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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.

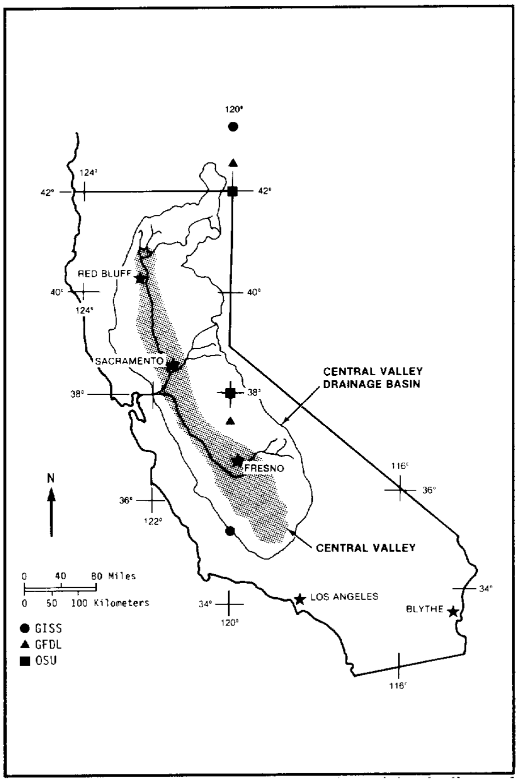

Figure 14-1. The Central Valley (shaded) and Central Valley Drainage Basin of California. Symbols refer to locations of general circulation model (GCM) gridpoints. (See California Regional Climate Scenarios section of this chapter for details on GCMs).

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.

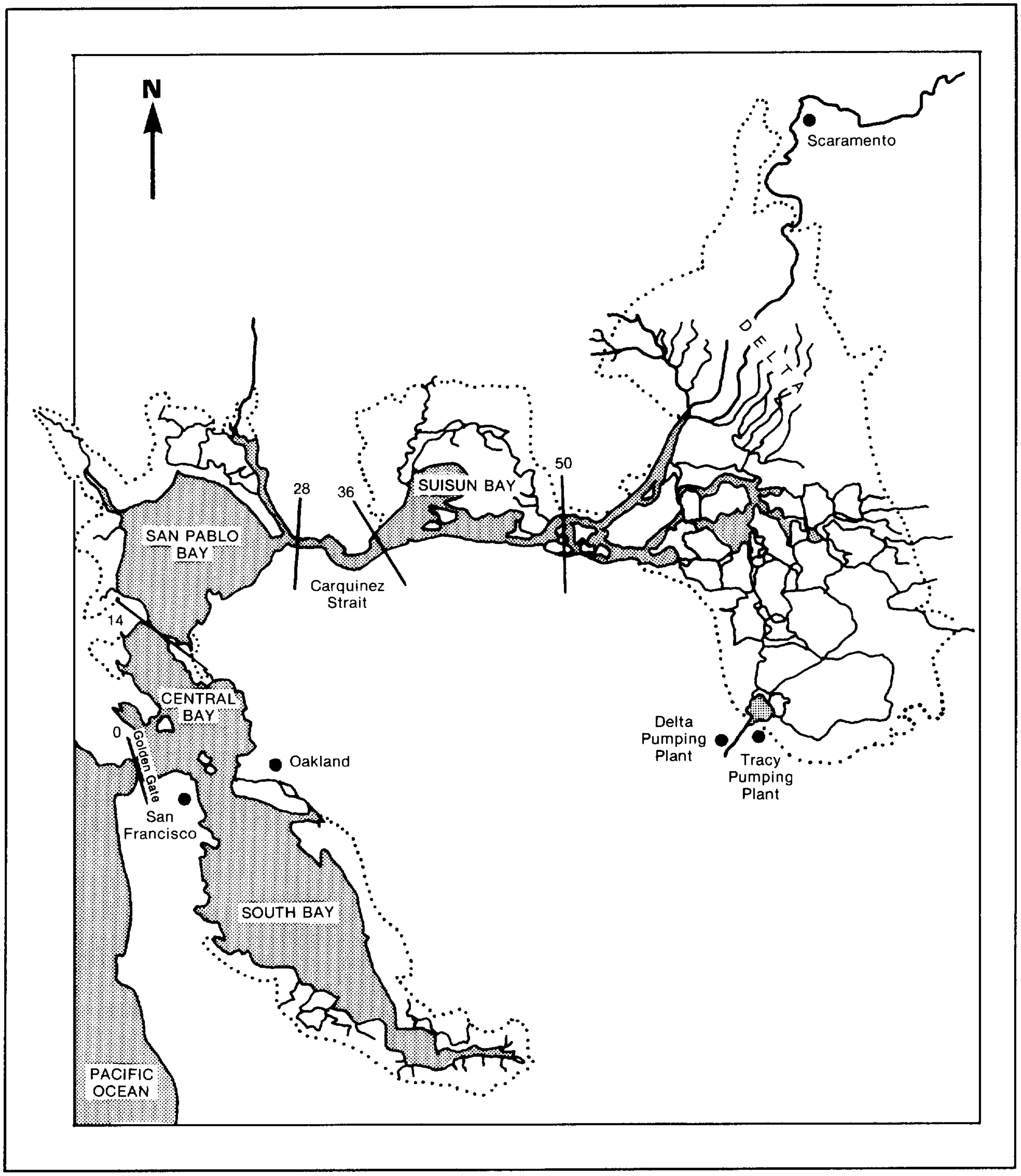

Figure 14-2. The San Francisco Bay estuary and locations of the freshwater pumping plants in the delta. The numbered bars indicate distance (in miles) from the Golden Gate. The dotted line indicates the maximum area affected by a 100-year high tide with a 1-meter (40-inch) sea level rise.

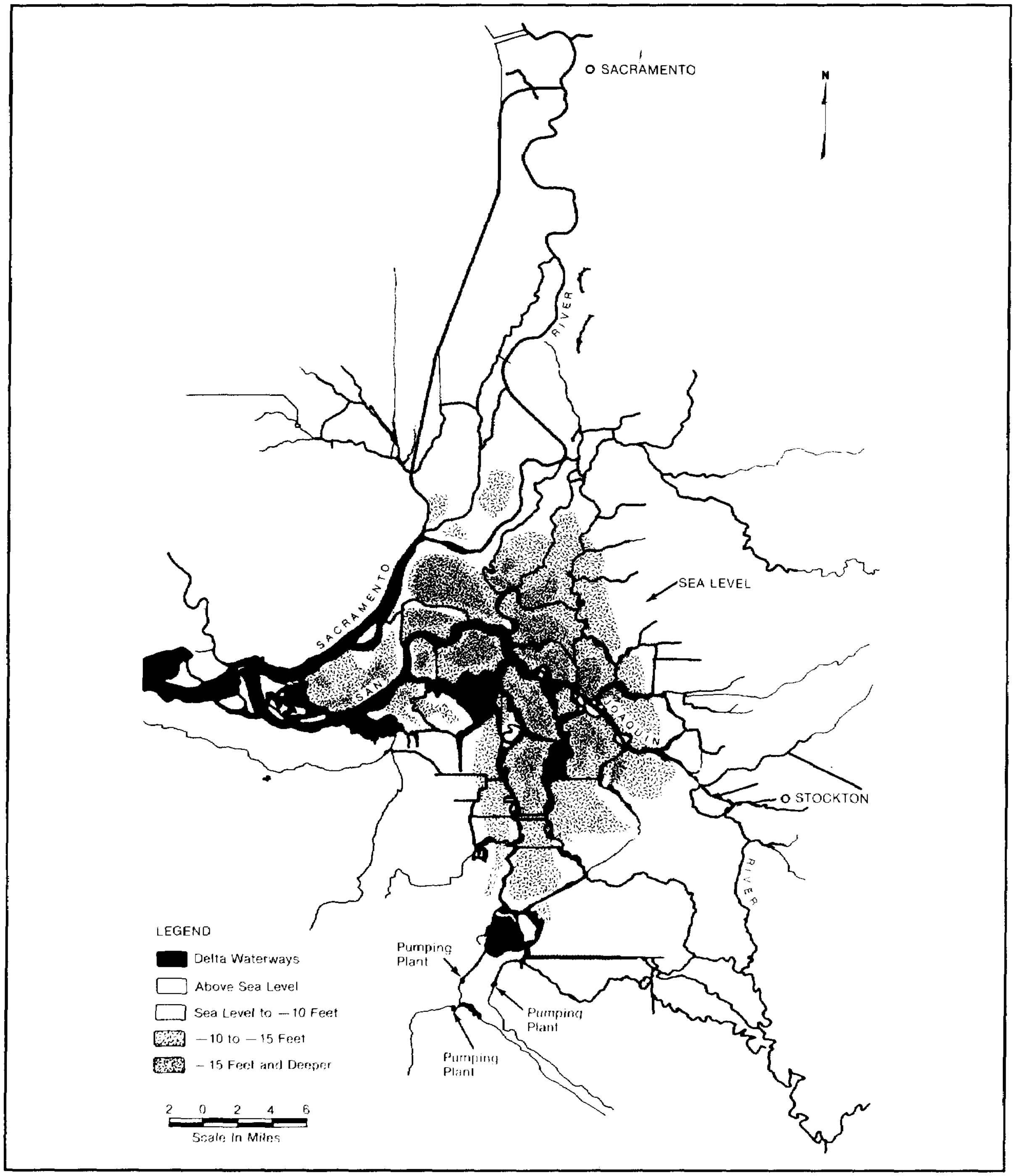

Figure 14-3. The Sacramento-San Joaquin River Delta. Shaded areas indicate land below sea level. See Figure 14-2 for location of the delta in the San Francisco Bay estuary.

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).

