. This shift could severely reduce waterfowl populations that depend on freshwater habitats. The timing, magnitude, and location of phytoplankton production could shift. Marine fish species could increase in abundance, while saltwater species that breed in freshwater areas would most likely decline.

- Higher temperatures in subalpine lakes could increase annual primary production (such as algae) by between 16 and 87%, which could degrade lake water quality and change the composition of fish species.

Agriculture

- The impacts of climate change on agriculture in California are uncertain. The effects of changes in temperature and precipitation alone would most likely reduce yields by 3 to 40%, depending on the crop. However, with the combined effects of climate and higher CO_2 levels, yields for all modeled crops, except corn and sugarbeets, might increase.

- The potential growth in irrigation in some parts of the state may require increased extraction of groundwater because of current full use of surface water supplies. This would decrease water quality and affect water management options.

- Yields in California may be less adversely affected than those in most parts of the country. Crop acreage could increase because of the shifts in yields and the presence of irrigation infrastructure.

Natural Vegetation

- Drier climate conditions could reduce forest density, particularly pine and fir trees, and timber productivity. (The full impacts on California forests were not assessed in this report.)

Air Quality

- If today's emissions exist in a future warmer climate, ozone levels in central California could increase and could change location because of higher temperatures. As a result, the area in central California with ozone levels exceeding EPA standards (0.12 parts per hundred million (pphm)) on a given day could almost double unless additional steps are taken to control emissions. These additional controls would increase the cost of pollution control.

Electricity Demand

- The annual demand for electricity in California could rise by 3 to 6 billion kilowatthours (kWh) (1 to 2%) over baseline demand in 2010 and by 21 to 41 billion kWh (3 to 5%) over baseline demand in 2055.

- By 2010, 2 to 3 gigawatts (GW) would be needed to meet the increased demand. By 2055, 10 to 20 GW would be needed -- a 14 to 20% increase over baseline additions that may occur without climate change. The additional capital cost by 2055 would be $10 to $27 billion (in 1986 dollars).

Policy Implications

- Water management institutions, such as the U.S. Bureau of Reclamation and the California Department of Water Resources, should analyze the potential impacts of climate change on water management in California. They should consider whether and how the Central Valley Project and State Water Project should be modified to meet increasing demands in the face of diminishing supplies due to climate change. They may also consider whether to change water allocation procedures to encourage more efficient use of water.

- The California Water Resources Control Board should consider the impact of climate change on surface and groundwater quality.

- State and local entities should consider the impacts of climate change on levee and wetland management in San Francisco Bay and the delta.

- The California Air Quality Board should review the long-term implications of climate change on air quality management strategies.

- The California Energy Commission should consider the impacts of climate change on the energy supply needs for the state.

CLIMATE-SENSITIVE RESOURCES OF CALIFORNIA

California's Central Valley is the most productive and diverse agricultural region of its size in the world. The Central Valley Basin, which includes the drainages of the Sacramento and San Joaquin Rivers, encompasses several large metropolitan areas, dispersed manufacturing, major port facilities, important timber reserves, heavily used recreational areas, and diverse ecosystems.

Much of the region's economic and social importance is derived from its water resources. Over 40% of California's total surface water runoff drains from the Central Valley Basin into the San Francisco Bay area (Miller and Hyslop, 1983). The basin supplies water for irrigated agricultural, municipal, and industrial uses, and for a host of other resources and activities.

The Central Valley Basin encompasses approximately 40% of California's land area (Figure 14-1). Elevations range from just below sea level on leveed islands in the Sacramento-San Joaquin River Delta to peaks of over 4,200 meters (14,000 feet) in the Sierra Nevada (Figures 14-2 and 14-3). Mountains ring most of the basin: the Sierra Nevada along the eastern side and the Coast Ranges on the west. The only outlet to the Pacific Ocean is via the San Francisco Bay estuary (Figure 14-2).

Current Climate

California's climate is characterized by little, if any, summer precipitation and by generally wet winters (Major, 1977). Both temperature and precipitation vary with elevation and latitude in the Central Valley Basin. Extremes in mean annual precipitation range from about 15 centimeters (6 inches) in the southern San Joaquin River Basin to about 190 centimeters (75 inches) in the mountains of the Sacramento River Basin. While almost all valley floor precipitation falls as rain, winter precipitation in the high mountains often falls as snow. Storage of water in the snowpack controls the seasonal timing of runoff in the Central Valley rivers and has shaped the evolution of strategies for water management and flood protection. Under current climatic conditions, peak runoff occurs between February and May for individual rivers within the Central Valley Basin (California Department of Water Resources, 1983; Gleick, 1987b).

Water Resources

Water Distribution

California's water resources are poorly distributed relative to human settlement patterns in the state. Over two-thirds of the state's surface water supply originates north of Sacramento, and 70% of its population and 80% of its total demand for water lie to the south (California Department of Water Resources, 1985). In addition, about 85% of the Central Valley Basin's total annual precipitation occurs between November and April, whereas peak water use occurs during the summer.

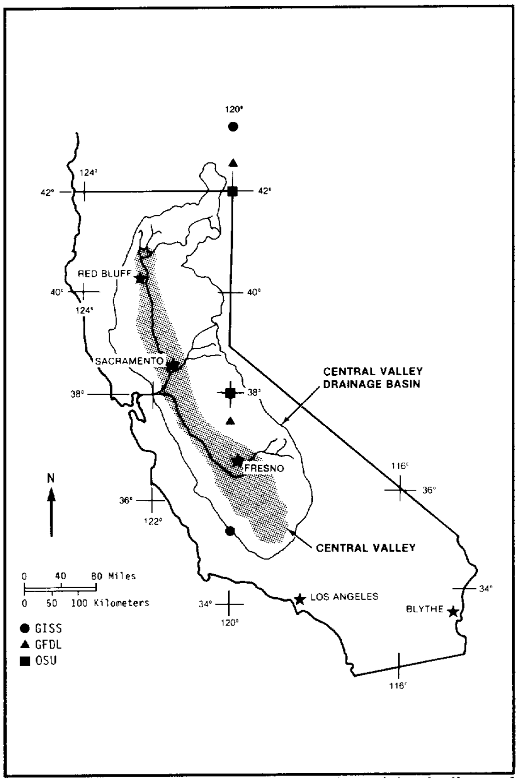

Figure 14-1. The Central Valley (shaded) and Central Valley Drainage Basin of California. Symbols refer to locations of general circulation model (GCM) gridpoints. (See California Regional Climate Scenarios section of this chapter for details on GCMs).

In working to solve these water distribution problems, the U.S. Government and California have built two of the largest and most elaborate water development projects in the world: the Federal Central Valley Project (CVP) and the California State Water Project (SWP). Both are essentially designed to move water from water-rich northern California to the water-poor south, and to supply water for agricultural, municipal, and industrial purposes. Currently, the CVP has a water surplus and the SWP has a shortage, especially in relationship to users' projected requirements. Thus, the SWP is particularly susceptible to dry years.

Flood Control and Hydroelectric Power

Another objective of the CVP and SWP is flood control. By 1984, CVP facilities had prevented almost $500 million in flood damages (U.S. Bureau of Reclamation, 1985). Flood control, however, comes at the expense of water storage (and hence water deliveries), because reservoir levels must be kept low to absorb high riverflows during the rainy season.

Hydroelectric power generation is also an objective of the CVP and SWP, and surplus power is sold to utility companies. CVP powerplants produce an average of 5.5 to 6 billion kWh per year. In 1976 and 1977, precipitation was 35 and 55% below normal, respectively, and hydroelectric power generation fell to 50 and 40%, respectively, of target production.

Sacramento-San Joaquin River Delta

The delta at the confluence of the Sacramento and San Joaquin Rivers is the focal point of major water-related issues in California (Figure 14-3). For example, most islands in the delta lie below sea level and are protected by levees, some of which are made of peat and are relatively fragile. These islands would be vulnerable to inundation from rising sea level associated with climate warming. The deep peat soils on these islands support highly productive agriculture that would be lost if inundated.

In addition to agricultural importance, the delta is also the source of all CVP and SWP water exports to points farther south, and in this regard basically functions as a transfer point of water from the north to the south. The freshwater pumping plants (see Figure 14-3) in the delta are the largest freshwater diversions in California (Sudman, 1987). Delta outflow must be maintained at a required level to prevent saltwater intrusion into the pumping plants. The volume of water released from upstream reservoirs to achieve this level is known as carriage water.

Commerce

The San Francisco Bay estuary includes the largest bay on the California coast (see Figure 142). The bay's northern reach between the Golden Gate and the Sacramento-San Joaquin River Delta is a brackish estuary dominated by seasonally varying river inflow (Conomos et al., 1985). The southern reach between the Golden Gate and the southern terminus of the bay is a tidally oscillating lagoon-type estuary. The port facilities of the San Francisco Bay area are vital to California's internal trade, to Pacific coast commerce, and to foreign trade, particularly with Asian countries. The ports of Oakland and San Francisco, combined, ranked fourth in the United States in tonnage of containerized cargo handled in 1983 (U.S. Maritime Administration, 1985). These facilities and operations are sensitive, in varying degrees, to both sea level change and fluctuation in freshwater runoff.

Agriculture

California annually produces about 10% of the cash farm receipts in the United States and produced $14.5 billion in farm income in 1986 (U.S. Department of Agriculture, 1987). Central Valley farms make up significant proportions of total U.S. production of many crops, including cotton, apricots, grapes, almonds, tomatoes, and lettuce.

Agriculture, the primary land use and the largest consumer of water in the Central Valley Basin, accounts for 87% of total net water use in the region. Furthermore, the region accounts for 72% of total net water use for the entire state and almost 80% of net agricultural use (California Department of Water Resources, 1987a).

Forestry

Silviculture is extensively practiced in California's mountains. The nine national forests substantially within the Central Valley Basin recorded over $88.6 million in timber sales in fiscal year 1986 (U.S.

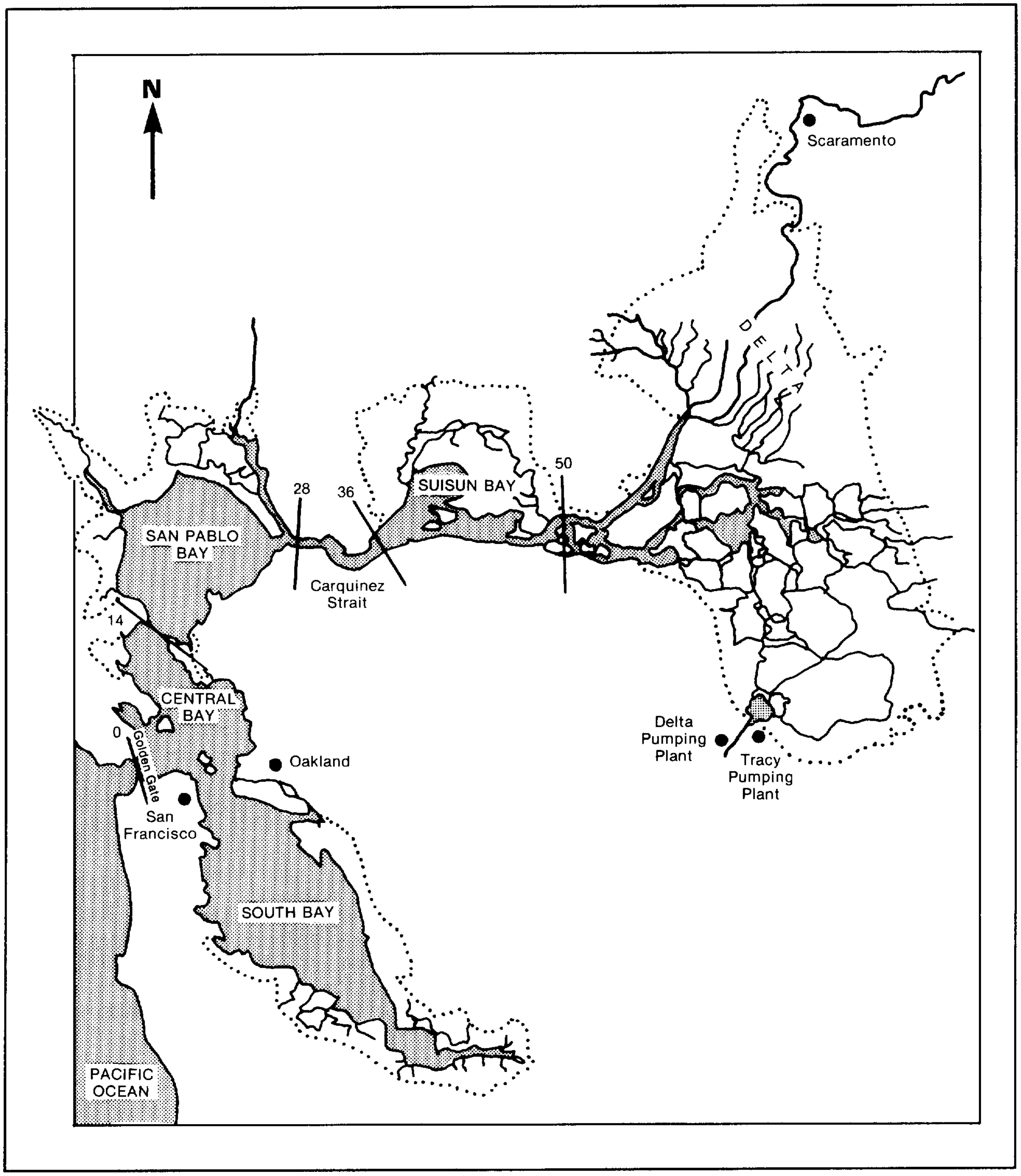

Figure 14-2. The San Francisco Bay estuary and locations of the freshwater pumping plants in the delta. The numbered bars indicate distance (in miles) from the Golden Gate. The dotted line indicates the maximum area affected by a 100-year high tide with a 1-meter (40-inch) sea level rise.