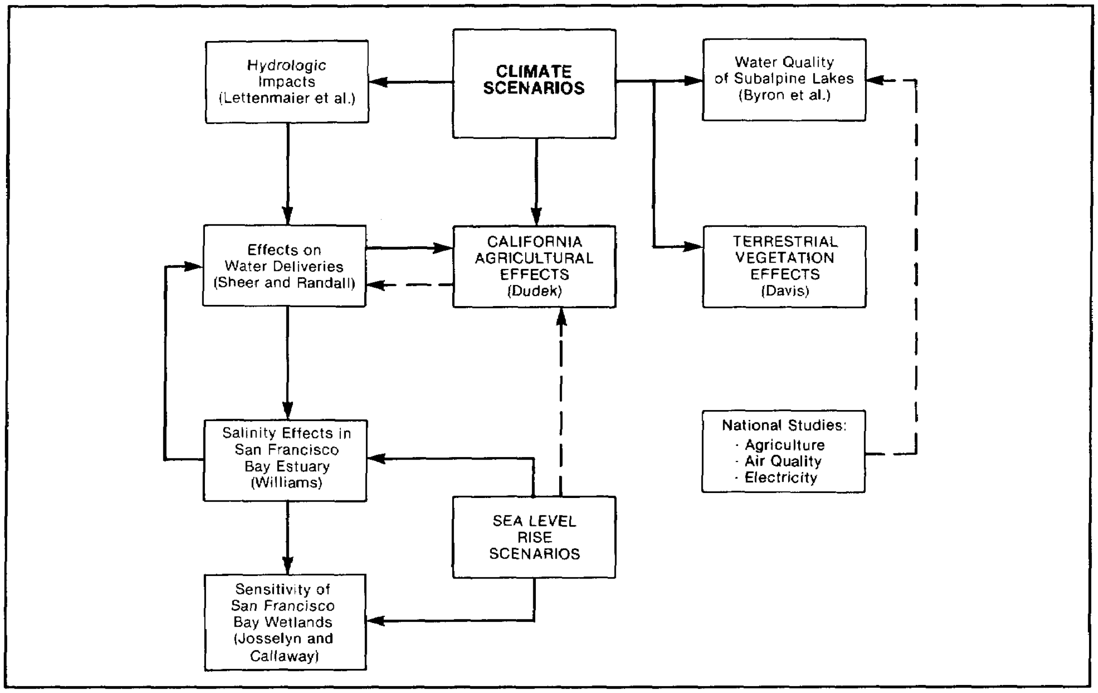

Figure 14-4. Organization of the study, showing paths of data input from scenarios and between projects (solid lines). Dashed lines indicate some important linkages between projects that were not quantitatively made in this study.

- 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.

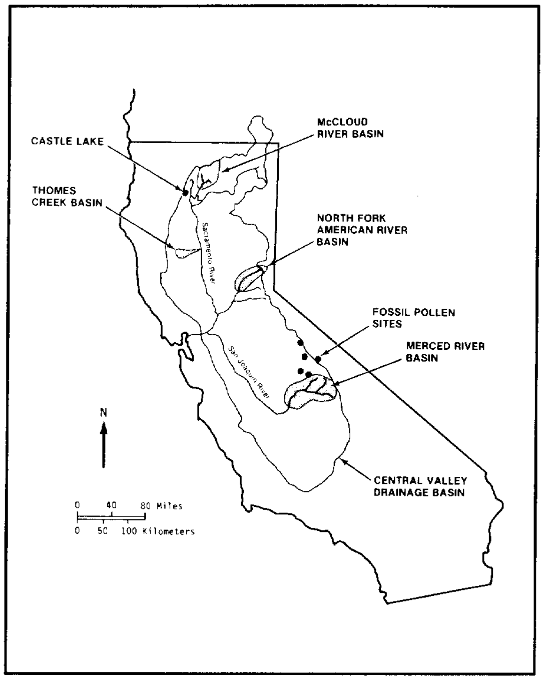

Figure 14-5. The Central Valley Drainage Basin of California. Shaded areas refer to the four study catchments used by Lettenmaier et al. Dots indicate the positions of the Castle Lake study site (Byron et al., Volume E) and the five fossil pollen sites (Davis, Volume D).

- <u>The Effects of Global Climate Change on Water Quality of Mountain Lakes and Streams</u> - 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).

- <u>Ancient Analogs for Greenhouse Warming; of Central California</u> - 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).

<u>National Studies That Included Results for California</u>

- <u>The Economic Effects of Climate Change on U.S. Agriculture: A Preliminary Assessment</u> - 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.

- <u>The Potential Impacts of Climate Change on Electric Utilities: Regional and National Estimates</u> - 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.

- <u>Examination of the Sensitivity of a Regional Oxidant Model to Climate Variations</u> -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.

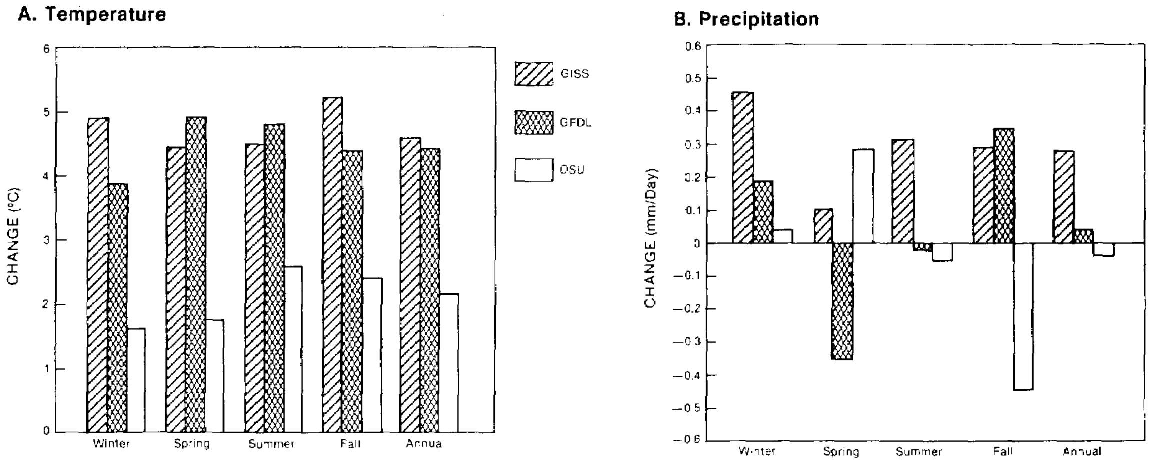

Figure 14-6. General circulation model (GCM) scenario results showing seasonal and annual (A) temperature and (B) precipitation changes between GCM model runs at doubled CO 2 and current CO_2 concentrations. The values are averages of the two gridpoints used by the water resource modelers. (See Figure 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

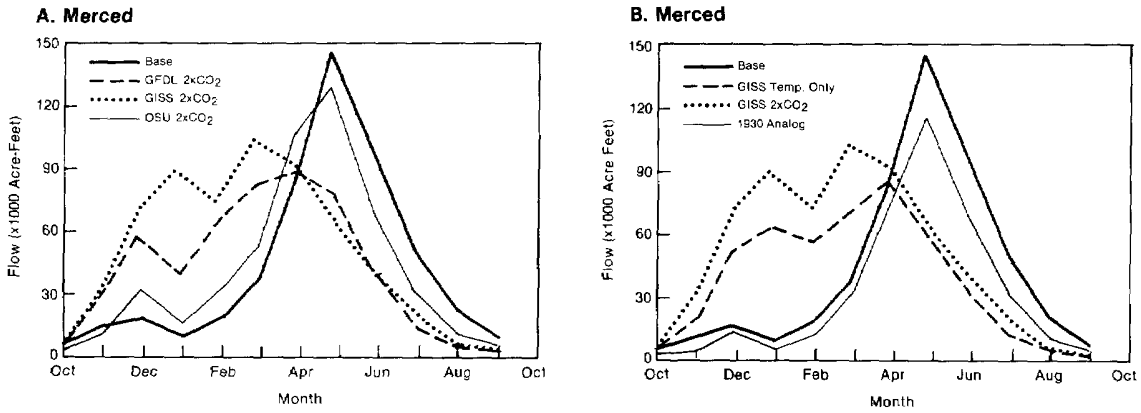

Figure 14-7. Mean monthly streamflows under difference climate scenarios for the Merced River Basin, one of the the four study catchments modeled (see Figure 14-5 for locations of the study catchments): (A) results from the three doubled CO_2 scenarios; and (B) results from the scenario incorporating 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).

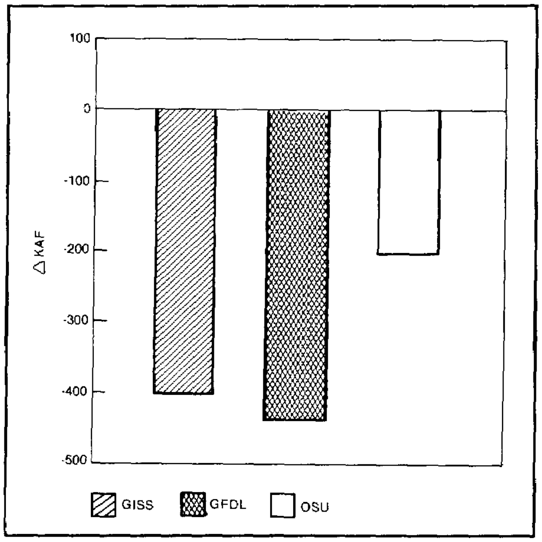

Figure 14-8. Mean annual change in SWP deliveries (base case minus scenario). KAF = thousands of acre-feet (Sheer and Randall, Volume A).

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.