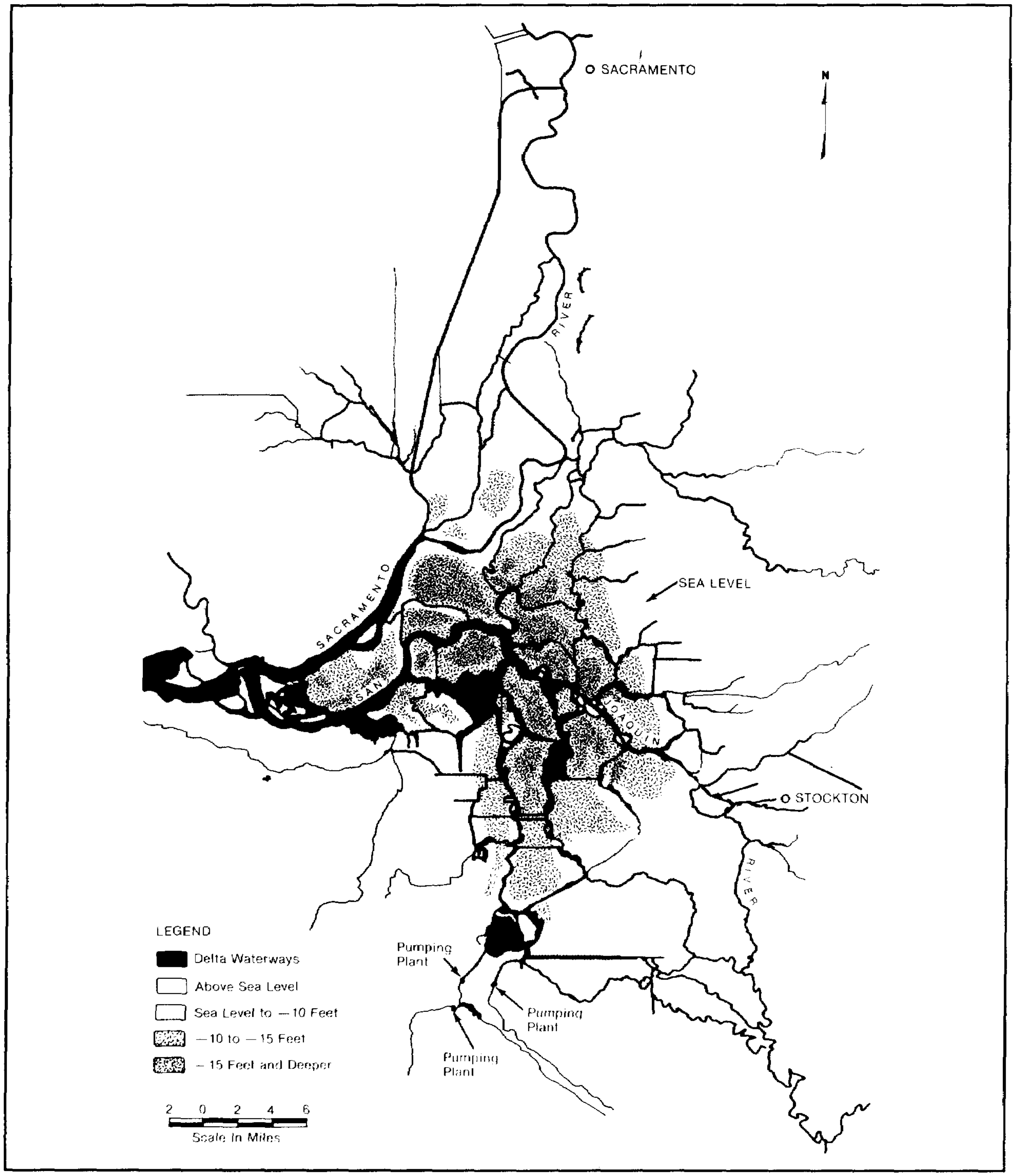

Figure 14-3. The Sacramento-San Joaquin River Delta. Shaded areas indicate land below sea level. See Figure 14-2 for location of the delta in the San Francisco Bay estuary.

Department of the Interior, 1986). Forest productivity is sensitive to climate variation. For example, the drought of 1976-77 contributed to significant tree mortality because of large infestations of bark beetles (California Division of Forestry and Fire Protection, 1988).

Natural Vegetation

Approximately one-fourth of all the threatened and endangered plants in the United States are found in California. About 460 species, or about 9% of the California species listed by Munz and Keck (1959), are either extinct or in danger of becoming extinct.

California contains about 5,060 native vascular plant species; of these, about 30% occur only in California (Munz and Keck, 1959; Raven, 1977). These species are more numerous than those present in the entire central and northeastern United States and adjacent Canada, a region about eight times larger than California (Fernald, 1950).

Within the Central Valley Basin, terrestrial vegetation may be grouped into the following broad classes, listed according to decreasing elevation: alpine, subalpine forest, montane forest, mixed evergreen forest, chaparral and oak woodland, and valley grassland (Barbour and Major, 1977).

Wetlands

The San Francisco Bay estuary includes approximately 90% of the salt marsh area in California (Macdonald, 1977). Nichols and Wright (1971) documented a 60% reduction in San Francisco Bay marsh between 1850 and 1968. This reduction was largely the result of reclamation for salt ponds, agriculture, expanding urbanization, shipping facilities, and marinas. Further loss of wetlands could result in substantial ecological and economic losses for the region. For example, the managed wetlands north of Suisun Bay support a hunting and fishing industry producing over $150 million annually (Meyer, 1987). Tourism, rare and endangered species, and heritage values also could be harmed.

Wildlife and Fisheries

The San Francisco Bay estuary provides vital habitat for many bird and fish species (California Department of Water Resources, 1983). The estuary is an important wintering area for waterfowl of the Pacific flyway. Important sport fish include striped bass, chinook salmon, sturgeon, American shad, and steelhead rainbow trout. These species are anadromous (i.e., saltwater species that enter freshwater areas for breeding), and the delta is an important nursery for these species. Chinook salmon also constitute an important commercial fish species, and Central Valley rivers support about 75% of California's chinook salmon catch, valued at $13.4 million at 1981 prices. The populations of these species are affected by water quality in the estuary.

To protect aquatic organisms in the delta, the State Water Resources Control Board (SWRCB) adopted water right Decision 1485 in 1978 that sets water quality standards to protect the delta and Suisun Marsh. The standards vary from year to year, with less stringent requirements in dry years. The standards are achieved by meeting minimum delta outflow requirements. If delta outflow falls below the required level, then releases from upstream state and federal reservoirs must be increased so that the outflow requirement is met. The water quality standards take precedence over water export from the delta.

Recreation and Nature Preservation

Recreation and nature preservation are important in California. Major recreational areas in the Central Valley Basin include four national parks (Lassen Volcanic, Sequoia, Kings Canyon, and Yosemite) and nine national forests that lie either completely or largely within its boundaries. Two national recreation areas and 13 designated wildlife refuges and management areas also are situated in the region. Downhill skiing and other winter sports are economically important in the state. Water projects throughout the Central Valley Basin provide significant recreational opportunities.

PREVIOUS CLIMATE CHANGE STUDIES

Two of the few studies previously undertaken to assess the potential effects of climate change on the region are discussed in this section.

Forests

Leverenz and Lev (1987) estimated the potential range changes, caused by CO_2-induced climate change, for six major commercial tree species in the western United States. Two of the species, ponderosa pine and Douglas-fir, have significant populations in California. Leverenz and Lev based their estimates of range changes on the species' response to increased temperature, decreased water balance, and higher CO_2 concentrations. The scenario of climate change used was based on a simulation using the Geophysical Fluid Dynamics Laboratory (GFDL) model (a different run from that used for this study), with CO concentrations double their present levels. heir results suggest that in California, ponderosa pine could increase in range and abundance because of its ability to withstand long summer drought. Douglas- fir could be eliminated from coastal lowlands in California but might occur in coastal areas at higher elevations.

Water Resources

Gleick (1987a,b) applied 18 general circulation model (GCM)-based and hypothetical scenarios of climate change to a hydrologic model of the Sacramento River Basin. He used a two-part water balance model to estimate monthly runoff and soil moisture changes in the basin. His results suggest that winter runoff could increase substantially, and summer runoff might decrease under most of the scenarios. Summer soil-moisture levels might also decrease substantially. These changes are driven by higher temperatures, which decrease the amount of winter precipitation falling as snow and cause an earlier and faster melting of the snowpack that does form.

CALIFORNIA STUDIES IN THIS REPORT

Seven studies were completed as part of this regional study of the possible impacts of climate warming on California (Figure 14-4). These studies were quantitatively integrated as much as possible within the overall timeframe of this report to Congress to obtain as complete a picture of those impacts as possible. Also, several of the national studies have results pertaining to California. At the outset, it should be emphasized that most of these studies used existing models, and most evaluated potential climate change in terms of present demands, values, and conditions (including the current population and water delivery system).

Water is a key limiting resource in both managed and unmanaged ecosystems in the Central Valley Basin, and freshwater is important in estuarine ecosystems in the delta region. Consequently, the California studies were organized so that the impacts of climate warming on the entire hydrologic system could be examined, starting at subalpine lakes in the mountains surrounding the valley and finishing at the freshwater outflow into the delta region and estuary (Figure 14-4). The individual projects examined the potential impacts of climate change and sea level rise on particular ecosystems and water-delivery systems in the Central Valley (see Chapter 4: Methodology). One of the major goals of this regional study was to determine how much runoff would flow into the Central Valley from the surrounding mountains under different scenarios of climate change, how much of that runoff would be available for delivery to the water users in the state, and how much would reach the delta.

Analyses Performed for This Study

The following analyses were performed for this study.

- Interpretation of Hydrologic Effects of Climate Change in the Sacramento-San Joaquin River Basin - Lettenmaier and Gan, University of Washington, and Dawdy, consultant (Volume A)

The Lettenmaier et al. project is the first of a series of four projects designed to determine the impact of climate change on runoff and water deliveries within the Central Valley Basin (Figures 14-4 and 14-5). Their project was designed to estimate changes in runoff from the mountains to the water resource system in the floor of the valley. Lettenmaier et al. used data from climate scenarios supplied by EPA as input to their modeling studies. (See Chapter 4: Methodology, and the following section, California Regional Climate Change Scenarios).

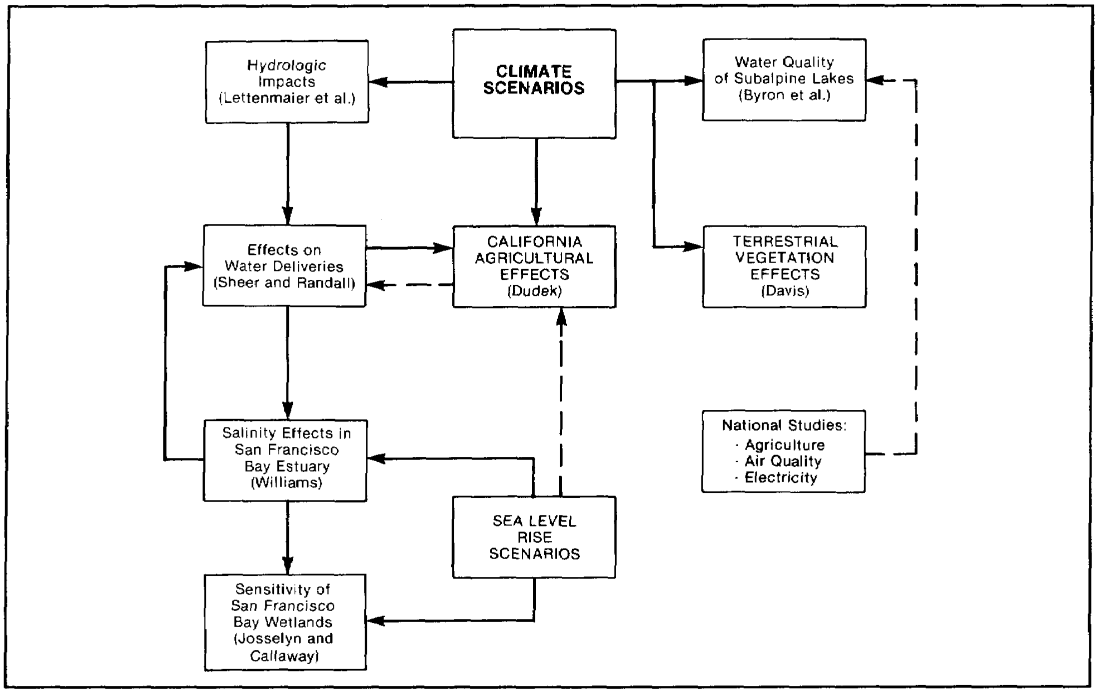

Figure 14-4. Organization of the study, showing paths of data input from scenarios and between projects (solid lines). Dashed lines indicate some important linkages between projects that were not quantitatively made in this study.

- Methods for Evaluating the Potential Impacts of Global Climate Change: Case Studies of the Water Supply Systems of the State of California and Atlanta, Georgia - Sheer and Randall, Water Resources Management, Inc. (Volume A)

Sheer and Randall used the projected runoff from the mountains determined by Lettenmaier et al. to simulate the response of the Central Valley and State Water Projects to climate change. Output from this study includes estimated total water deliveries to State Water Project users.