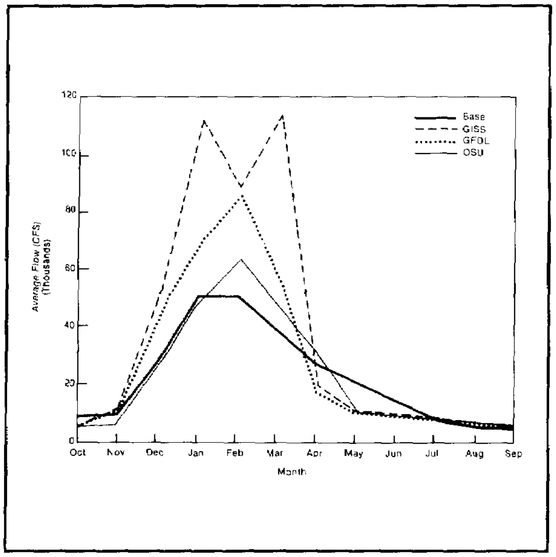

Figure 14-9. Projected monthly delta outflows under different general circulation model climate scenarios (adapted from Sheer and Randall, Volume A).

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.

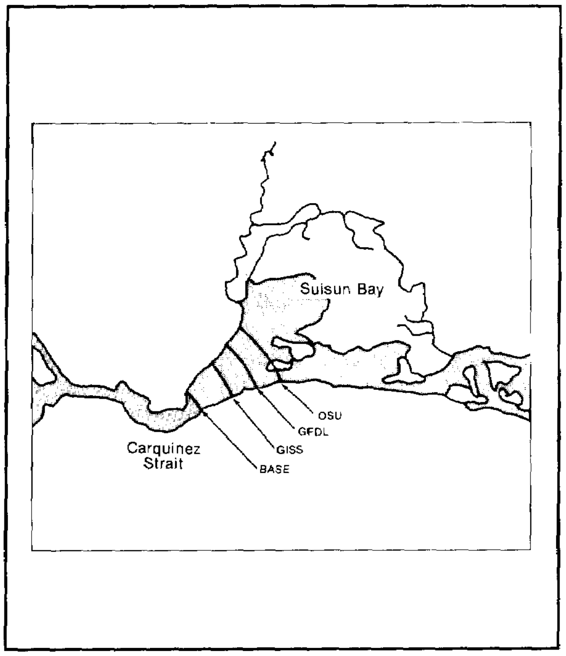

Figure 14-10. Movement of mean annual salinity of 10 parts per thousand under different hydrology scenarios. Other salinity levels move similar distances (see Figure 14-2 for location of Suisun Bay; Williams, Volume A).

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.

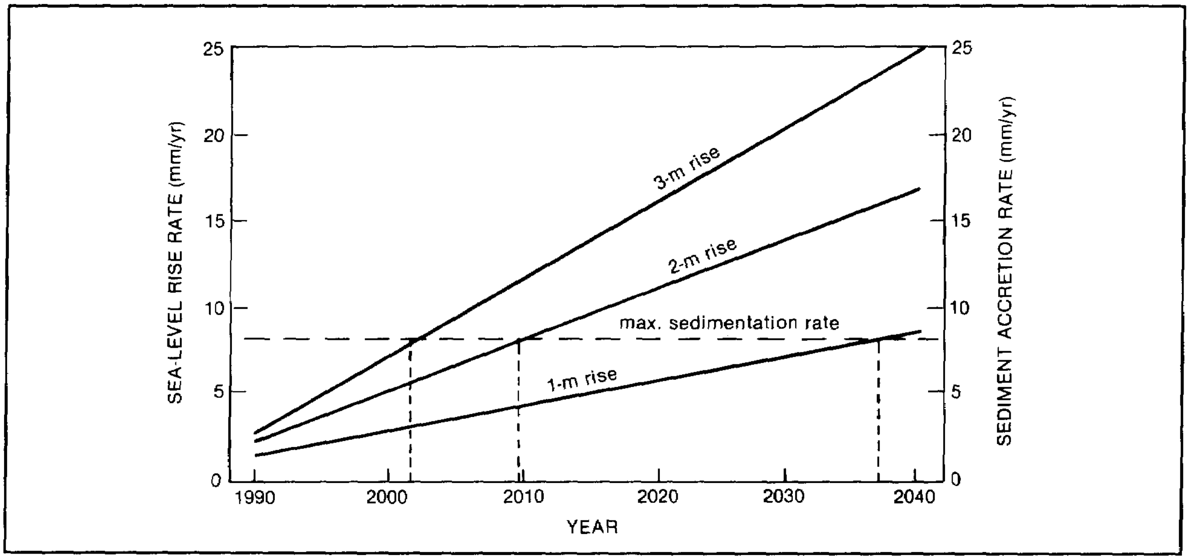

Figure 14-11. Estimated sea level rise at San Francisco for three scenarios by the year 2100 (Josselyn and Callaway, Volume E).

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	Crop							
		sugarbeets		corn		cotton		tomatoes	
		CC	Net	CC	Net	CC	Net	CC	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.)

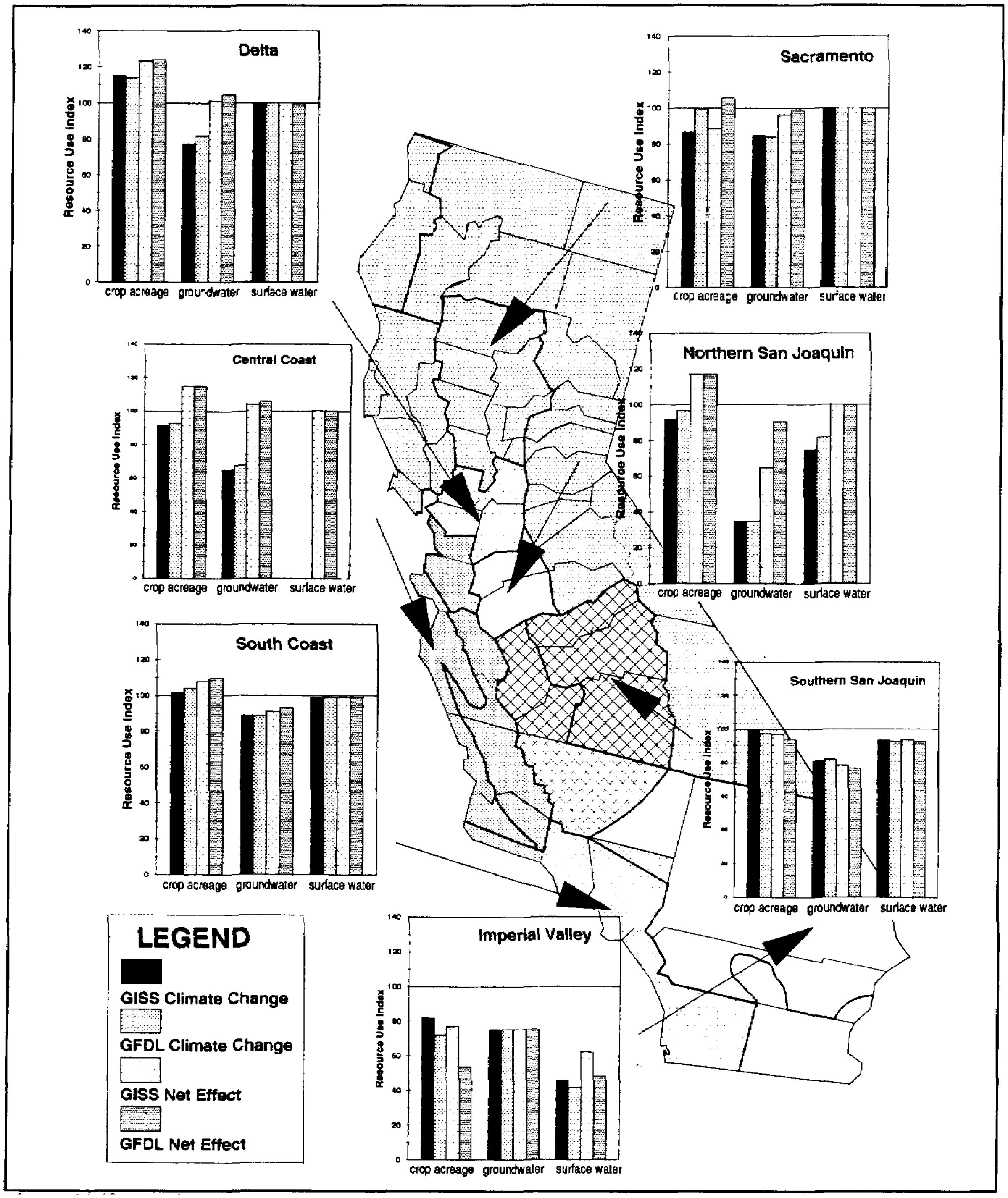

Figure 14-12. Regional crop acreage, groundwater use, and surface water use under different GCM climate scenarios. Net effect includes the direct effects of increases in CO_2 and climate change. The resource use indices represent the ratio (as percentages) of scenario results to the 1985 base period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

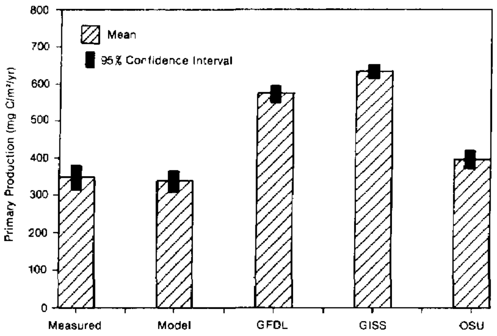

Figure 14-13. Annual primary production estimates for Castle Lake showing actual and model values for present conditions and model values for three GCM climate scenarios (see Figure 14-5 for the location of Castle Lake). Solid bars show the 95% confidence interval for each estimate (Byron et al., Volume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

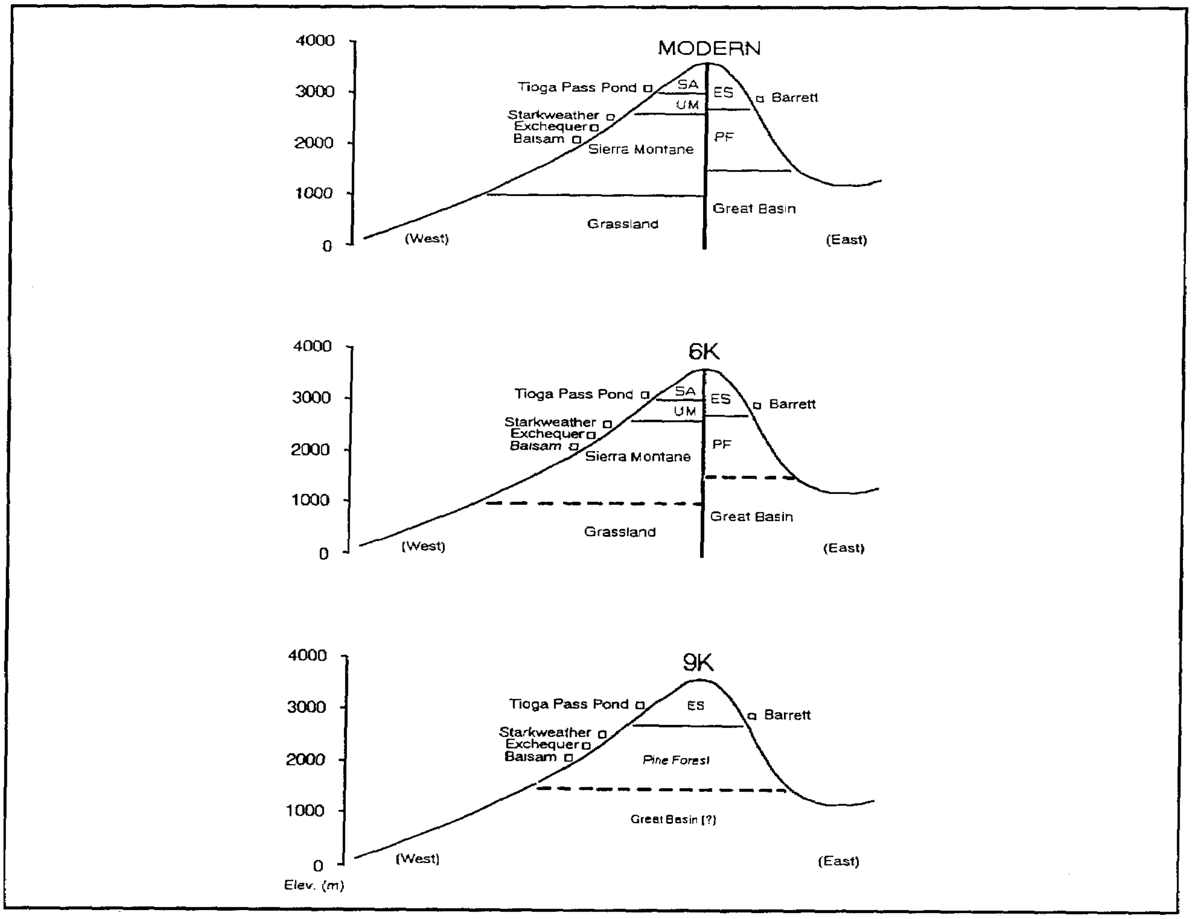

Figure 14-14. Vegetation zonation in the central Sierra Nevada at present; 6,000 years (6K) before present; and 9,000 years (9K) before present. (See Figure 14-5 for approximate locations of fossil pollen sites.) The dashed lines indicate uncertainty in the placement of vegetation zone boundaries (Davis, 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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CHAPTER 15
GREAT LAKES

by Joel B. Smith

FINDINGS

Global climate change could affect the Great Lakes by lowering lake levels, reducing ice cover, and degrading water quality in rivers and shallow areas of the lakes. It could also expand agriculture in the northern states, change forest composition, decrease regional forest productivity in some areas, increase open water fish productivity, and alter energy demand and supply.

Lakes

- Average lake levels could fall by 0.5 to 2.5 meters (1.7 to 8.3 feet) because of higher temperatures under the doubled CO_2 scenarios in this report. A drop of 1 meter would leave average levels below historic lows. Even if rainfall increases, the levels would fall because higher temperatures would reduce the snowpack and accelerate evaporation. The estimates of lake level drop are sensitive to assumptions about evaporation; under certain limited conditions, lake levels could rise.

- As a result of higher temperatures, the duration of ice cover on the lakes would be reduced by 1 to 3 months. Ice could still form in near-shore and shallow areas. Changes in windspeed and storm intensity would affect the duration of ice cover.

- Shoreline communities would have to make adjustments to lower lake levels over the next century. Hundreds of millions of dollars may have to be spent along the Illinois shoreline alone, dredging ports, harbors, and channels. Water intake and outflow pipes may have to be relocated. On the other hand, lower levels would expose more beaches, which would enhance shoreline protection and recreation.

- Climate change could have both good and bad effects on shipping. Lower lake levels may necessitate increased dredging of ports and channels or reduced cargo loads. Without dredging, shipping costs could rise 2 to 33% as a result of reduced cargo capacity. However, reduced ice cover would lengthen the slopping season by 1 to 3 months. Under scenarios of relatively smaller lake level drop (0.7 to 1 meter), the shipping season would be lengthened sufficiently to allow for the transport of at least the same amount of cargo. Under a scenario of larger lake level drops (1.65 meters) and no dredging, total annual cargo shipments could be reduced.

Water Quality and Fisheries

- Higher temperatures could change the thermal structure of the Great Lakes. The result would be a longer and greater stratification of the lakes and increased growth of algae. This result is very sensitive to changes in windspeed and storm frequency -- two areas of relative uncertainty. These two factors would combine to reduce dissolved oxygen levels in shallow areas of lakes such as Lake Erie. A study of southern Lake Michigan indicated that annual turnover of the lakes could be disrupted.

- Climate change could increase concentrations of pollutants in the Great Lakes Basin. Dredging of ports could suspend toxic sediments in near-shore areas. Potential reductions in riverflow in the basin would create higher concentrations of pollutants in streams. The disposal of toxic dredge spoils was not studied in this report.

- The effects on fisheries would be generally beneficial. Higher temperatures may expand fish habitats during fall, winter, and spring, and accelerate the growth and productivity of fish such as black basses, lake trout, and yellow perch. On the other hand, fish populations could be hurt by decreased habitats and lower dissolved oxygen levels during the summer. The effects of potential changes in wetlands due to lower lake levels, reductions in ice cover, introduction of new exotic species, and increase in species interaction were not analyzed, although they could offset the positive results of these studies.

Forests

- The composition and abundance of forests in the Great Lakes region could change. Higher temperatures and lower soil moisture could reduce forest biomass in dry sites in central Michigan by 77 to 99%. These mixed hardwood and oak forests could become oak savannas or grasslands. In northern areas such as Minnesota, boreal and cedar bog forests could change to treeless bogs, and mixed northern hardwood and boreal forests in upland areas could become all northern hardwoods. Productivity could decrease on dry sites and bogland sites, but it could increase on some well-drained wet sites. Softwood species that are currently commercially important could be eliminated and replaced by hardwoods, such as oak and maple, which are useful for different purposes.

- Depending on the scenario, changes in forests could be evident in 30 to 60 years. These results do not reflect additional stresses, such as pests and increased fire frequency, nor do they reflect the possible beneficial impacts of increased CO_2 levels.

Agriculture

- Considering climate change alone, corn and soybean yields in northern areas, such as Minnesota, could increase by 50 to 100% and could decline in the rest of the region by up to 60%. The combined effects of climate and higher CO 2 levels could further increase yields in the north and result in net increases in the rest of the region, unless climate change is severe.

- Agricultural production in the northern part of the region may expand as a result of declines elsewhere. However, the presence of glaciated soils in northern states could limit this expansion. Acreage in the Corn Belt states may change little. Wider cultivation in the north could increase erosion and runoff, and degrade surface and groundwater quality. Increased agriculture would require changes in the infrastructure base, such as in transportation networks.

Electricity Demand

- There could be little net change in annual electricity demand. In northern areas, such as Michigan, reduced heating needs could exceed increased cooling requirements, while in southern areas, such as Illinois, cooling needs may be greater than heating reductions. The annual demand for electricity in the entire region could rise by 1 to 2 billion kilowatthours (kWh) by 2010 and by 8 to 17 billion kWh (less than 1%) by 2055. This study did not analyze the reduced use of other fuels such as oil and gas in the winter, changes in demand due to higher prices, and the impacts on hydroelectric supplies. Previous studies have suggested that reduced lake levels and river flows could lead to reductions in hydroelectric power production.

- By 2010, approximately 2 to 5 gigawatts (GW) could be needed to meet the increased demand, and by 2055, 23 to 48 GW could be needed -an 8 to 11% increase over baseline additions that may be needed without climate change. These additions could cost $23 to $35 billion by 2055.

Policy Implications

- U.S. and Canadian policymakers, through such institutions as the International Joint Commission, should consider the implications of many issues for the region. This study raises additional issues concerning the following:

- The water regulation plans for Lake Ontario and possibly for Lake Superior lake levels.
- The potential increased demands for diverting Great Lakes water for uses outside the basin. Before such a potential demand could be accommodated, additional analysis would be required. This is not currently allowed by federal statutes.
- Long-range industrial, municipal, and agricultural water pollution control strategies. Agencies such as EPA may wish to examine the implications for long-term point and nonpoint water pollution control strategies.
- The research, planting, and land purchase decisions in northern forests by federal, state, and private institutions.