- The Impacts of Climate Chance on the Salinity of San Francisco Bay - Williams, Philip Williams and Associates (Volume A)

The main goal of Williams' project was to determine the impact of sea level rise and changing freshwater outflow into the delta on salinity within the bay. Williams also determined how much carriage water might be required to hold back salinity intrusions from the delta pumping plants after sea level rise. The new carriage water requirements were then factored into Sheer and Randall's simulation of the water resource system, and they represent an important feedback between the hydrologic effects of climate change and sea level rise effects in the delta (see Figure 14-3).

- Ecological Effects of Global Climate Change: Wetland Resources of San Francisco Bay - Josselyn and Callaway, San Francisco State University (Volume E)

Josselyn and Callaway used results from Williams and Park (see Chapter 7: Sea Level Rise) to assess the impact of changing salinity and sea level rise on the wetlands within San Francisco Bay.

- Climate Chance Impacts upon Agriculture and Resources: A Case Study of California - Dudek, Environmental Defense Fund (Volume C)

Dudek simulated the impact of changing climate on California agriculture. Besides using the climate data from the different climate scenarios to estimate crop productivity impacts, Dudek used estimates of mean annual water deliveries for deliveries for irrigation under the different climate scenarios as input to a regional economic model to estimate shifts in land and water use. This information was qualitatively used to compare available future water supplies and future water demand (see Figure 14-4). The ability of water policy changes to compensate for climate impacts was also evaluated.

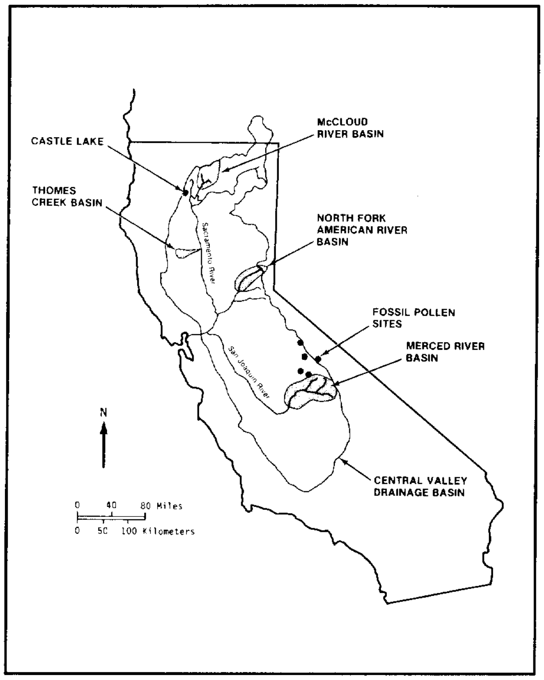

Figure 14-5. The Central Valley Drainage Basin of California. Shaded areas refer to the four study catchments used by Lettenmaier et al. Dots indicate the positions of the Castle Lake study site (Byron et al., Volume E) and the five fossil pollen sites (Davis, Volume D).

- The Effects of Global Climate Change on Water Quality of Mountain Lakes and Streams - Byron, Jassby, and Goldman, University of California at Davis (Volume E)

Byron et al. studied the impact of climate change on the water quality of a subalpine lake in northern California (see Figure 14-5).

- Ancient Analogs for Greenhouse Warming; of Central California - Davis, University of Arizona (Volume D)

Davis reconstructed the vegetation present in the Sierra Nevada during warm analog periods of the Holocene to estimate the potential impact of warming on the present-day vegetation in these mountains (see Figure 14-5).

National Studies That Included Results for California

- The Economic Effects of Climate Change on U.S. Agriculture: A Preliminary Assessment - Adams and Glyer, Oregon State University, and McCarl, Texas A&M University (Volume C)

Adams et al. conducted a national study of agriculture to estimate shifts in land and water use. Results pertaining to California are discussed in this chapter.

- The Potential Impacts of Climate Change on Electric Utilities: Regional and National Estimates - Linder and Inglis, ICF, Inc. (Volume H)

As part of a national study, Linder and Inglis estimated future California electrical demands in response to climate change.

- Examination of the Sensitivity of a Regional Oxidant Model to Climate Variations -Morris, Gery, Liu, Moore, Daly and Greenfield, Systems Applications, Inc. (Volume F)

Morris et al. describe possible interactions of climate change and air pollution. Results pertaining to California are discussed in thus chapter.

CALIFORNIA REGIONAL CLIMATE CHANGE SCENARIOS

Results from two GCM gridpoints were used to drive the effects models used in most of the California studies. (For a discussion of how the scenarios were developed and applied, see Chapter 4: Methodology.) Both gridpoints lie at 120°W, with the northern gridpoint near the Oregon-California border and the southern gridpoint south of Sacramento (see Figure 14-1). Average temperature and precipitation changes for both gridpoints are displayed in Figure 14-6. Generally large seasonal increases in mean temperature are projected by the models. Winter temperatures are between 1.7°C (OSU) and 4.9°C (GISS) warmer, and summer temperatures are between 2.6°C (OSU) and 4.8°C (GFDL) warmer. The OSU model generally projects less warming than the other two GCM models.

Annual precipitation increases in GISS by 0.28 millimeters per day (4.02 inches per year) and remains virtually unchanged in the GFDL and OSU scenarios. Seasonal changes are more varied. For instance, spring rainfall in GFDL is 0.35 millimeters per day (0.41 inches per month) lower, while spring rainfall in the OSU and GISS scenarios is higher. The scenarios also show a large difference in fall precipitation (Figure 14-6).

Overall, the OSU scenario represents a smaller change from the present climate, and GFDL and GISS show larger temperature changes. The GISS scenario has higher precipitation than the other two scenarios. Generally, temperature increases are larger in the northern gridpoints than in the southern gridpoints. Changes in annual precipitation are greater in the north in GISS and show little regional difference for the other models.

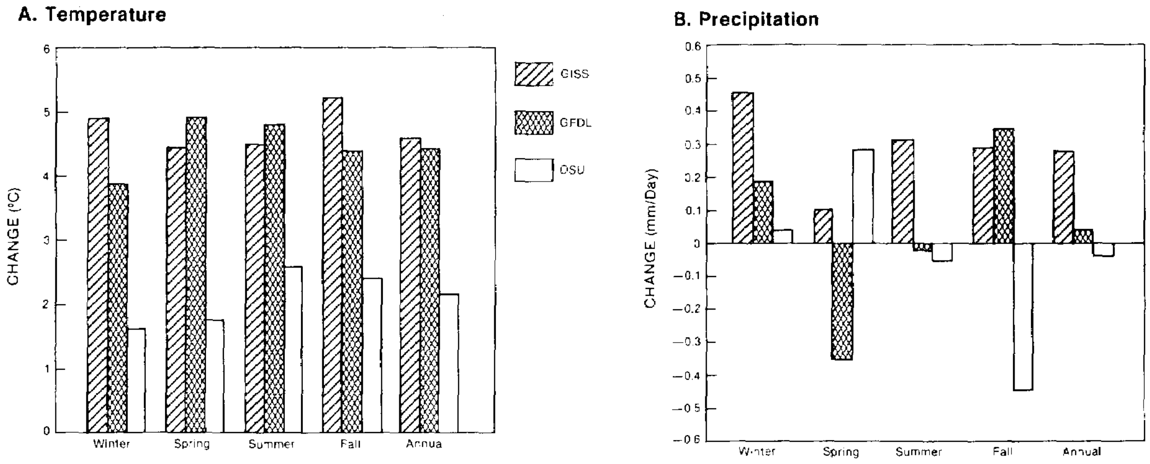

Figure 14-6. General circulation model (GCM) scenario results showing seasonal and annual (A) temperature and (B) precipitation changes between GCM model runs at doubled CO 2 and current CO$_2$ concentrations. The values are averages of the two gridpoints used by the water resource modelers. (See Figure 14-1 for the location of the gridpoints.)

RESULTS OF THE CALIFORNIA STUDIES

Hydrology of Catchments in the Central Valley Basin

Changes in mountain snowpack and runoff could have a major impact on water supply and quality in the Central Valley Basin. Lettenmaier et al. used a hydrologic modeling approach to simulate runoff under different climate scenarios; these estimates then served as input to the simulation of the Central Valley Basin water resource system response to climate change (Sheer and Randall, Volume A).

Study Design

The approach taken was to model the hydrologic response of four representative medium-sized catchments in the Central Valley Basin. Then streamflows for 13 larger sub-basins in the Central Valley Basin were estimated using the results from the four catchments. The four catchments chosen (see Figure 14-5) for modeling range in size from 526 to 927 square kilometers (203 to 358 square miles). Outflows for each basin were determined using two hydrologic models that estimate snow accumulation, ablation, and daily runoff. The models were calibrated using a subset of the historic record and were verified using an independent subset of the data.

Lettenmaier et al. developed an additional climate scenario besides those specified by EPA to test the sensitivity of their results to changes in the scenarios. The scenario they developed included only the GISS doubled CO temperature estimates; precipitation was kept unchanged from the current values. The purpose of this scenario was to determine the sensitivity of runoff to temperature changes alone.

To provide input for the water resource simulation model of Sheer and Randall (Volume A), Lettenmaier et al. developed a statistical model that relates historic flows in the four study catchments to historic flows in 13 larger subbasins in the Central Valley Basin. This statistical model was then used to estimate flows in the 13 subbasins under the different climate scenarios.

Limitations

Results would be different if geographic and temporal variability were not held constant within each grid. Several assumptions made in this study are important considerations in terms of limitations of the results. The intensity of rainfall is the same. Fewer rainfall events of higher intensity could increase runoff relatively more than a greater number of rainfall events of lower intensity. One implicit assumption is that no long-term changes in vegetation cover and composition would occur, when in fact such changes are virtually certain (but their hydrologic manifestations are difficult to predict). If vegetation cover decreases, runoff could increase, since less precipitation would be used by plants.

Lettenmaier et al. assumed that the flows into the water resource system were adequately estimated from the study catchment flows using their statistical model. One limitation of this model was that the study catchments are at high elevations and their runoff is strongly affected by changes in snowfall, whereas some of the areas contributing runoff to the water resource system are at lower elevations with runoff driven primarily by rainfall under present climatic conditions. Since the principal change under the scenarios was a change in snowfall accumulation patterns, the statistical model was biased toward these effects and may have somewhat overestimated the total effect of snowfall change on the water resource system. However, because basins at lower elevations have a relatively small impact on the total hydrology, thus bias minimally affected the results.

Despite these limitations, the results from thus study are qualitatively robust. Any improvement in the hydrologic modeling probably would not alter the general nature of the results, although their precision probably would increase.

Results

Total annual runoff from the four subbasins would remain about the same or increase slightly under the doubled CO_2 scenarios, but major changes occur in the seasonality of the runoff. Runoff could be higher in the winter months than it is today, because less of the precipitation would fall as snow and the snowpack could melt earlier (Figure 14-7A). As a consequence of higher early winter snowmelt, spring and summer runoff would substantially decrease under these scenarios. The variability of the runoff could substantially increase in the winter months. Winter soil moisture could increase; evapotranspiration could increase in the spring; and late spring, summer, and fall soil moisture could decrease. A major shift in the seasonality of runoff could occur in 50 to 75 years, according to the transient scenario GISS A.

When only temperature changes were incorporated into the climate scenario and precipitation was held equal to the base case, total annual runoff was estimated to be lower in all four catchments than in the scenario in which both temperature and precipitation were changed (Figure 14-7). However, the seasonal stuff in runoff, which is the dominant effect of a general warming, would be similar.

The scenario producing results that differed the most from the other scenarios was the 1930s analog. In this case, runoff was estimated to be lower in most months in the four subbasins, but the seasonal distribution of runoff was similar to the base case (Figure 14-7B). The reason for this difference is that the 1930s drought was mainly caused by a reduction in precipitation, rather than by an increase in temperature.

These results are consistent with those of Gleick (1987b), in that higher temperatures cause a major change in the seasonality of runoff. Since two different modeling approaches using many climate change scenarios produced similar results, these results can be viewed as relatively robust.

Implications

The potential change in seasonality of runoff could have significant implications for stream ecosystems and the water resource system in the Central Valley Basin. Reduction in streamflows in the late spring and summer could negatively affect aquatic organisms simply because of decreased water volume. Wildlife using streams for food and water also could be harmed. Water quality probably could be degraded because pollutants would become more concentrated in the streams as flows decrease. The possible impacts on the water resource system are discussed in the next section.

The decrease in spring, summer, and fall soil moisture could have a strong impact on the vegetation in the basin, with plants adapted to drier conditions becoming more abundant at the expense of plants adapted to higher moisture conditions. These potential vegetation changes also could affect wildlife, and perhaps water quality, through changes in the nutrient composition of upland runoff and changes in erosion rates.

Water Resources in the Central Valley Basin

Changes in runoff under the different climate scenarios could have a major impact on water resources in the Central Valley. The study by Sheer and Randall (Volume A) used estimates from Lettenmaier et al. of streamflows into the Central Valley to simulate how the water resource system would perform under the various climate scenarios. Particular emphasis was given to how water deliveries to users would be affected by climate change.

Study Design

To estimate the climate scenarios' impact on water deliveries, Sheer and Randall used an existing model of the California water resource system currently used by the southern California Metropolitan Water District (MWD) (Sheer and Baeck, 1987). The model emulates the State of California's Department of Water Resources Planning Simulation Model (California Department of Water Resources, 1986). The model used hydrologic inputs to project water-use demands, instream and delta outflow requirements, and reservoir operating policies. Water requirements were set at levels projected for 1990.

Two different sets of runs were made with the model. The first involved running the model for the different climate scenarios using current carriage water requirements. Williams (see the following section of this chapter, Salinity in San Francisco Bay) determined that in response to rising sea level and levee failure, carriage water might have to be doubled to maintain the water quality at the delta pumping plants (see Figure 14-2). Consequently, Sheer and Randall ran the model a second time to determine the effects of doubling the carriage water requirement on water deliveries. Both simulations were run with a monthly time step, with water deliveries summarized on a yearly basis. Interannual variation was used as an indicator of delivery reliability.

Sheer held a meeting with representatives of

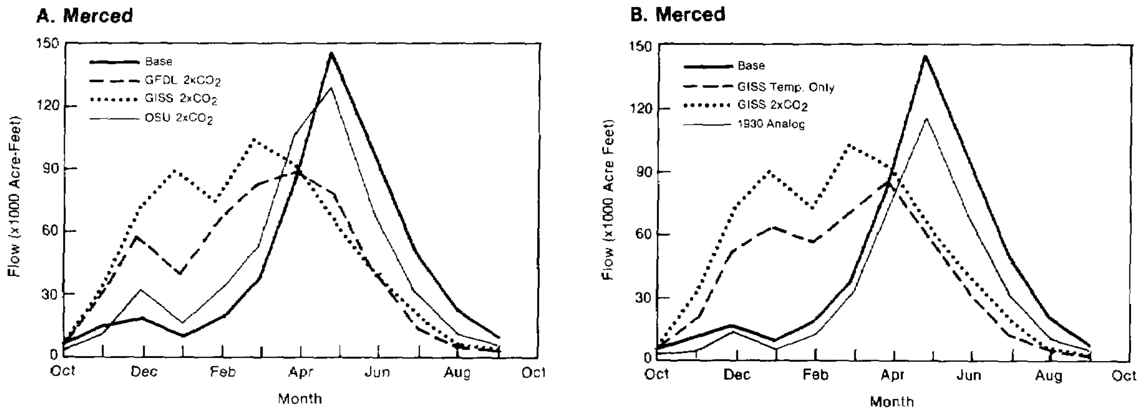

Figure 14-7. Mean monthly streamflows under difference climate scenarios for the Merced River Basin, one of the the four study catchments modeled (see Figure 14-5 for locations of the study catchments): (A) results from the three doubled CO_2 scenarios; and (B) results from the scenario incorporating only the temperature change projected in the GISS model run, and from the 1930s analog scenario (Lettenmaier et al., Volume A).

the California Department of Water Resources and the U.S. Bureau of Reclamation to discuss the results of his analyses and to obtain their responses on how the water resource system would handle the changes in runoff.

Limitations

The limitations to Lettenmaier's study carry over to this one. Thus, interpretation of the results of the simulation of the water resource system's response to climate change should focus on how the system deals with the change in seasonality of runoff, rather than on the absolute values of the model output. Also, the model was run using 1990 conditions, and changes in future management practices, operating rules, physical facilities, water marketing, agriculture, and demand were not considered in the simulation.

Results

The simulation results suggest that both the amount and reliability of water deliveries could decrease after global warming. The decreases in mean annual SWP deliveries were estimated to range from 7% (OSU) to 14% (GISS) to 16% (GFDL) (200,000 to 400,000 acre-feet) (Figure 148). In some years, the decreases would be over 20% for all three doubled CO_2 scenarios. The projected decrease in water deliveries occurs despite a slight increase in precipitation over current levels in the climate scenarios and greater total outflow from the delta. Deliveries to the CVP are not reduced under the scenarios. Average monthly outflow from the delta increases in the late fall and winter under the climate scenarios and is lower in the spring (Figure 14-9). In comparison, the state estimates that population growth and other factors will increase demand for SWP deliveries by 1.4 million acre-feet by 2010 (California DWR, 1983).

The driving factor behind this decrease is the change in seasonality of runoff. Higher winter temperatures could lead to more of the winter precipitation in the mountains falling as rain rather than snow, and also to an earlier melt of the snowpack. Consequently, more water would flow into the system during the winter, and less during the spring and summer. Given current operating rules and storage capacity, much of the higher winter runoff would be spilled from the reservoirs to maintain enough storage capacity to capture heavy runoff later in the rainy season and thus prevent downstream flooding. When the threat of floods decreases at the end of the rainy season in the spring and the reservoirs could be filled, runoff into the system would be reduced because of the smaller snowpack. Thus, total storage would be lower at the end of spring and water deliveries would be lower during the dry summer months. With system changes, the extra runoff could be stored. The shift in the seasonality of runoff and the response of the water resource system to that shift determine the changes in monthly delta outflow (Figure 14-9).

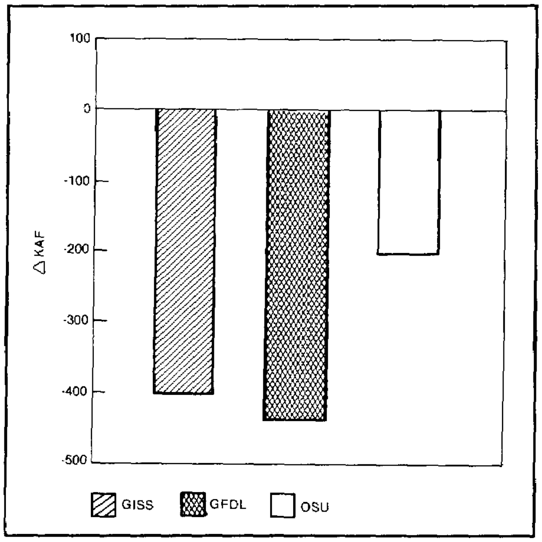

Figure 14-8. Mean annual change in SWP deliveries (base case minus scenario). KAF = thousands of acre-feet (Sheer and Randall, Volume A).

Doubling the carriage water requirement in the model run for the GFDL scenario would only minimally affect SWP deliveries. This is because the base period (1951-80) does not include a lengthy drought period, during which the doubled carriage water requirement could have a substantial impact on deliveries.

The consensus of the meeting of the representatives from the state DWR and the Bureau of Reclamation concerning the potential changes in seasonality of runoff was that the magnitude of this change would be such that operational changes alone would not markedly improve the system's performance. One factor limiting the potential for adjusting the system to the projected changes is the likely need to provide for additional flood control storage during the winter months because of higher peak flows.

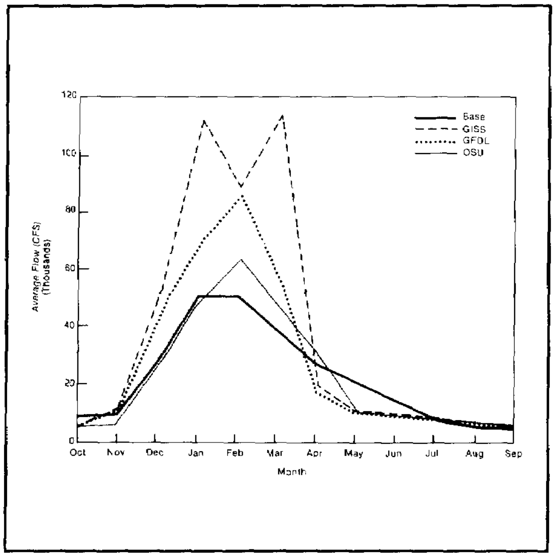

Figure 14-9. Projected monthly delta outflows under different general circulation model climate scenarios (adapted from Sheer and Randall, Volume A).

Implications

Under the three doubled CO_2 climate scenarios, water deliveries would be less than the base case and could fall short of 1990 requirements. Moreover, if carriage water requirements are doubled, shortages during a prolonged drought could become more significant. In comparison to these projected changes, the severe drought of 1977 reduced water deliveries by over 50% from the previous year. This decrease is over three times greater than those projected by Sheer and Randall. However, their study produced estimates of average changes, while the 1977 value reflects an extreme event over a short time period, which would have to be dealt with less frequently and in a potentially different manner than a more persistent shortfall in average supply. Also, Sheer and Randall did not consider future increases in water requirements caused by population increases and changes in the state's economy, which would exacerbate the projected water shortages. For instance, users and managers project a 55% (1.3 million acre-feet) increase in water required by SWP users in 2010 over the amount the system can reliably supply to them today (California Department of Water Resources, 1983).

The potential decrease in water deliveries could affect urban, agricultural, and industrial water users in the state. How the potential decrease should be managed has many policy implications, which are discussed at the end of this chapter.

On a positive note, the increase in delta outflow shows that more water could flow through the Central Valley Basin under these scenarios, and water deliveries could be increased if major new storage facilities were constructed. However, this would be an environmentally and politically controversial option (see Policy Implications section of this chapter).

Salinity in San Francisco Bay

Climate change could affect the San Francisco Bay estuary in two ways: first, changes in precipitation and temperature could affect the amount of freshwater runoff that will flow into the bay; and second, global warming could cause sea level to rise because of thermal expansion of the water and glacial melting, which could in turn affect a wide range of physical characteristics in the bay. The major objective of the study by Williams (Volume A) was to estimate the implications of global warming and rising sea level on the size and shape (morphometry) of the San Francisco Bay estuary and on salinity in the estuary.

Study Design

Williams' project was conducted in three parts, using two sea level rise scenarios and delta outflows estimated by Sheer and Randall (Volume A). The sea level rise scenarios are a 1-meter (40-inch) rise with the levees in the Sacramento-San Joaquin Delta and San Francisco Bay maintained, and a 1meter sea level rise with levee failure. The first part of this study involved estimating how sea level rise would affect the shape of the bay by establishing the elevation/area and elevation/volume relationships for all areas below + 3 meters (+ 10.0 feet) according to National Geodetic Vertical Datum (NGVD). In the second part of the study, the bay's tidal exchange characteristics were determined for its future shape by using a tidal hydrodynamic model (Fischer, 1970).

Finally in the third part of Williams' study, the bay's salinity under the combined impacts of sea level rise and changing delta outflows was calculated using a mixing model developed by Denton and Hunt (1986). This model was first run with nine different constant delta outflows (all months the same) to establish new carriage water requirements after sea level rise. (These requirements will also meet the state water quality standards for Suisun Marsh, as detailed in Water Rights Decision 1485.) Once these were established, and Sheer and Randall (Volume A) had run their simulation model with the new requirements, the mixing model was run again to determine the salinity regime in the estuary after climate change. Included in the model output were average monthly and average annual salinities in different parts of the estuary under the different scenarios.

Limitations

Because of the short time available for analysis, Williams used some old and inaccurate surveys in the morphometric analysis instead of making new surveys. These could produce errors of plus or minus 20% in the estimates of the estuary's volume. In addition, some levees probably would be maintained under any delta management plan, and thus the flooding of the delta islands would not be as extensive as assumed in the levee failure scenario. Williams did not consider changes in siltation and erosion of sediments that would likely occur under the different climate change scenarios. However, erosion would probably have a significant impact on water flow in the delta. For instance, deepening of the tidal channels in the delta could lead to intrusion of salinity farther upstream than projected in this study. In addition, more sophisticated models of salinity and tidal ranges and exchanges might improve the accuracy of the results. Finally, the new carriage water requirements were based on a steady-state analysis (e.g., constant delta outflows). Changes in the hydraulics of the Sacramento-San Joaquin Delta and Suisun Bay with sea level rise could increase these requirements. Williams' results should be viewed as a preliminary estimate of estuarine changes, with emphasis placed on the direction of change, rather than on the absolute amount of change.

Results

The morphometric analyses suggested that given a 1-meter (40-inch) sea level rise and failure of the levees, the total area of the estuary might triple, and its volume could double. If the levees are maintained, the increases in area and volume could be about 30 and 15%, respectively. The amount of sea level rise would be less important to the physical size of the bay than whether or not the levees are maintained.

Under the sea level rise scenarios with levees maintained, tidal ranges would not change significantly from current conditions. If the levees failed, downstream constrictions at Carquinez Strait and to the east of Suisun Bay (see Figure 14-2) would limit tidal transport and reduce tidal range in the delta, assuming that erosion does not alter the tidal characteristics of the delta.

The results from the initial application of the salinity model to constant delta outflows indicate that monthly carriage water requirements might have to be doubled to repel saline water from the upper part of the delta. Also, whether or not the levees are maintained would have little effect on the salinity regimes in the bay according to the model's results. However, because possible scouring of tidal channels was not incorporated into the model, the predicted salinity after levee failure is probably underestimated.

Using Sheer and Randall's estimated delta outflow with double carriage water, Williams also estimated annual salinity in the bay. The results suggest that after a climate warming, a 1-meter sea level rise, and failure of the levees, water of a given average annual salinity could migrate inland between 4 kilometers (2.5 miles) (GISS scenario) and 9.6 kilometers (6 miles) (OSU scenario) (Figure 14-10).

Williams also calculated the average monthly salinity for Suisun Bay for the three climate scenarios, levee failure, and double carriage water requirements. Monthly salinities would be higher for all months as compared with the base case, except for winter and early spring months in the GISS scenario. The greatly increased runoff of the GISS scenario (see Figure 14-9) during these months kept the salinity at the same level as the base case. Williams additionally modeled the frequency of a given salinity value in any month. In June, for example, salinities that were exceeded in 50% of the years in the base case might be exceeded in 80% of the years in both the GISS and OSU scenarios because of the lower outflows predicted under these scenarios.