CLIMATE-SENSITIVE NATURAL RESOURCES IN THE GREAT LAKES REGION

The Great Lakes region' is highly developed, largely because of its natural resources. The steel industry developed along the southern rim of the lakes, in part because iron ore from the north could be inexpensively transported over the lakes. Rich soils, moderate temperatures, and abundant rainfall have made the southern part of the region a major agricultural producer. Forests are abundant in the north and support commercial and recreational uses. The basin has become the home of over 29 million Americans and produces 37% of U.S. manufacturing output (U.S. EPA and Environment Canada, 1987; Ray et al., Volume J).

Current Climate

The Great Lakes region[1] has a midlatitude continental climate. Winter is sufficiently cold to produce a stable snow cover on land and ice on the lakes. The average January temperature over Lake Superior is -15°C (5°F), and the average July temperature in the southern part of the region is 22°C (72°F). The average rainfall varies from 700 to 1,000 millimeters (27 to 39 inches), depending on location (Cohen, in Glantz, Volume J).

The Lakes

The Great Lakes consist of a system of five major lakes that contain approximately 18% of the world supply of surface freshwater and 95% of the surface freshwater in the United States (U.S. EPA and Environment Canada, 1987) (see Figure 15-1, Map of the Great Lakes). The natural flow of the lake system begins in Lake Superior, the largest of the lakes, which drains via the St. Mary's River into Lakes Michigan and Huron (considered a single hydrologic unit because they are connected by the Straits of Mackinac). Water from Lakes Michigan and Huron flows out through the St. Clair River into Lake St. Clair. From there, the water flows through the Detroit River and into Lake Erie, the shallowest lake. The Niagara River connects Lakes Erie and Ontario, and the system ultimately empties into the Atlantic Ocean via the St. Lawrence River and Seaway.

The greatest influence on lake levels is nature. Seasonal fluctuations are on the order of 0.3 to 0.5 meter (1 to 1.7 feet), with the lakes peaking in late summer because of condensation over the northern lakes and reaching minimum levels in late winter. Interannual lake level changes have been much larger, approximately 2 meters (6.6 feet).

<u>Lake Regulation</u>

The flow between the lakes is controlled by dams at two points: (1) the St. Mary's River to control

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[1] This chapter will cover only the U.S. side of the Great Lakes and the eight states bordering them (see Figure 15-1).

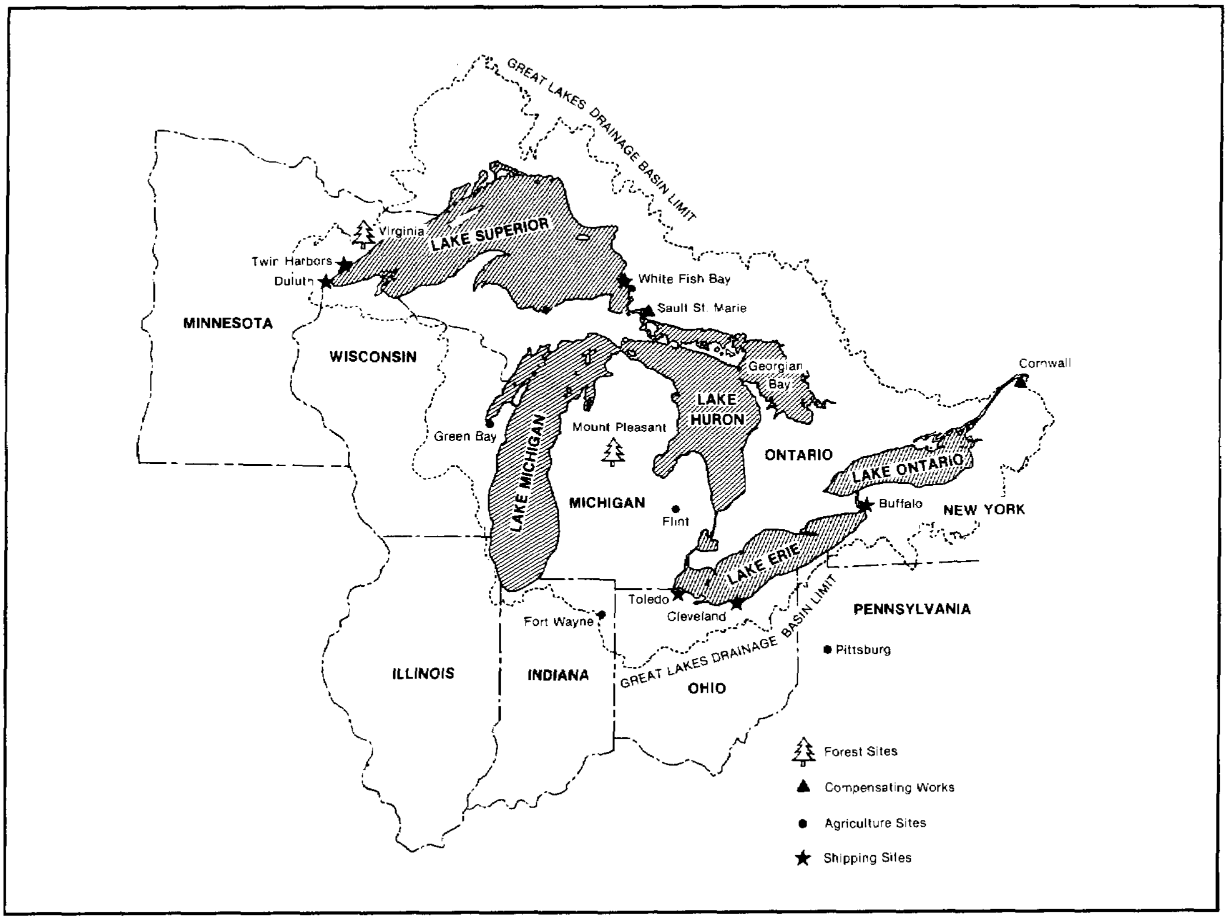

Figure 15-1. Map of the Great .Lakes study sites.

levels of Lake Superior; and (2) Iroquois, Ontario, to control Lake Ontario. The major diversion out of the lakes is the Chicago diversion, which transfers water from Lake Michigan through the Illinois River into the Mississippi River. Human influence on lake levels is relatively small. Doubling the flow down the Chicago diversion would lower lake levels only by 2.5 inches in 15 years (F. Quinn, Great Lakes Environmental Research Lab., 1987, personal communication).

Joint control of lake supply was codified in the Boundary Waters Treaty of 1909 between Canada and the United States, which created the International Joint Commission (IJC) consisting of representatives from both countries. The IJC regulates flow through the control structures and diversions by balancing the needs of shipping, hydropower, and consumptive uses among the lakes and along the St. Lawrence River and Seaway. Two regulatory plans (Plan 1977 for Superior and Plan 1958D for Ontario) set ranges of levels between which Lakes Superior and Ontario must be maintained. Diversion out of the lakes is also limited by law. Flow through the Chicago diversion was limited by the Supreme Court to 90 cubic meters per second (3,200 cubic feet per second) (Tarlock, 1988), and the 1986 Water Resources Development Act forbids diversion out of the lakes' basin without the consent of all Great Lakes governors (Ray et al., Volume J).

Climate-Sensitive Uses of the Lakes

Shipping

The U.S. Great Lakes fleet, which consists of approximately 70 ships, transported over 171 million tons of cargo in 1987 (The New York Times, 1988). The tonnage of U.S. shipping consists of iron ore, coal, and limestone, all primary inputs for steel (77%); lake grain (13%); and petroleum products, potash, and cement (10%) (Nekvasil, 1988). Cargo volumes are displayed in Table 15-1. Most of the goods are shipped within the Great Lakes, with only 7% of the tonnage (mainly grains) slopped to overseas markets (Ray et al., Volume J). Although shipping activity had declined as a result of reductions in U.S. steel production, recent increases in steel output have led to additional demand for shipping (The New York Times, 1988).

Great Lakes ships last over half a century and are designed to pass within a foot of the bottom of channels and locks. Cargo capacity is quite sensitive to lake and channel depth because of this low clearance. The presence of ice usually shuts down Great Lakes shipping up to 4 months each year.

Table 15-1. 1987 U.S. Great Lakes Shipping Cargo (thousands of tons)

Cargo	Weight	Percentage
Iron ore	61,670	36
Coal	37,731	22
Stone	33,164	19
Grain	22,338	13
Petroleum products	11,491	7
Cement	3,806	2
Potash	1,702	1
Total	171,902	100

Source: Nekvasil (Lake Carriers Association, 1988, personal communication).

Hydropower

The eight Great Lakes States use the connecting channels and the St. Lawrence River to obtain 35,435 gigawatt hours of hydropower each year, which is about 5% of their electricity generation. About four-fifths of the hydropower is produced in New York State, which derives over 26% of its electricity from hydropower (Edison Electric Institute, 1987).

Municipal Consumption

Most water used for the domestic and industrial consumption in the basin is taken from the lakes. Surface waters supply 95% of the basin's water needs. By the year 2000, consumption is estimated to increase by 50 to 96% (Ray et al., Volume J; Cohen, 1987b; IJC, 1985).

Fisheries

In 1984, the value of the harvest to the U.S. commercial fishing industry was approximately $15 million (U.S. EPA and Environment Canada, 1987; U.S. Department of Commerce, 1987). Although most fishing in the Great Lakes is for recreation, fisheries are managed by the states; the Great Lakes Fishery Commission coordinates activities among the states.

Tourism

Three national and 67 state parks are located along the shores of the lakes, as are numerous local parks. Over 63 million people visited these parks in 1983 (Ray et al., Volume J; Great Lakes Basin Commission, 1975). In 1984, lake-generated recreation yielded revenues of $8 to 15 million. Fishing, boating, and swimming are very popular.