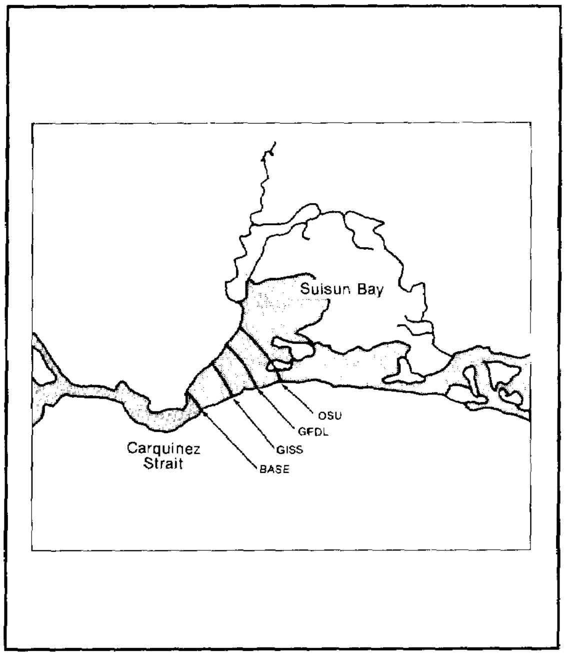

Figure 14-10. Movement of mean annual salinity of 10 parts per thousand under different hydrology scenarios. Other salinity levels move similar distances (see Figure 14-2 for location of Suisun Bay; Williams, Volume A).

Implications

Rising sea level could place the delta islands under increased risk of inundation, not only because of higher water levels but also because the larger area and volume of the San Francisco Bay estuary could result in greater wave energy and higher erosion rates of the levees. Improving the levees just to protect them against flooding at the current sea level could cost at least $4 billion (California Department of Water Resources, 1982). With higher sea levels, the cost of maintaining the levees would increase.

The large body of water created if all the levees failed would have a longer water residence time. This means that any contamination (salt or other pollutant) would be more difficult to flush out of the delta region. Also, if saline water fills the islands when levees fail, significant amounts of freshwater would be needed to flush out the salt.

Increasing salinity could necessitate increases in carriage water to maintain freshwater at the export point in the delta or could require developing a different method to convey freshwater from reservoirs to users. Assuming the current water management system is not expanded, the increase in carriage water coupled with the decrease in reservoir storage would most likely mean reduction in water deliveries to at least some of the system's users during extended droughts. With higher future water requirements, shortages caused by the higher carriage water requirements may not be limited to extended droughts. An increase in sea level could make navigation easier, temporarily reducing the need for dredging of navigation channels. On the other hand, a rising sea level could threaten fixed port terminals and piers.

Wetlands in the San Francisco Bay Estuary

Climate warming could alter two important physical factors that affect wetland distribution: sea level and freshwater outflow. Major impacts of sea level rise could include erosion and marsh inundation. Changes in freshwater outflow can change the distribution and productivity of estuarine plants and animals. Josselyn and Callaway (Volume E) estimated the possible effects of climatic warming on deep-water and wetland habitats of the San Francisco Bay estuary (see Figure 14-2).

Study Design

Josselyn and Callaway examined the impacts of a 1-, 2-, and 3-meter (40-, 80-, and 120-inch) sea level rise by the year 2100. Of the three scenarios, a 1-meter rise by the year 2100 is regarded as the most probable (NRC, 1987). Models were used to estimate rates of sea level rise from 1990 through 2100 under these three scenarios. The relationship between sedimentation rates required for marsh maintenance and sea level rise rates was examined. The effects of salinity changes on the distributions and abundances of organisms were related to various freshwater outflow scenarios developed by Sheer and Randall (see Figure 14-9). In the absence of appropriate quantitative models, biotic changes in the estuary in response to changing salinity were qualitatively determined based on literature review and expert judgment.

Limitations

Circulation and sedimentation in the estuary could change dramatically as sea level rises and if levees fail. The specific characteristics of these biologically important changes are unknown at present and were not considered in this study. The sea level rise scenarios did not consider the possibilities of sudden changes in sea level. Increased water temperature, which may directly affect the reproduction, growth, and survival of estuarine organisms, or may have an indirect effect through changes in oxygen availability, also was not considered. Although specific impacts on plant and animal species in the estuary are difficult to assess, the general impacts would most likely be similar to those reported here.

Results

Rates of sea level rise from 1990 to 2040 for the three scenarios are presented in Figure 14-11. Once the rate of sea level rise exceeds the rate of sediment accretion, tidal marsh habitats would become inundated and erosion of the marsh edge could increase. For the 1-meter rise scenario, the rate of rise was not estimated to exceed maximum accretion rates (7 to 8 millimeters per year) until about the year 2040. For the 2- and 3-meter (80and 120-inch) rise scenarios, the rate of sea level rise could exceed accretion rates after 2010 and 2000, respectively (Figure 14-11).

Peak primary productivity, at present, occurs in early spring in San Pablo Bay and in the summer in Suisun Bay. These maximum productivity levels could be substantially reduced, particularly for brackish and freshwater plant species, under the higher salinities of the OSU scenario (see Figure 14-10). Peak spring production might also shift upstream into the delta if levees fail. However, under the higher freshwater outflows of the GFDL and GISS scenarios, the locations of maximum production levels might remain in their present positions if the levees are maintained. If the levees fail, primary production could increase in the extensive shallow water and mudflat areas created.

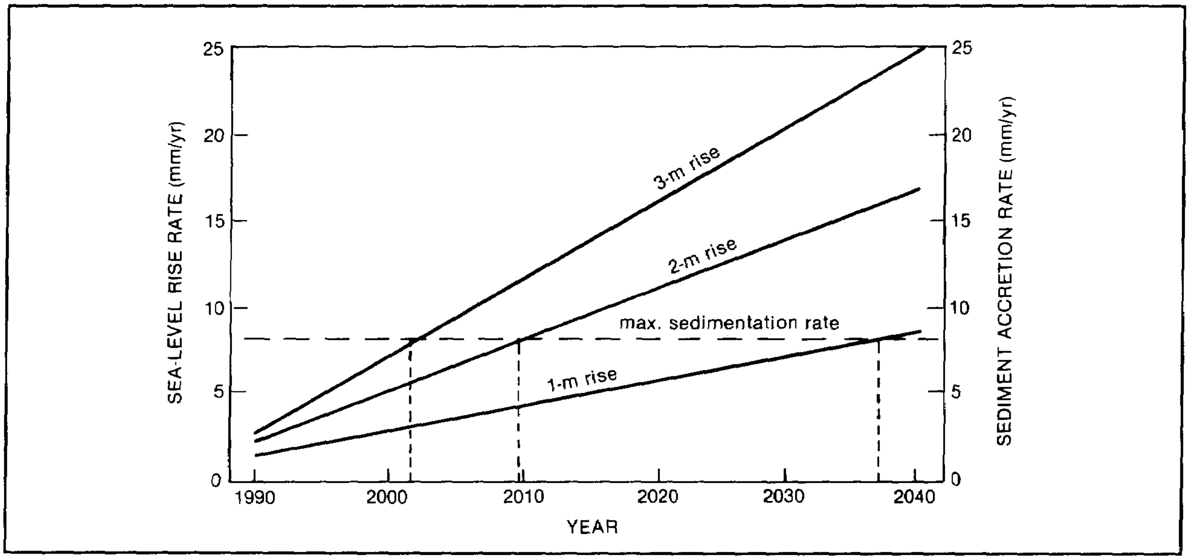

Figure 14-11. Estimated sea level rise at San Francisco for three scenarios by the year 2100 (Josselyn and Callaway, Volume E).

Since many areas currently protected by levees are 1 to 2 meters (40 to 80 inches) or more below sea level, levee failure would cause them to become deepwater areas rather than marshes (see Figure 14-3). Eventually, enough sediment might be deposited in these formerly leveed areas to support marsh development. Inundation of marshes and salinity impacts on freshwater and brackish-water plant species could reduce sources of food and cover for waterfowl. Loss of emergent vegetation could significantly reduce the numbers of migratory waterfowl using the managed wetlands along Suisun Bay's north shore.

If levees are maintained under conditions of sea level rise, salt may build up behind them from the evaporation of standing water. This salt would cause marsh vegetation to die back and reduce the value of these wetlands to wildlife.

Freshwater outflows estimated during springtime under the climate change scenarios (see Figure 14-9) may be too low to support anadromous fish (saltwater fish that enter freshwater areas for spawning). Lower outflows could result in declines among these populations (Kjeldson et al., 1981).

If levees failed, a large inland lake with fresh to brackish water quality could be created in the delta. Striped bass and shad spawn in essentially freshwater conditions and their spawning could be reduced under increased salinity, especially if they did not move upstream to relatively fresh water. Marine fish species could increase in abundance in the Suisun and San Pablo Bays in response to the projected higher salinities, and freshwater and anadromous species could decrease.

Implications

The loss of wetlands could result in substantial ecological and economic losses for the region. For example, the managed wetlands north of Suisun Bay support a hunting and fishing industry valued at over $150 million annually (Meyer, 1987). Tourism, hunting, fishing, rare and endangered species, and heritage values also could suffer.

California Agriculture

California's agricultural production is highly dependent on irrigation, which accounts for approximately 80% of the state's net annual water use. Dudek (Volume C) used existing agroecological models to explore potential responses of California agriculture to climate change.

Study Design

Climate changes from the GISS and GFDL doubled CO_2 scenarios were linked to an agricultural productivity model adapted from Doorenbos and Kassam (1979). Growth responses to both climate change and climate change plus direct effects of carbon dioxide were modeled. These productivity responses were then introduced into the California Agriculture and Resources Model (CARM) (Howitt and Mean, 1985), which estimates the economic and market implications of such changes. Mean surface water supplies under the base, GISS, and GFDL scenarios, calculated from the simulations of Sheer and Randall (Volume A), were also used as inputs into CARM.

Limitations

The CO_2 direct effects results should be viewed as preliminary, since they are based on data from growth chamber experiments that may poorly represent field conditions. This study did not consider changes in crop varieties, planting dates, energy costs, water-use efficiency, changes in the status of groundwater resources under a changed climate, or possible changes in delta agricultural acreage caused by flooding after levee failure. Also, new crop/location combinations were not considered, nor were changes in soil quality such as increases in salinity. The interaction between climate change and direct CO_2 effects on productivity were not examined but may significantly limit potential growth increases. The effects of climate changes on other agricultural production regions in the nation and the rest of the world were not considered. These could be major factors in determining how California farmers respond to climate change. Given these limitations, realistic estimates of agricultural responses to climate change may be difficult to obtain. The results may be more valuable as indications of sensitivity than as specific impacts.

Results

Relative to the 1985 base, yields could be significantly reduced for California crops in response to climate changes alone (i.e., without consideration of the direct effects of CO_2). Generally, the greatest impacts are estimated under the hotter GISS scenario. Table 14-1 presents regional yield changes for sugarbeets, corn, cotton, and tomatoes. These projections were generated by the agricultural productivity model and did not consider economic adjustments or water supply limitations. Tomatoes might suffer the least damage, with yields reduced by 5 to 16%. Sugarbeets could be hardest hit, with declines of 21 to 40%. Yield reductions in sugarbeets were estimated to be greatest in the relatively hot interior southern regions. Differences in growth response between the two climate scenarios are greatest for corn and least for tomatoes.

Without economic adjustments, corn yields are estimated to decline by 14 to 31%, based on the agricultural productivity model under the GISS scenario (Table 14-1). With economic adjustments, declines of roughly 15% were estimated, a result at the lower end of the direct productivity impacts.

When the direct effects of CO_2 on crop yields were considered, yields of cotton and tomatoes generally increased over the 1985 base (Table 141). Corn and sugarbeets were generally estimated to be unable to increase growth in response to increases in CO_2 oncentration, although yield reductions were not as great as with climate change alone (Table 14-1). Cotton could benefit the most from inadvertent CO_2 fertilization, with yields increasing in most cases by 3 to 41% (although under the GISS scenarios in the Sacramento Valley, they were estimated to decrease by 2%).

Potential increases in yields in response to CO_2 fertilization might be achieved only at a cost of increased groundwater extraction in many areas. For example, when surface water use was projected at 100% of capacity, as in the Central Coast regions, higher water requirements would necessitate increased groundwater usage (Figure 14-12). However, increased crop yields may offset increased economic costs of water.

Regionally, across all scenarios (not considering potential changes outside California) the largest reductions in crop acreage were projected in the Imperial Valley, while the delta region showed the largest gains in acreage (Figure 14-12). This expansion of agriculture in the delta region would depend on maintenance of levees protecting the farmland. Without a consideration of CO fertilization, statewide crop acreage was estimate to be reduced by about 4 to 6% from the 1985 base. When CO_2 direct effects were considered, statewide crop acreage was estimated to be

Table 14-1. Regional and Statewide Percentage Yield Changes (relative to 1985) Under Different General Circulation Model Climate Scenarios[a]

Region	Scenario	sugarbeets CC	sugarbeets Net	corn CC	corn Net	cotton CC	cotton Net	tomatoes CC	tomatoes Net
South Coast									
Los Angeles	GISS	-27	-3	-22	-18	-22	11	-8	17
	GFDL	-21	5	-3	3	-4	41	-5	20
North Interior									
Red Bluff	GISS	-34	-11	-17	-12	-30	3	-16	10
	GFDL	-26	0	-14	-9	-26	9	-14	12
Sacramento Valley									
Sacramento	GISS	-29	-3	-14	-9	-34	-2	-14	13
	GFDL	-24	3	-8	0	-32	2	-12	15
Southern San Joaquin									
Fresno	GISS	-34	-14	-19	-14	-29	6	-15	10
	GFDL	-32	-13	-13	-7	-26	11	-15	10
Southern Deserts									
Blythe	GISS	-40	-2	-31	-27	-28	6	-13	13
	GFDL	-39	0	-14	-8	-19	21	-12	15
CARM Statewide									
	GISS	-31	-8	-15	-10	-29	6	-14	12
	GFDL	-25	-1	-10	-4	-26	11	-13	13

[a] Regional changes were projected by the Doorenbos and Kassam agricultural productivity model, while statewide production changes were projected by the California Agriculture and Resources Model (CARM). The latter estimates included economic adjustment. "Net" includes the direct effects of increases in CO_2 and climate change (CC).

[b] Refer to Figure 14-12 for locations.

Source: Dudek (Volume C).

approximately equal with 1985 base levels.

Implications

Regional changes in cropping locations and patterns of water use imply potential exacerbation of existing nonpoint source pollution and accelerated rates of groundwater overdraft with ensuing environmental impacts.

Changing water supply requirements may result in increased conflicts between water users. In addition, shifts in the location of agricultural production could affect the future viability of natural systems. Such shifts could also have a significant impact on the economic health of small agricultural communities.

Regional Implications of National Agriculture Changes

Adams et al. conducted a national agricultural study that included results relevant to California (Adams et al., Volume C). The results of the study are not directly comparable with the results from Dudek's study (discussed above), since Adams et al. considered national agricultural impacts and aggregated California into a Pacific region with Oregon and Washington. Further, the two studies did not examine the same set of crops and modeled productivity differently. (For a description of the study's design and methodology, see Chapter 6: Agriculture.)

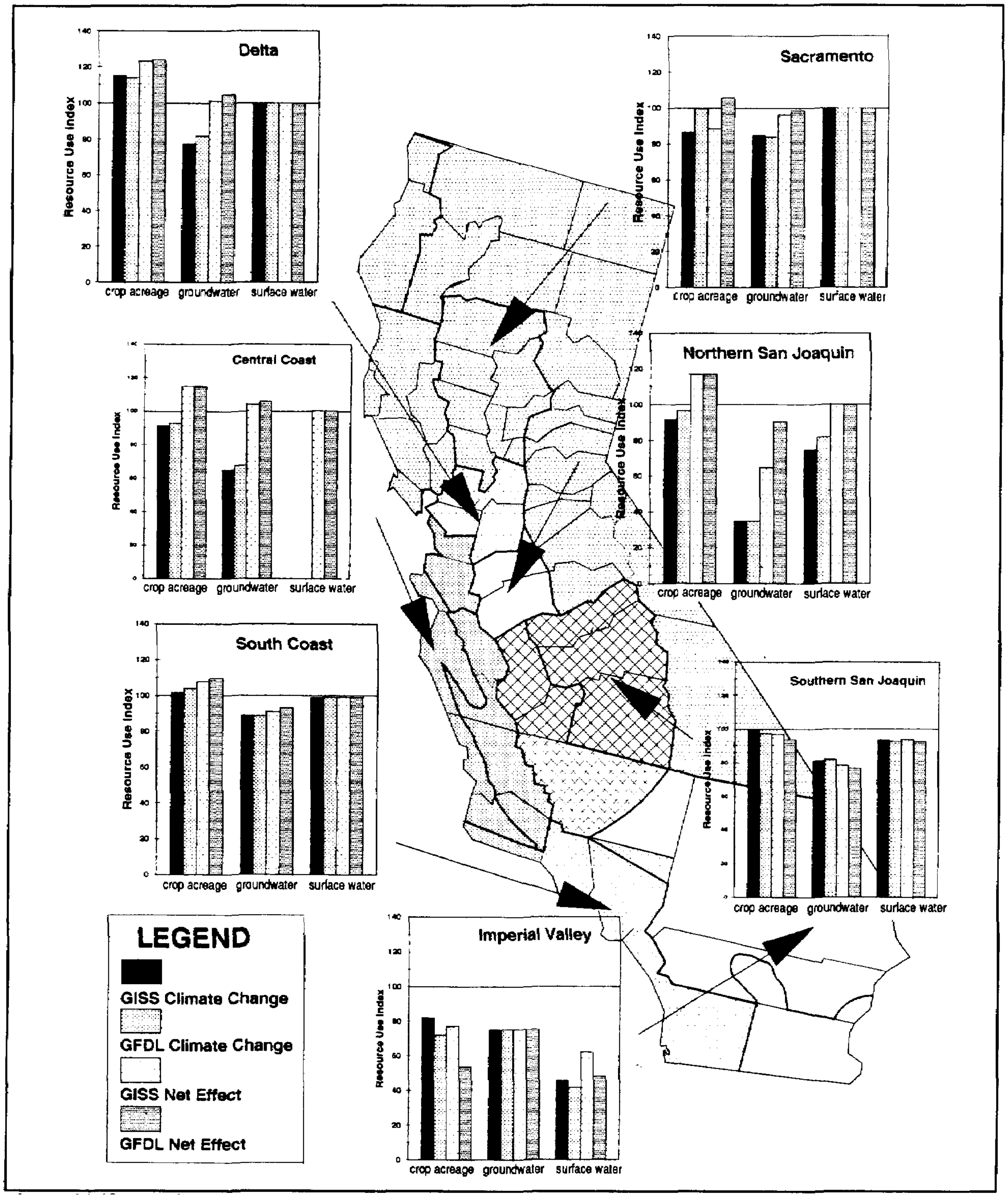

Figure 14-12. Regional crop acreage, groundwater use, and surface water use under different GCM climate scenarios. Net effect includes the direct effects of increases in CO_2 and climate change. The resource use indices represent the ratio (as percentages) of scenario results to the 1985 base period (Dudek, Volume C).

Results

Adams et al. (Volume C) estimated that national crop acreage could decline by 2 to 4% in response to climate change, but Pacific Coast State acreage could increase by 18 to 20%. This increase in the Pacific region is attributable to the region's extensive use of irrigated agriculture. In contrast, most other regions of the United States predominantly use dryland farming, and crop acreage might decline in response to moisture stress. The Adams et al. approach was based on maximizing farmers' profits and indicates that higher yields associated with direct CO_2 effects might result in further declines in crop acreage (or in the case of the Pacific Coast States, a smaller increase), since fewer acres might be required to produce the necessary crops.

Water Quality of Subalpine Lakes

Subalpine lakes are common in the California mountains, and many of these are the source of streams and rivers flowing down into the lowlands. Changes in the water quality of these lakes could significantly alter their species composition and nutrient dynamics and also could have an impact on downstream water quality and ecosystems. The sensitivity of California's subalpine lakes to weather variability and climate change has not been extensively studied. Consequently, Byron et al. studied how climate controls the water quality of Castle Lake, a subalpine lake in northern California (see Figure 14-5).

Study Design

Goldman et al. (1989) correlated an index of water quality, primary production (i.e., the amount of biomass produced by algae in the lake) with climate variability at Castle Lake. Subsequently, Byron et al. (Volume E) were able to develop empirical models relating primary production with various climate parameters.

Limitations

Their model was limited to estimating annual values of primary production; seasonal variability was not calculated. The model also did not project changes in species composition and nutrient dynamics, which could have important consequences for water quality. Changes in upland vegetation and nutrient cycling, which could also affect the lake's water quality, were not part of the model.

The estimates of annual primary production produced by this model are precise, although the results are general in the sense that no species specific projections are made.

Results

Byron et al. estimate that mean annual primary production could increase under all three doubled CO_2 scenarios, with increases ranging from 16% (OSU scenario) to 87% (GISS scenario) (Figure 1413). The OSU results are within one standard error of present production. Thus, under this scenario, there would be no significant decrease in water quality. The increase in annual primary production in the transient scenario was only statistically significant in the last decade of the transient scenario (2050-59). Primary production in the last decade was estimated to be 25% greater than the base case.

The increase in annual primary production is attributed principally to the temperature increase projected by the scenarios. The higher temperatures would result in less snow accumulation, which is correlated with an earlier melting of the lake ice and a longer growing season.

Implications

Higher primary production could result in climatic effects being indirectly felt at higher points in the Castle Lake food web and could affect the lake's nutrient dynamics.

Extrapolating these results to other subalpine lakes suggests their water quality could decrease and their species composition might change after climate warming. Increased primary production could provide additional food for other aquatic organisms, such as fish, but could also degrade water quality by ultimately causing a decrease in dissolved oxygen and by blocking light filtration to lower levels. Fisheries in unproductive lakes may be enhanced, although trout populations may suffer in lakes where temperatures rise past a threshold value and oxygen levels drop too low.

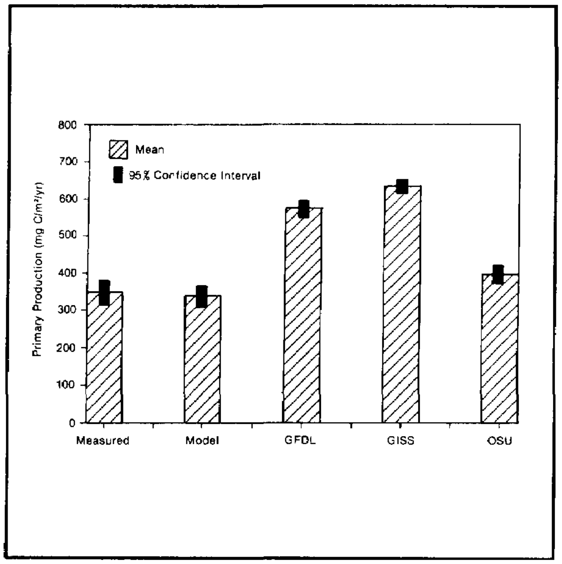

Figure 14-13. Annual primary production estimates for Castle Lake showing actual and model values for present conditions and model values for three GCM climate scenarios (see Figure 14-5 for the location of Castle Lake). Solid bars show the 95% confidence interval for each estimate (Byron et al., Volume E).

Changes in production and concomitant changes in nutrient dynamics could affect downstream river and reservoir water quality. However, since the streams draining subalpine lakes are well oxygenated, the increased biomass entering them would most likely be rapidly decomposed and probably would not affect the water quality of lower reaches of streams and rivers.

Summary of Effects on Water Resources

In terms of economic and social importance, changes in water resources are among the most important possible effects of climate change in California. A wide variety of factors related to climate change could affect water resources, ranging from those factors changing water supply to those affecting water requirements. All the individual projects discussed above addressed some aspect of climate impacts on water resources in the state. However, these studies did not consider all the major factors that could affect California water resources in the next century, mainly because of the complexity and inherent difficulties in forecasting future requirements for water. This section discusses other factors that would affect future water demands not directly considered by the individual studies, including future changes in agriculture, population, water-use efficiency, and sources of water, including groundwater.

Dudek's study used estimates of water deliveries from Sheer and Randall's study, but changes in agriculture that he determined, and hence changes in agricultural demand for water, are not factored back into the water simulation model. For instance, Dudek's results indicate that because of climate conditions, crop acreage in the Imperial Valley decreases, freeing water used there for irrigation to be used elsewhere in the state if water institutions permit such transfers. Also, as cropping patterns change, so does the pattern of needed water transfers via the water resource system, thus affecting water deliveries. Finally, Dudek found that groundwater usage can increase when the direct effects of CO_2 are included in his model. Estimated groundwater usage is projected to increase when full use of surficial water sources does not meet agricultural demands estimated in the model. Thus, Dudek's results suggest that agricultural demand for water could exceed surficial supplies after climate warming, further exacerbating water shortages.

Not considered in the overall California study, but critical to determining the magnitude of potential water shortages in the next century, are population growth and accompanying changes in water demands. Projections of population growth place the state's population at about 35 million in 2010 as compared with 24 million in 1980, an increase of 45% (California Department of Water Resources, 1983). As mentioned earlier, requirements for SWP deliveries by urban, agricultural, and industrial users could increase by 50% over what the system can reliably supply today. This shortfall by itself is significantly greater than the decrease in deliveries caused by the climate scenarios as determined by Sheer and Randall.

If water shortages become more common, agricultural, industrial, and residential users will probably change their water-use efficiency. Changes in efficiency could moderate possible future shortages. Any change in water pricing or water law also could affect water demand and supply, but these changes are very difficult to project far into the future.

Groundwater usage is discussed by Dudek, but the overall impacts of climate change on groundwater are not addressed in this project. As demand for water increases beyond the capability of the water resource system to deliver the needed water, mining of groundwater (as Dudek shows for agriculture) is one option users could adopt to meet their demand. Using groundwater could lessen the severity of water shortagesin the short term but presents environmental problems, such as land subsidence, over the long term.

In general, given the current water resource system, qualitative considerations of future changes in water requirements suggest that future water shortages could be significantly greater than estimated here for climate change alone.

Vegetation of the Sierra Nevada

To better understand the sensitivity of natural vegetation in California to climate change, Davis (Volume D) studied changes that have occurred over the past 12,000 years in terrestrial vegetation growing in the California Sierra Nevada. Changes in vegetation that occurred during this period suggest how the vegetation that currently exists in the mountains could respond to future climate changes. The middle latitudes of the Northern Hemisphere are believed to have been warmest (1 to 3°C warmer than today) about 6,000 years ago (Budyko, 1982), and parts of western North America were apparently warmest 9,000 years ago (Ritchie et al., 1983; Davis et al., 1986). Thus, the period between 6,000 and 9,000 years ago in California could present a possible analog to a warmer future climate.

Study Design

The composition of the vegetation that existed in the central Sierra Nevada over the last 12,000 years was determined using fossil pollen analysis. Fossil pollen samples were collected from five lakes situated along an east-west transect (see Figure 145) passing through the major vegetation zones of the Sierra Nevada. Dissimilarity values were calculated between modern and fossil pollen samples to determine the past vegetation at a particular site.