Shoreline Development

Over 80% of the U.S. side of the Great Lakes shoreline is privately owned. One of the most developed shorelines is the 101-kilometer Illinois shoreline, where many parks and residential structures, including apartment houses, are built near the water's edge. Shoreline property owners have riparian rights to use adjoining waters. The shoreline property owners cannot substantially diminish the quantity or quality of surface waters (Ray et al., Volume J).

Climate and Water Quality

Water quality is directly affected by climate. Lower stream runoff increases concentrations of pollutants. Every summer, the lakes stratify into a warmer upper layer and a cooler lower layer. This stratification can limit biological activity by restricting the flow of nutrients between layers. In addition, warm temperatures and an excess supply of nutrients (phosphorous and other chemicals from agricultural runoff and sewage effluent) can lead to algal blooms that decay and cause a loss of oxygen (eutrophication) and reduction in aquatic life in the lower layers of lakes such as Lake Erie. Cool weather and the formation of ice help to deepen the mixed layer, break up the stratification, and thoroughly mix the lakes in the winter.

Development, industrialization, and intensive agriculture in the Great Lakes Basin have created serious pollution in the lakes, especially Lake Erie. In the early 1970s, nutrient loadings were so high that Lake Erie experienced significant eutrophication problems for several years (DiToro et al., 1987).

Two measures have helped improve water quality. The U.S.-Canada Great Lakes Water Quality Agreement of 1972 called for controlling nutrient inputs and eliminating the discharge of toxic chemicals, and the Clean Water Act mandated construction of sewage treatment plants and controls on industrial pollutants. The United States and Canada spent a total of $6.8 billion on sewage treatment in the Great Lakes. By 1980, nutrient loadings into Lake Erie had been cut in half (Ray et al., Volume J; DiToro et al., 1987), and water quality had markedly improved.

Fluctuating Lake Levels

Recent high and low lake levels have significantly affected users of the lakes. In 1964, Lake Michigan was 0.92 meters (3 feet) below average, making some docks and harbors unusable. Shipping loads were reduced by 5 to 10% and more shipments were required, subsequently raising the cost of raw materials and supplies by 10 to 15%. In addition, many water intakes had to be extended or lowered (Changnon, Volume H). Flow through the Niagara hydropower project fell by more than 20%, with electricity generation off by more than 35%. Flow through New York's St. Lawrence hydro project was more than 30% below its mean, with electricity generation decreased by 20% (Linder, 1987). However, low lake levels also provided benefits, for example, beaches became larger.

In the mid-1980s, a series of cool and wet years caused the lakes to rise to record heights. Apartment houses that were built too close to the shoreline during the low levels of the 1960s were flooded, as were roadways built close to the shore. The low water levels in the 1960s exposed the supporting structures along Chicago's shoreline to air, causing dry rot. When lake levels rose, the wood pilings and sections of the revetment collapsed. The estimated construction cost for rebuilding the damaged shoreline protection system is $843 million (Changnon, Volume H). The last 2 years have been relatively hot and dry, causing lake levels to recede to average levels. The lower levels have forced shippers to reduce tonnage just as the steel industry in the region is undergoing a resurgence.

Land Around the Lakes

The land in the Great Lakes region is extensively used for industry, agriculture, and forestry. Many of the uses are sensitive to climate.

Land Uses

Urban Development

Approximately 29 million people live in the Great Lakes Basin, mostly in the urban areas around the cities on the southern edge of the Great Lakes: Chicago, Detroit, Cleveland, Toledo, and Buffalo. Many of the residents work in manufacturing industries, which despite recent declines, still provide 23% of payroll employment (Ray et al., Volume J).

Agriculture

Agriculture is the single largest user of land: 42% of all land in the eight Great Lakes States is devoted to crops, and an additional 10% is used for pasture. The Great Lakes States encompass most of the Corn Belt. In 1983, roughly 59% of all U.S. cash receipts for corn and 40% of the receipts for soybeans came from this region. Overall, the Great Lakes States produced 26% of the total U.S. agricultural output, or $36 billion (Federal Reserve Bank of Chicago, 1985). Most crops are grown on dryland, as only about 1% of the region's croplands were irrigated in 1975 (U.S. Department of Commerce, 1987).

Livestock are also important to the agricultural economy of the region. Approximately 18% of U.S. cattle are raised in these eight states; of these, 52% are dairy cows (USDA, 1987). (The sensitivity of livestock to climate change is discussed in Chapter 6: Agriculture.)

Forests

The forests in the region have commercial, recreational, and conservation uses. The forests in the south are mainly oak and northern hardwoods, such as maple. The north has almost 21 million hectares (52 million acres) of forests consisting mostly of northern hardwoods, such as maple, birch, and beech, and boreal forests, such as spruce and fir trees. The federal and state governments own, respectively, 11 and 13% of the forests in Michigan, Minnesota, and Wisconsin, while over half are privately owned (USDA, 1982). The pulp, construction, and furniture industries are major consumers of such species as aspen, pines, balsam fir, spruce, maples, paper birch, and oak. The forest industry is a major employer in the northern part of the region. In Wisconsin, for example, 283,000 jobs are in timber harvesting and manufacturing related to forestry (Botkin et al., Volume D; U.S. EPA and Environment Canada, 1987). Forestry is considered to be a growth industry in the region, since Miclvgan has identified forest products as one of the three key industries targeted for expansion in the stale (Ray et al., Volume J).

PREVIOUS CLIMATE CHANGE STUDIES

The impacts of climate change on many of the systems in the Great Lakes have been analyzed in previous studies, mainly by Canadian researchers. These studies are summarized in Cohen and Allsopp (1988). Several Canadian studies have examined the potential impacts of climate change on Great Lakes levels and concluded that levels would fall. Southam and Dumont (1985) used the Goddard Institute for Space Studies (GISS) scenario to estimate that lake levels would fall by 0.2 to 0.6 meters (0.7 to 2 feet). Cohen (1986) used hydrologic calculations to estimate that the lakes might fall between 0.2 and 0.8 meters. More recently, Marchand et al. (1988) also used a hydrologic model of the lakes to estimate that the lakes would drop by an average of 0.2 to 0.6 meters. Cohen (1987a) found that changes in lake levels are very sensitive to humidity and windspeed. It is not known how climate change would affect these parameters on a regional scale. Wall (1985) concluded that lower lake levels could reduce ecological diversity and dry up enclosed marshes. In another study, Cohen (1987b) estimated that withdrawals of water from the lakes for municipal consumption would increase by about 2.5% on an annual basis and would only marginally affect lake levels.

Assel et al. (1985) studied the extent of ice cover during the winter of 1982-83, which had temperatures 3.3 to 4.4°C warmer than the 30-year mean. They found that ice cover on Lake Superior was reduced from a normal 75% coverage to 21%. On Lake Erie, ice coverage was down to 25% from the normal 90%. Meisner et al. (1987) conducted a literature review on the possible effects of global warming on Great Lakes fish. Results are discussed in the fisheries section of this chapter.

Marchand et al. (1988) (see also Sanderson, 1987) estimated the combined effects of lower lake levels and reduced ice cover due to climate change, and higher water consumption and shipping tonnage due to population and economic growth of Canadian shipping and hydropower production. They found that without economic changes, lower lake levels would increase shipping costs by 5%. After consideration of economic growth, lower lake levels and reduced ice cover could increase shipping costs by 12%.

Linder (1987) used the transient scenarios to estimate impacts on electricity demand and hydropower generation in 2015 in upstate New York. He found total energy demand declining by 0.21 to 0.27%, but peak demand increasing by 1 to 2%. Meanwhile, hydropower production could decline between 6 and 8.5% as a result of reductions in streamflow.

Impacts on managed and unmanaged vegetation have also been studied. The Land Evaluation Group examined the potential impacts of climate change on agriculture in Ontario and found that yields could decrease in southern Ontario and farming could become feasible in northern Ontario. The study also indicated that the direction of change for yields depends on whether rainfall increases or decreases (Land Evaluation Group, 1986). Solomon and West (1986) used a stand simulation model (see this chapter, Forests) to estimate the impacts of doubling and quadrupling of CO_2 levels on a northwest Michigan coniferous-deciduous transitional forest. They found that doubled CO_2 would lead to an eventual disappearance of boreal forests and an increase in deciduous trees. Total biomass would decline at first and rebound in about two centuries.

Two studies by Canadian researchers examined the possible impacts of climate change on tourism and recreation in Ontario. Both studies used climate change scenarios based on the GISS and Geophysical Fluid Dynamics Laboratory (GFDL) models (although these may have been earlier model runs). Crowe (1985) estimated that snowfall would decrease by 25 to 75%, and the ski season would be cut by 75 to 92% (7 to 12 weeks) in southern Ontario and by 13 to 31% (2 to 4 weeks) in northern Ontario. Wall found similar results. He concluded that reduced snowfall could eliminate skiing in southern Ontario and would shorten the northern Ontario ski season by 30 to 44%. A longer summer season could increase such summer tourism activities as camping. Wall (1985) also thought that lower lake levels could decrease ecological diversity and dry up enclosed marshes.

GREAT LAKES STUDIES IN THIS REPORT

Unlike previous studies, the studies for this report used common scenarios to address some of the potential impacts of climate change on a number of natural and societal systems in the Great Lakes region. The studies address the direct effects of climate change on the resources and some of the indirect effects on infrastructure and society. They focused on the lakes themselves, examining such issues as lake levels, ice cover, thermal structure, and fisheries. They also looked at the effects of these changes on shipping and shoreline properties, and examined the sensitivities of agriculture and forest to climate change. Finally, the studies examined the implications of climate change for Great Lakes policies and institutions. Some of the studies were linked quantitatively, but most were conducted independently of each other.

The studies involved either new topics or approaches that were not used in previous studies. For example, the analysis of lake levels used a more complex hydrologic model than was used previously. The agriculture analysis complements the Land Evaluation Group's study of Ontario by using a different model to examine impacts on the U.S. side of the lakes. The potential impacts of climate change on thermal structure were examined for the first time. Also for the first time, models were used to analyze impacts on fisheries. This study complements previous studies on forests by using a combination of modeling techniques to test the similarity of results.