Limitations

The climate estimated in the three doubled CO_2 scenarios is different from the climate that probably existed between 6,000 and 9,000 years ago in the Sierra Nevada, according to Davis's interpretation of the region's vegetation history. Davis suggests that 9,000 years ago, the climate was drier than it is today. Whether it was warmer or cooler is uncertain. The climate 6,000 years ago was not much different from the modern climate. Thus, the analog climates are in marked contrast to the warmer climate estimated by all three GCMs for the gridpoint closest to the western slope of the Sierra Nevada. Also, the models suggest that total annual precipitation will not significantly change.Consequently, the results of this study do not provide an indication of how the present-day vegetation could respond under the climate scenarios constructed from the GCMs. Nevertheless, they do present a possible analog for how Sierra Nevada vegetation could respond to an overall warmer Northern Hemisphere climate that produces a drier but not significantly warmer Sierra Nevada climate.

Furthermore, the warming 6,000 to 9,000 years ago occurred over thousands of years, as opposed to the potential warming within a century. Thus, the analog does not indicate whether vegetation would be able to migrate and keep up with a relatively rapid warming.

Another constraint associated with using the past as an analog to trace gas-induced warming is that carbon dioxide levels were lower during the past 12,000 years than those projected for the next century. Higher carbon dioxide concentrations could partially compensate for adverse effects of higher temperatures and lower moisture levels on tree growth. The extent of this compensating effect is uncertain at this time. Nevertheless, the possibility exists that the magnitude of the vegetation change in the past to a warmer hemispheric climate could have been less if carbon dioxide concentrations had been higher.

A relatively small set of modern pollen samples was available for comparison to the fossil samples; therefore, the precision of the vegetation reconstruction is uncertain. Also, the precision of the estimated elevational shifts in the vegetation zones is low because of the limited number of fossil sites available for the analysis. Nevertheless, this study provides a good general summary of the vegetation changes in the Sierra Nevada during the past 12,000 years.

Results

The forests existing in the western Sierra Nevada 9,000 years ago resembled those found east of the crest today (Figure 14-14), with lower forest cover and tree density. Pine and fir densities, in particular, were lower. Between 9,000 and 6,000 years ago, the vegetation gradually became similar to the modern vegetation in the same area, and by 6,000 years ago the modern vegetation zones were established on both sides of the Sierra crest. The vegetation 6,000 years ago was subtly different from that in the area today, with less 6r and more sage. The forests may have been slightly more open than today.

Implications

If climate conditions of the Sierra Nevada in the next century become similar to those that existed 9,000 years ago, major changes could occur in forest composition and density. The vegetation changes could generate significant environmental impacts, ranging from changes in evapotranspiration and related hydrogeological feedbacks to changes in nutrient cycling and soils, which could degrade the water quality of mountain streams. Fire frequency could increase as a function of changes in fuel loads and vegetation. If dead wood rapidly builds up because of the decline in one or more tree species, large catastrophic fires could occur.

If future forests west of the Sierra crest become similar to current forests east of the crest, timber production could significantly decline. Based on inventory data from national forests, timberlands east of the crest currently support only about 60% of the wood volume of timberlands west of the crest (U.S. Forest Service, Portland, Oregon, personal communication, 1988). Different future climates could also necessitate changes in timber practices (e.g., reforestation techniques).

Vegetation change in response to climate change could produce additional stress for endangered animal species as their preferred habitats change. Populations of nonendangered wildlife also could be affected as vegetation changes.

Since the GCMs estimate a different future climate than the climate reconstructed for the analog period, it isimportant to consider how the vegetation in the Sierra Nevada could respond under the GCM-based climate scenarios as compared with the way it responded during the analog period. Recall that the climate in the GCMs is estimated to be significantly warmer than today's climate, with similar amounts of precipitation, while the analog climate was significantly drier with similar temperatures. One major difference in the impact of the two types of climate scenarios could be in the response of species at higher elevations in the Sierra Nevada. Since growing season length and warmth are generally considered to control the position of timberline (Wardle, 1974; Daubenmire, 1978), warmer temperatures under the GCM scenarios could be expected to raise the timberline. The timberline was not significantly higher during the analog period. Higher temperatures could also increase the elevation of other vegetation zones in the Sierra Nevada.

Another effect of higher temperatures in the GCM scenarios that would probably affect vegetation at all elevations is a reduction in effective moisture during the growing season. Lettenmaier et al. (Volume A), in fact, estimate such a decrease as soil moisture decreases in late spring, summer, and fall compared with the base case. Furthermore, for lower elevations at least, the growing season could be effectively shortened because of the earlier onset of moisture stress after winter rains. One result of this could be the extension of grasslands and chaparral higher up the slopes of the Sierra Nevada. Also, reduced moisture availability could alter the outcome of competition between plant species with different growth forms and longevity, thus changing the composition of the vegetation zones. Plant species with drought-resistant characteristics would probably increase in relative abundance. One possible consequence of this shift in species abundance is the formation of plant communities that resemble in some aspects plant communities that occurred 9,000 years ago. However, the complicating factor of more direct effects of higher temperatures makes such a projection uncertain, as does the lack of consideration of the direct effects of increasing concentrations of carbon dioxide.

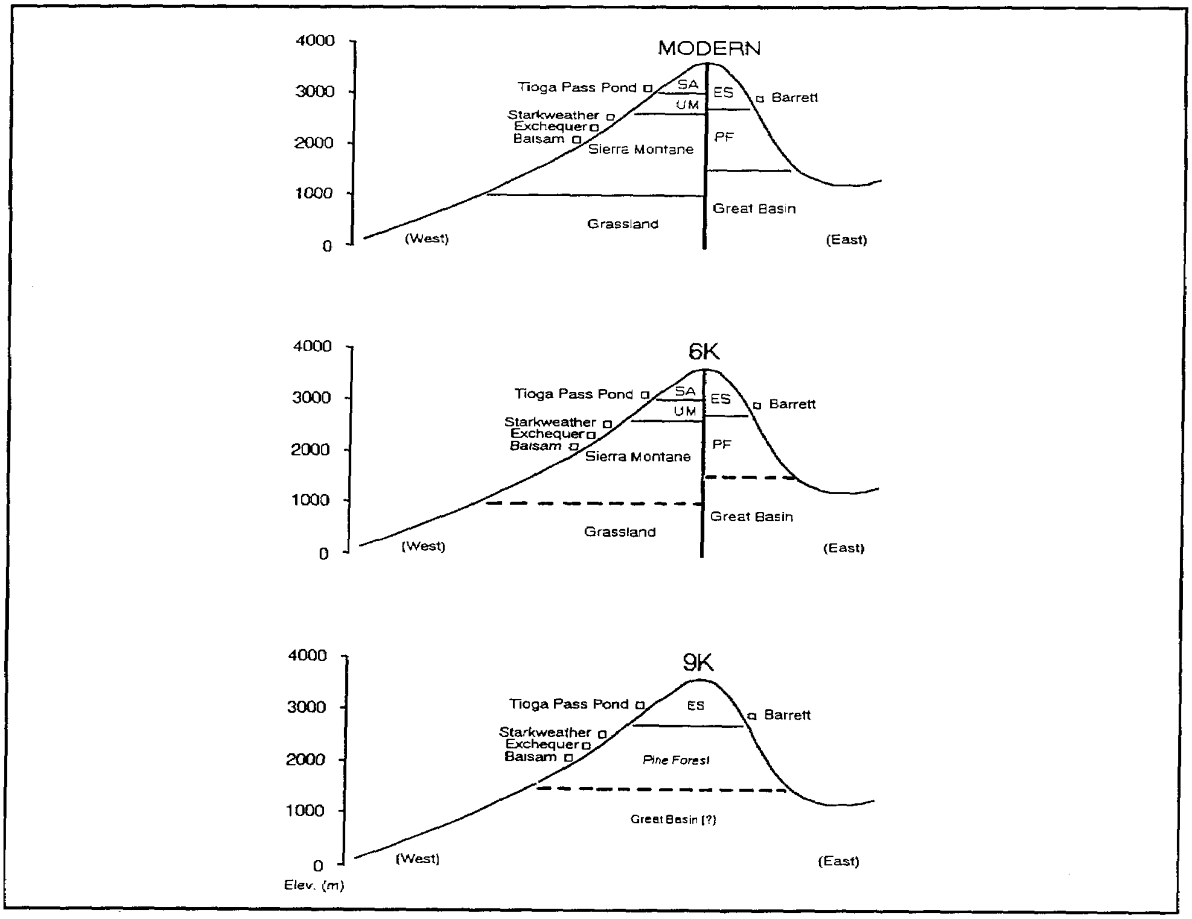

Figure 14-14. Vegetation zonation in the central Sierra Nevada at present; 6,000 years (6K) before present; and 9,000 years (9K) before present. (See Figure 14-5 for approximate locations of fossil pollen sites.) The dashed lines indicate uncertainty in the placement of vegetation zone boundaries (Davis, Volume D). SA = subalpine; UM = upper montane; ES = eastern subalpine; and PF = pine forest.

Electricity Demand

Electric power demand is sensitive to potential climate change. As part of a national study, Linder and Inglis estimated California's energy demand for the years 2010 and 2055. (For a description of the studs design and methodology, see Chapter 10: Electricity Demand.)

Results

In California, climate change scenarios result in only small changes in estimated electrical utility generation and costs by the year 2010. Annual power generation is estimated to increase by 1 to 2% (over the 345 billion kWh estimated to serve the California population and economy in 2010), and new generation capacity requirements would be less than 1% greater than increases without climate change. By the year 2055, annual power generation is estimated to increase by 3% under lower growth of electricity demand (604 billion kWh base) to 5% under higher growth (794 billion kWh base). New generation capacity requirements would be 14 to 20% greater than non-climate-induced needs. Then cumulative investments in new capacity could cost $10 to $27 billion (in 1986 dollars).

Implications

More powerplants may be required. These would need more cooling water, further depleting the water supply. Climate-induced changes in hydrology may reduce hydropower generation and increase dependence on fossil fuels and nuclear power. Increased use of fossil fuels may provide positive feedback for the greenhouse effect and may deteriorate local air quality. The increased utility rates that may be required to pay for new power generation capacity may limit groundwater pumping for agriculture.

Air Pollution

Morris et al. (Volume F) studied possible interactions of climate change and air pollution in California. They estimated the impacts of climate change on ozone concentrations using a regional transport model. The values they calculated should be viewed as coarse approximations because of the limitations in the application of the model. For instance, the study looked only at changes in temperature and water vapor and kept as unchanged many other important meteorological variables. An important unchanged variable was mixing height. Instead of remaining unchanged, mixing height could increase with rising temperatures. This would have a dilution effect on air pollution. (The study's design limitations and methodology are discussed in Chapter 11: Air Quality.)

Results

Morris et al. estimated that ozone concentrations could increase up to 20% during some days in August in response to a 4°C (7°F) climate warming in central California. The National Ambient Air Quality Standard (NAAQS) for ozone is 12 ppm. Morris et al. estimated that the number of August days that exceed this standard could increase by 30%. Furthermore, the area exceeding the NAAQS could increase by 1,900 square kilometers (730 square miles), and the number of people exposed to these elevated ozone levels could increase by over 275,000.

Implications

Trace gas-induced climate change may significantly affect the air's chemistry on local and regional scales. These changes may exacerbate existing air quality problems around California metropolitan areas and agricultural areas of the Central Valley, causing health problems and crop losses. Increases in air pollution may directly affect the composition and productivity of natural and managed ecosystems.

POLICY IMPLICATIONS

An overall question applies to resource management in general: What is the most efficient way to manage natural resources? Currently, management is based on governmental jurisdiction with, for example, forests managed at the local, state, or federal level. Management of hydrologic systems is also based on governmental jurisdiction. An alternative would be to manage these systems using natural boundaries as the criteria for determining management jurisdiction. The pros and cons of such a management strategy deserve at least some preliminary research.

Water Supply and Flood Control

Water supply is the basis for most economic development in California. Yet, almost all the water available in the SWP is allocated for use. A major problem is to accommodate rising demand for water, interannual climate fluctuations, and the need to export water from northern to southern California.

In addition, the results from these studies suggest that climate change over the next 100 years could cause earlier runoff, thus reducing water deliveries below their projected 1990 level. This situation (together with increasing requirements for water caused by increasing population) would create a set of major policy problems for the water managers and land-use planners in California.

Two major policy questions can be raised concerning the possible reduction in water deliveries: How can the water resource system be changed to prevent a decrease in water deliveries caused by climate change? If water deliveries fall short of demand, how should potential water shortages be allocated?

Approaches for Modifying the Water Resource System

Several possible approaches can be attempted to increase water deliveries. First, system management can be modified. For instance, the most recent SWP development plan suggests the possibility of state management of both SWP and CVP facilities (California Department of Water Resources, 1987a). Complete joint management could produce more than 1 million acre-feet (maf) additional reliable yield in the system. Steps toward greater cooperation have been taken. The Coordinated Operating Agreement (H.R. 3113) between the SWP and the CVP, ratified in 1986, allows the SWP to purchase water from the CVP. Using conservation techniques and improving the efficiency of transfer might also increase water deliveries.

Operating rules for the reservoirs also could be modified to increase allowable reservoir storage in April, which would increase water storage at the end of the rainy season and deliverable water during the peak demand season in midsummer. However, an increase in storage in the late winter and early spring would likely reduce the amount of flood protection (increase the risk of flooding) in the region; this in itself could negatively affect owners of floodplain property. Floods also place the delta islands at risk because of higher water levels. The tradeoff between water supply and flood control in northern California represents a potentially serious policy conflict affecting all levels of government in the region. In fact, the meeting between representatives of the State DWR and Bureau of Reclamation, which was held to discuss Sheer and Randall's results (Volume A), concluded that any likely changes in reservoir operation that would avoid a significant loss of flood safety would most likely bring about little improvement in the system's performance under the given climatic scenarios. Detailed study of this point is needed, however.

The second approach to maintain or increase water deliveries might be to construct new water management and storage facilities. However, trends over the past decade have shifted away from planning large physical facilities (e.g., the Auburn Dam and Delta Peripheral Canal). Building new facilities is expensive and raises serious environmental concerns about such issues as wild and scenic rivers. Another option is to use smaller facilities, such as the proposed new offstream storage facility south of the delta, and to improve the delta's pumping and conveyance facilities. With the help of these facilities, the SWP plans to achieve a 90% firm yield (the amount that can be delivered in 9 out of 10 years) of about 3.3 maf by 2010 (California Department of Water Resources, 1987a). Another relatively inexpensive option for off-line storage is artificial recharge of groundwater during wet years. The SWP is currently pursuing a proposal to deliver surplus water to groundwater recharge areas in the southern Central Valley to provide stored water for dry years.

The third approach to increase water deliveries is to turn to other sources of water. For instance, use of groundwater could be increased. However, in many metropolitan areas, groundwater bodies are currently being pumped at their sustainable yields. Any increase in pumping could result in overdraft. Furthermore, decisions to use groundwater are made by local agencies and/or individual property owners, and groundwater is not managed as part of an integrated regional water system. Whether or not to include it in the system is an important policy issue.

Another option is for southern California to choose to fully use its allotment of Colorado River water (which could lead to conflicts between California and other users of that water, especially Arizona). Other possibilities include desalinization plants, cloud seeding over the Sierras, and reuse of wastewater. However, desalinization plants are energy intensive and may exacerbate air quality problems. Also, cloud seeding is controversial, since downwind users may not be willing to lose some of their precipitation.

Options for Allocating Water Shortages

The second major policy question is how best to allocate potential water shortages. One way would be to allow greater flexibility in water marketing. The adverse effects of this policy change (e.g., perhaps water becoming too expensive for agriculture and possible speculative price increases) could be ameliorated through a variety of governmental policies. Yet, even with regulation, any changes in the current system along these lines would most likely be very controversial.

A second way to allocate the shortages is to rely on mechanisms used in the past to deal with droughts and water shortages, specifically governmental restrictions on water use. In the past, these mechanisms have included increased use efficiency, transfers of agricultural water to municipal and industrial uses, and restrictions on "nonessential" uses of water (e.g., watering of lawns). Increased efficiency of water usage through various conservation techniques could effectively increase the number of water users without actually increasing the amount of water delivered. If climate gradually changed and water shortages became more common, these restrictions could become virtually permanent.

Sacramento-San Joaquin River Delta

The delta area of the Sacramento and San Joaquin Rivers in the San Francisco Bay estuary receives great attention from governmental bodies at all levels because of its valuable agricultural land, its crucial role in the state's water resource system, and its sensitive environment. The results of the studies in this overall project suggest that this region could be significantly affected by climate change. Major changes could occur in delta island land use and in the water quality of the San Francisco Bay estuary. The policy implications of these possible changes are discussed below.

Delta Island Land Use

A critical land use issue is whether to maintain the levees surrounding islands threatened by inundation. Much of the land present on these islands is below sea level and is usable for agriculture, recreation, and settlement only through levee protection.

The individual delta islands have a significant range of values. For example, some islands contain communities and highways, and others are strictly agricultural. The property value of the islands is about $2 billion (California Department of Water Resources, 1987b). The islands also help repel saline water from the delta pumping plants (see Figure 14-2).

The levees have been failing at an increasing rate in recent years, and further sea level rise could increase failure probability. Improving the levees to protect the islands from flooding at the existing sea level and flood probability would cost approximately $4 billion (California Department of Water Resources, 1982).

The issue of levee failure raises three important policy questions. First, will some or all of the levees be maintained? The range of options concerning the levees includes inaction, maintenance of the status quo, strategic inundation of particular islands, and construction of polder levees.

Inaction, meaning the levees would not be improved with time, could eventually lead to the formation of a large brackish-water bay as all of the levees failed. Williams (Volume A) suggests that the area of the San Francisco Bay estuary could triple if all the levees failed.

Currently, the general policy is to maintain the delta's configuration. One important policy favoring the maintenance of the levees is the Delta Levee Maintenance Subventions Program, in which state financial assistance is available for maintaining and improving levees. The value of the islands for agriculture and maintenance of water quality (see below) has created additional institutional support for maintaining the levees, even though the cumulative cost may exceed the value of the land protected. Future funding decisions for this and related programs should consider the possibility of climate change. If the levees are maintained, an important policy question must be considered: Who will pay for the maintenance?

Not all the islands are equal with regard to their value in protecting the freshwater delivery system. A possible future policy response to rising sea level would be to maintain only certain levees and not reclaim other islands as they became flooded. In essence, this would be a strategic inundation policy. Some precedence exists for this policy, as Mildred Island was flooded in 1983 and not reclaimed; the high cost of reclaiming the island relative to its value was cited as a rationale.

Construction of large levees similar to the polders in Holland is an option for protecting the islands and maintaining shipping channels. However, this approach would be expensive and, although it has been discussed, has not attracted much serious attention.

The second policy question concerns failure of the levees. If all or some levees are allowed to fail, will landowners be compensated? If so, where will the money come from? The delta islands contain some of the most valuable agricultural land in the state. Loss of this land would be a severe economic hardship for the local farmers and for the associated business community. Whether these farmers should be compensated for their loss is an important public policy issue.

A final policy question remains: How will management of the delta islands be coordinated? Four government bodies have jurisdiction over the islands at the local, state, and federal levels. These bodies will need to coordinate activities to reach decisions regarding the future of individual delta islands.

Water Quality of the San Francisco Bay Estuary

The intrusion of saline waters into the upper reaches of the San Francisco Bay estuary could be a major problem in a warmer climate. Climate change is projected to cause increased salinity in the estuary, largely as a result of sea level rise, levee failure, and the inadequacy of freshwater outflow to offset the increase in salinity. Furthermore, land subsidence due to groundwater extraction could augment sea level rise. In some areas of the estuary, subsidence up to 1.5 meters (59 inches) has occurred within the past 40 years (Atwater et al., 1977).

Maintenance of current salinity levels is addressed in the water right Decision 1485 (D-1485) of 1978. This decision requires that water quality standards in the delta be maintained. If they are not, additional water must be released from reservoirs to improve delta water quality, which could reduce the amount of water available for delivery. Current policy does not explicitly take into account the potential for future climate change. Thus, D-1485 could be interpreted as requiring maintenance of delta water quality standards even if sea level rises and causes further penetration of saline water into the delta. Delta water quality standards are currently being reviewed at the BayDelta Hearing in Sacramento, which began in mid1987 and is expected to continue for 3 years. The choice of future options will be greatly affected by decisions made at the hearing.

Possible methods of combating the impacts of saltwater intrusion include maintaining levees, increasing freshwater outflows, reducing withdrawals, enlarging channels, constructing a barrier in the Carquinez Strait or lower delta, and/or constructing a canal around the delta's periphery. Alternatively, the freshwater pumping plants could be moved to less vulnerable sites. Decisions regarding response options will not be easily made. Levee maintenance and construction are costly. The water delivery agencies might be reluctant to increase delta outflows or to reduce withdrawals. Enlargement of delta channels, construction of saltwater barriers, and construction of a peripheral canal are extremely controversial environmental issues. Another possible response to these climatic impacts would be a gradual, planned retreat from the delta, devoting resources to options compatible with the absence of a freshwater delta. This response would also be very controversial, both politically and environmentally.

Water Quality of Freshwater Systems

The water quality of lakes, streams, and rivers could change as climate changes. Results from the Castle Lake study indicate that primary production of subalpine lakes could increase, with the potential for changes in the water quality of mountain streams (Byron et al., Volume E). Reduction in summer flows of streams and rivers in the Central Valley Basin could concentrate pollutants in these aquatic systems. A major policy question relates to these potential changes: How will potential reductions in water quality below levels mandated in the current Water Quality Act of 1987 (Public Law 100-4) be prevented?

Maintaining water quality despite decreased summer flows could be difficult and expensive. Controlling nonpoint source pollution is a goal of the Water Quality Act of 1987, and meeting this goal in the future could be more difficult and expensive because of the lower summer flows. Changes in land use near streams and rivers may be required to prevent runoff from agricultural land from reaching them. Reducing herbicide and pesticide use could also be another response, but this could harm agricultural production. Another option for preventing increased concentrations of pollutants in river reaches below reservoirs is to increase releases from reservoirs during summer months; this strategy would dilute the pollutants. However, this strategy would also have obvious negative impacts on water deliveries.

Municipalities that release treated sewage into rivers also could face increased difficulties in meeting water quality standards. Options include expanding sewage treatment facilities, which is expensive; releasing water from reservoirs to dilute the pollutants, as discussed above; or controlling the production of wastewater. Any municipalities planning for new sewage treatment plants should include climate change as one factor in the design criteria.

Reductions in summer flows could harm populations of aquatic organisms and terrestrial organisms that use riparian habitats. To the extent that these species become threatened with extinction, laws requiring preservation of endangered species (e.g., Endangered Species Act of 1973) may be invoked as a legal basis for increasing reservoir releases to preserve these species. This could place into conflict the governmental agencies and public constituencies concerned with preserving biodiversity and those concerned with the economic impacts on agriculture and industry.

Terrestrial Vegetation and Wildlife

Changing species composition and productivity might alter the character of forestry operations and the esthetic appeal of currently popular recreational areas. Climate-induced reductions in growth and regeneration rates, and increases in losses from wildfire and insect damage, could decrease the size and value of industrial forests in the state. How these changes would be managed is a complex question involving all levels of government as well as private landowners.

One major step in response to possible future climate change is to incorporate climate considerations into current planning processes. Federal planning for the effects of climate change on forests is discussed in Chapter 5: Forestry. Similar changes in the planning process could be considered at other levels of government. Coordinating the actions of government agencies involved with land management to climate change in California is another possible response.

The flora and fauna in California are highly diverse and include many rare and endangered species. Climate could change faster than some species could adapt, leading to local extinction of these species. Species conservation (as mandated by the Rare and Endangered Species Act of 1973) might require habitat reconstruction and/or transplanting in some situations. Monitoring programs may need to be instituted to track trends in populations and communities. Extensive programs have been developed for currently endangered species in the state (e.g., the California condor), and similar efforts probably could be mounted in the future for other highly valued species.

Agriculture

Changes in water availability and temperature stresses are projected to affect agricultural production. How will changes in agricultural production and crop types be managed, and how will California agriculture respond in national and international settings? (For further discussion, see Chapter 6: Agriculture.)

Historically, agriculture has quickly adapted to climate fluctuations. New technology and reallocation of resources might offset the impact of changed climatic conditions and water availability. Improved farm irrigation efficiency, such as extensive use of drip irrigation, could mitigate the impact of water-delivery shortages. Water marketing may provide a cost-effective means of meeting water demands and providing market opportunities for conserving water (Howitt et al., 1980). For example, water marketing may provide rights holders with the financial ability to invest in water conservation programs to cope with climate warming impacts on water availability.

Changes in cropping locations and patterns of water use could exacerbate nonpoint source pollution and accelerate rates of groundwater overdraft. Furthermore, changing water supply demands may heighten the conflicts between water allocation strategies and ecosystem and wildlife values.

It is uncertain how agricultural effects would be manifest in California's evolving economic and policy environment. For example, increased commodity prices could mitigate the financial impacts of potential reductions in crop acreage and production.

Wetland Vegetation and Fisheries

Wetland species are valuable ecologically, esthetically, and economically (photography, hunting, fishing, etc.). With rising sea level, areas supporting shallow-water vegetation might be inundated and converted to deep-water habitats supporting different species. New shallow-water sites could be created by artificially adding sediment. This option features its own environmental impacts and would most likely be expensive. However, maintaining shallow-water vegetation is important not only to the conservation of plant species but also to migratory birds, which feed on such vegetation.

Salinity impacts on phytoplankton and fisheries might be controlled via levee maintenance coupled with increases in delta outflow.

Shoreline Impacts of Sea Level Rise

The California coast includes a diverse array of shorelines ranging from cliffs to sandy beaches. Erosion along these coastlines may increase as a consequence of sea level rise. Such erosion could substantially damage shoreline structures and recreational values. Preventing the erosion would be very costly. For example, protecting the sewer culvert of the San Francisco Westside Transport Project from potential damage caused by sea level rise may cost over $70 million (Wilcoxen, 1986). Sound planning for shoreline structures should consider future erosion that may be caused by sea level rise. (For further discussion of these issues, see Chapter 7: Sea Level Rise.)

The accumulation of sediment behind water project dams and the effects of diversion structures, dredging operations, and harbor developments have limited the sources of sediment for beach maintenance (particularly along the southern California coast). Individual landowners and institutions constructing such infrastructures should consider their effects on sedimentation processes. Only through artificial deposition of sand (primarily from offshore sources) have southern California beaches been maintained. Beaches provide recreational areas and storm buffers, and their maintenance will require a major and continued commitment.

Energy Demand

A warmer climate could affect both energy demand and supply. For instance, higher temperatures could cause increased cooling demands, and changes in runoff could affect hydroelectric power generation. Institutions in California that are involved with energy planning, such as the State Energy Resources Conservation and Development Commission, should begin to consider climate change in their planning efforts so that future energy demands can be met in a timely and efficient fashion.

Air Quality

Increasing temperatures could exacerbate air pollution problems in California, increasing the number of days during which pollutant levels are higher than the National Ambient Air Quality Standards. Devising technological and regulatory approaches to meet ambient air standards is currently a major challenge in certain regions of the state, and these efforts must be continued. Under a warmer climate, achieving air quality standards may become even more difficult. To ensure that air quality standards are met under warmer conditions, policymakers, such as EPA and the California Air Quality Board, may wish to consider possible climate changes as they formulate long-term management options for improving air quality.

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