The following analyses were performed for this report:

Direct Effects on Lakes

- Effects of Climate Changes on the Laurentian Great Lakes Levels - Croley and Hartmann, Great Lakes Environmental Research Laboratory (Volume A)
- Impact of Global Warming on Great Lakes Ice Cycles - Assel, Great Lakes Environmental Research Laboratory (Volume A)

Impacts of Lake Changes on Infrastructure

The results from the first two studies were used in the following studies:

- Effect of Climatic Change on Shipping Within Lake Superior and Lake Erie -Keith, DeAvila, and Willis, Engineering Computer Optecnomics, Inc. (Volume H)
- Impacts of Extremes in Lake Michigan Levels Along Illinois Shoreline Part 1: Low Levels - Changnon, Leffler, and Shealy, Illinois State Water Survey (Volume H)

Water Quality

The following studies focus on water quality and the effects on aquatic life in the lakes. The first two studies examined the direct effects of climate on the thermal structure of some of the lakes.

- Potential Climatic Changes to the Lake Michigan Thermal Structure - McCormick, Great Lakes Environmental Research Laboratory (Volume A)

- The Effects of Climate Warming on Lake Erie Water Quality - Blumberg and DiToro, Hydroqual, Inc. (Volume A)

The results from these studies were used in the following:

Potential Responses of Great Lakes Fishes and Their Habitat to Global Climate Warming - Magnuson, Regier, Hill, Holmes, Meisner, and Shuter, Universities of Wisconsin and Toronto (Volume E)

Forests

A series of studies on forests was commissioned to examine shifts in ranges, transient impacts, and the potential for migration of some Great Lakes forests. Basically, these are different analytic techniques for understanding how climate change may affect the composition and abundance of forests in the region.

- Transient Effects on Great Lakes Forests -Botkin, Nisbet, and Reynales, University of California at Santa Barbara (Volume D)
- Hard Times Ahead for Great Lakes Forests: A Climate Threshold Model Predicts Responses to CO_2 Induced Climate Change - Zabinski and Davis, University of Minnesota (Volume D)
- Assessing the Response of Vegetation to Future Climate Change: Ecological Response Surfaces and Paleoecological Model Validation - Overpeck and Bartlein, Lamont-Doherty (regional results were taken from this study) (Volume D)

Agriculture

The potential changes in agriculture in the Great Lakes were analyzed by studying changes in crop yields in the region and integrating the results in a national analysis of production changes. That national analysis was used to determine if production in the region could increase or decrease. The results of these studies were used to examine potential farm level adjustments.

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- Effect of Global Climate Chanye on Agriculture: Great Lakes Region - Ritchie, Baer, and Chou, Michigan State University (Volume C)
- Farm Level Adjustments by Illinois Corn Producers to Climatic Change - Easterling, Illinois State Water Survey (Volume C)

This chapter will use regional results from the following:

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

Energy

This project analyzed potential changes in the national demand for electricity and estimated changes in regional demands. Results for the Great Lakes region are presented in this chapter.

- Electric Utilities - Linder and Inglis, ICF, Inc. (Volume H)

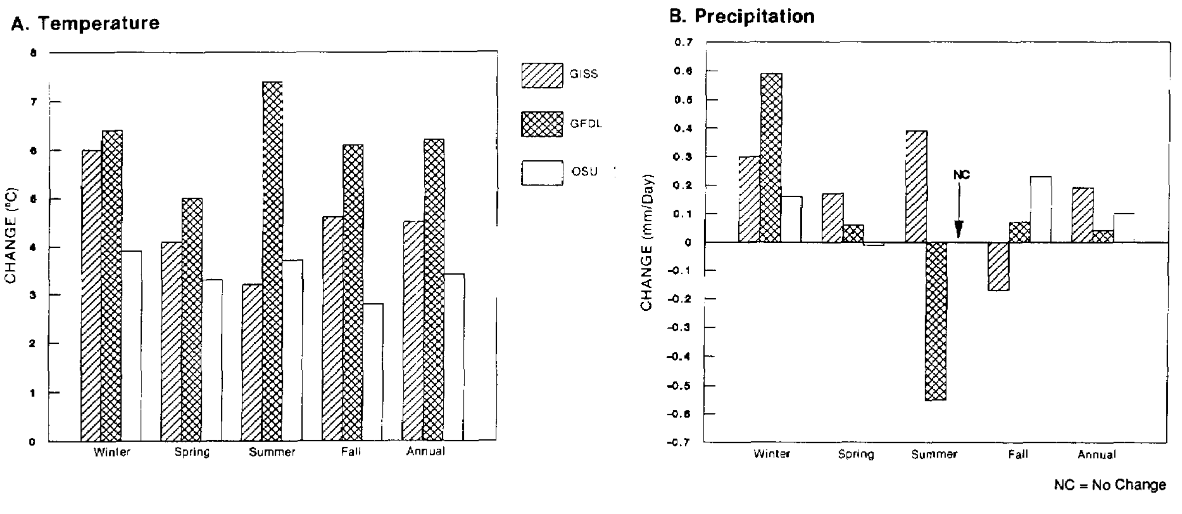
Policy

The potential policy implications of the changes indicated by these and previous studies for local, state, federal, and international decisionmaking are examined. This project provided information for the background and policy implications sections.

- Effects of Global Warming on the Great Lakes: The Implications for Policies and Institutions - Ray, Lindland, and Brah, The Center for the Great Lakes (Volume J)

GREAT LAKES REGIONAL CLIMATE CHANGE SCENARIOS

All three general circulation models (GCMs) that provide the basis for the climate change scenarios show rather large increases in temperature for the Great Lakes region under the doubled CO_2 climate. The seasonal and annual temperatures and precipitation are displayed in Figure 15-2. The Oregon State University (OSU) scenario has an annual temperature rise of 3.5°C, with no change in seasonal pattern. The Goddard Institute for Space Studies (GISS) scenario is about a degree warmer on average and has the largest warming in the winter and fall. The Geophysical Fluid Dynamics Laboratory (GFDL) scenario has the largest warming of the three models, about 6.5°C annually, with the largest warming in the summer. All three scenarios have annual increases in precipitation. OSU has an increase of approximately 0.1 millimeters per day (0.1 inches per year), with precipitation rising in all seasons. GISS has an increase of approximately 0.2 millimeters per day (0.03 inches per year), with precipitation declining slightly in the fall. GFDL has an annual precipitation increase of only 0.05 millimeters per day (0.07 inches per year), but rainfall drops by 0.5 millimeters per day (0.02 inches per day) in the summer. The large temperature increase and small rainfall increase combine to make GFDL the most severe scenario. This is especially true in summer months, when GFDL has the largest temperature rise of any scenario and is the only scenario that reduces rainfall. OSU is the mildest scenario owing to the smaller temperature increase. (Other runs of the GFDL model have lower temperature increases, although they still estimate a decline in summer rainfall.) GISS is in the middle in terms of severity, and OSU is the mildest of the three scenarios.



One limitation related to using the GCMs as a basis for climate change scenarios for the Great Lakes region is that the lakes are not well represented in the GCMs. The relatively large size of the GCM grid boxes results in little feedback from the lakes to the regional climate estimates from the GCMs.

RESULTS FROM THE GREAT LAKES STUDIES

Lakes

Lake Levels

Geologic records indicate that Great Lakes levels have fluctuated as paleohistoric climates have been wetter and drier (Larson, 1985). Recent shortterm variations have been the result of short-term changes in precipitation patterns. Croley and Hartmann examined the potential impacts of global warming on average lake levels.

Figure 15-2. Average change in temperature (A) and precipitation (B) over Great Lakes gridpoints in GISS, GFDL, and OSU models ($2xCO_2$ minus $1xCO_2$).

Study Design

Croley and Hartmann used a water supply and lake level model of the Great Lakes Basin developed by the Great Lakes Environmental Research Laboratory to estimate the potential impacts of climate change on levels of the Great Lakes (Croley, 1983a,b; Croley, 1988; Quinn, 1978). This model is the most detailed hydrologic model of the Great Lakes Basin and includes a separate model for each of the 121 watersheds in the basin. Croley and Hartmann simulated runoff in each of the subbasins, overlake precipitation, and evaporation.[2] Lake levels are very sensitive to evaporation; therefore, Croley and Hartmann ran each GCM scenario with different assumptions about evaporation. Finally, they used the current plans (Plan 1977 for Superior and Plan 1958-D for Ontario) and hydraulic routing models of outlet and connecting channel flow and estimated water levels on each of the Great Lakes.

The regulation plan for Lake Superior failed under the GFDL scenario. To obtain an estimate of changes in levels for Superior-Huron, St. Clair, and Erie, Croley and Hartmann assumed that over a 30-year period, total inflows into Lake Superior (runoff + overlake precipitation + diversions -evaporation) would equal total outflows, and Lake Superior levels would not change. No figures are presented for changes in the level of Lake Superior in the GFDL scenario. The levels of Lake Superior would probably fall. Only 30-year average lake levels were calculated for the other lakes.

Limitations

The relationships in this model were developed for a cool and wet climate. The analysis did not account for changes in the consumptive uses of the lakes (due to population and economic growth or climate change), and it did not consider changes in the regulation plans, or increases in or additions to diversions into or out of the lakes. The analysis also used the difference in vector winds from the GCMs as a proxy for the difference in scalar winds because GCM estimates of changes of scalar winds were not available. Thus, the wind estimates probably underestimate changes in windspeed (David Rind, Goddard Institute for Space Studies, 1988, personal communication). The uncertainty on winds is complicated by the uncertainties concerning evaporation. Different assumptions of evaporation in this analysis affect the magnitude of lake level drop, but they do not affect the direction of change -- lake levels fall under all evaporation assumptions. Cohen (1987a) found that potential changes in Great Lakes levels are very sensitive to estimates of changes in windspeed and humidity. He concluded that with the right combination of conditions, even with higher temperatures, it is possible for lake levels to rise.

Results

Lake levels were estimated to fall significantly under all three scenarios (see Table 15-2). The lake level changes are displayed in ranges from low to high evaporation.

Average levels for Lake Superior would be about 0.4 to 0.5 meters (1.3 to 1.7 feet) below average levels for the 1951-80 period under the OSU and GISS scenarios. These average levels would be generally lower than recorded lows of recent history. The lakes would likely still fluctuate around these average levels, so levels during some years would be lower. Even though precipitation rose in all three scenarios, lake levels were estimated to fall, primarily as a result of the higher temperatures. Apparently, only a large increase in rainfall or humidity or a large decrease in windspeeds could offset these changes. Lake levels were estimated to continue fluctuating on an annual basis. Specific

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[2] In Volume A, Croley focuses on results from his latest run. This run includes assumptions that lead to relatively high amounts of evaporation and larger drops in lake levels. Earlier runs had less evaporation and larger drops in lake levels. Results in this chapter include the latest run and an earlier run.

estimates of fluctuation are not discussed here, since variability was assumed not to change.

Croley and Hartmann also found that the flow in the St. Mary's could increase by less than 1% in the GISS high rainfall scenario and drop by 13% in the drier OSU scenario for Lake Superior. The flow in the Niagara River was estimated to be 2 to 30% lower. Croley and Hartmann did not estimate the flow of these rivers for the GFDL scenario.

The lowering of lake levels appears to be correlated with increased temperatures in the scenarios. Under all the doubled CO_2 scenarios, there could be declines in runoff to the lakes and increases in evaporation from the lakes. The reduction in runoff would be largely the result of changes in snowpack accumulation and ablation. Snowpack in the Lake Superior Basin could be reduced by one-third to two-thirds, and in the other basins, farther to the soutl4 the snowpack could be almost entirely absent. The reduction in runoff would reduce average streamflow in the basin. These results appear to be driven mainly by the temperature increase, since precipitation rises in all scenarios.

Table 15-2. Doubled CO_2 Scenarios: Reduction in Average Great Lakes Levels from 1951 to 1980 (meters).

Scenario	Superior	Michigan	Erie	Ontario
GISS	-0.43 to -0.47	-1.25 to -1.31	-0.95 to -1.16	NA
GFDL	NA	-2.48 to -2.52	-1.65 to -1.91	NA
OSU	-0.39 to -0.47	-0.86 to -0.99	-0.63 to -0.80	NA
Transient Scenario (average rate of change per decade 1980-2060)				
GISS-A	-0.006	-0.055	-0.04	NA

NA = Not applicable
Source: Croley and Hartmann (Volume A).

Evaporation would increase under all three scenarios. The increase in evaporation varied under different assumptions about the relationship of evaporation to change in climate variables and ranged from 20 to 48%. For a given assumption about evaporation, higher temperature scenarios would generally cause more evaporation. Lake level reductions could also be higher or lower, depending on these assumptions.

All of these changes could cause a reduction in net basin supply (the sum of overlake precipitation and runoff minus evaporation) by 14 to 68%. The exception to this is the GISS scenario for Lake Superior. In that scenario, annual rainfall increased by 18%, which could lead to a 1% increase in net basin supply.

The Ontario regulation plan would fail under all scenarios, including the transient run. Under these conditions, the system would not contain enough water to keep the level of Lake Ontario and the flow in the St. Lawrence River within ranges currently specified by the plan. The Lake Superior regulation plan was estimated to fail under the GFDL scenario. Although net basin supply in Lake Superior increased under GISS, the regulation plan would require increased flow through the St. Mary's River to the water-short lower lakes, resulting in a net drop in Lake Superior levels.

These results are consistent with other studies done on lake levels and climate change. Both Cohen and Sanderson agree with Croley and Hartmann that lake levels would drop under various climate change scenarios. The other two studies, however, estimated lake levels would drop less than 1 meter. Croley and Hartmann may have estimated greater changes because they used a more sophisticated runoff, evaporation, and routing model and because of different assumptions made about evaporation. Croley and Hartmann also used a more integrated approach and more variables from the GCMs. The estimates for GFDL may also be higher because the GFDL scenario used in this study had a higher temperature rise than the GFDL scenarios used by Cohen and Sanderson.

The results of the transient run (GISS A) are expressed as the average change in lake level per decade and are not indicative of what would happen in any particular decade. Lake Superior levels drop only 0.006 meters (0.2 inches) per decade, while the other lake levels fall 0.04 to 0.055 meter (1.6 to 2.2 inches) per decade. An extrapolation of the transient results to the decade of the 2060s (when the GISS A transient run reaches doubled CO_2 climate conditions) results in lake level reductions less than for the doubled CO_2 GISS scenario. This is because lake levels may not respond immediately to climate change, but must catch up. The results may also be affected by the variability assumptions in the transient scenarios (see Chapter 4: Methodology). By the end of the transient scenario, the 2050s, lake levels fall at a faster rate -- by more than 0.05 meters (2.0 inches) per decade. Thus, these studies do not clearly indicate the length of time required for the lakes to drop by the amounts shown in Table 15-2.

Croley and Hartmann found that enough heat could reside in Lakes Superior, Michigan, Huron, and Ontario to maintain water surface temperatures at a sufficiently high level throughout the year, so that buoyancy-driven turnovers of the water column may not occur at all. This could significantly affect lakewater quality and aquatic life (see this chapter, Thermal Structure of Southern Lake Michigan). Croley estimated that average surface water temperatures in the winter would be above 0°C and would significantly reduce ice concentrations.

Implications

Hydropower production could be reduced, as flows through the St. Mary's, the Niagara, and the St. Lawrence Rivers fall. Losses to hydropower were not estimated for the EPA study, although Linder's earlier work on hydropower losses by 2015 in New York State showed potential loss of 1500 to 2066 gigawatt-hours (6 to 9%) (Linden, 1987). Sanderson (1987) estimated that under a doubled CO z scenario, Canadian hydroelectric power production on the St. Mary's River could rise by 2.5% (because the level of Lakes Michigan-Huron falls more than that of Lake Superior) and power production on the Niagara River could fall by 13 to 18% as a result of a drop in flow. The impacts of lower lake levels on wetlands were not estimated, and the impacts on shipping and on shoreline infrastructure are discussed later in this chapter.

Lower lake levels and reduced riverflow would likely adversely affect water quality in the basin. Less water would reduce dilution of pollutants. Forty-two "hot spots" occupy many bays and harbors along the Great Lakes. These are contaminated with a wide variety of halogenated organics and heavy metals, as well as remobilizable nutrients. Lower lakes may cause emergence and near emergence of these toxic sediments through erosion, leaching, oxidization, or volatilization.

Higher temperatures may lead to increased withdrawals of water from lakes for municipal consumption. Climate change may also result in more calls for diversion of water out of the Great Lakes Basin for use elsewhere. However, lake levels may be lowered even more as a result of higher demand for withdrawals for use in the basin as a result of population and economic growth.

<u>Effects of Lower Lake Levels</u>

Coastal infrastructure around the Great Lakes has generally been built assuming average lake levels would not change. A drop in levels could make much of the current infrastructure unusable and necessitate reconstruction. Changnon et al. examined the potential impacts and adjustments to infrastructure along the 101-kilometer (63-mile) Illinois shoreline. This study and the shipping analysis used the lower range of the lake level drops from Table 15-2 because subsequent analyses that gave different lake levels were performed too late to be incorporated.

Study Design

Changnon et al. interviewed experts about the possible impacts and costs of adjustment along the Illinois shoreline to the lower lake level estimates described above. Results are expressed in current dollars.

Limitations

This analysis did not use economic models, used current prices, and did not consider changes in population, GNP, or technology. Results are based on expert judgment. Changnon et al. also assumed that lakes would reach the levels described above by 2030. The change in lake levels may not be reached until decades later (by the year 2060 or later) so costs may be borne over a longer period than Changnon estimated, allowing for more routine replacement of infrastructure. This study examined only the costs of rebuilding infrastructure and did not examine ecological impacts.

Results

The largest costs appear to accrue to recreational and commercial harbors (see Table 153). The major expenses are associated with dredging harbors and lowering bulkheads, which could cost approximately $200 to $400 million. If lake levels fall enough, keeping some harbors open (e.g., Waukegan, Illinois) may not be a cost-effective choice.

Changnon et al. concluded that slips and docks would be only slightly affected. Many of these probably would have been replaced anyway and could be set at lower levels as the lakes fall. (The impacts on commercial shipping in Lakes Superior and Erie are discussed below.)

Intake valves for municipal and industrial consumption could be exposed and may have to be lowered or moved farther offshore. Outfalls for stormwater would have to be extended. Changnon et al. estimated that extending urban water intakes and stormwater outfalls could cost $16 to 17 million.

Although the exposure of more land could present some erosion problems, it could also enlarge many beaches. An additional 1 to 2.2 square kilometers (0.3 to 0.8 square miles) of beaches would be added to the Illinois shoreline. In all, Changnon et al. estimated that the costs of adjusting to lower levels of 1.25 to 2.5 meters along the Illinois shoreline, excluding normal replacement of docks and piers, would be $220 to $430 million. If normal replacement costs do not account for lower lake levels, costs could be $30 to $110 million higher. To put these figures into context, the City of Chicago may spend over $800 million to repair shorelines damaged by high water levels in recent years.

Walker et al. (Volume H; for a discussion of methodology and results, see Chapter 13: Urban Infrastructure) examined the potential capacity of climate change on Cleveland's infrastructure. They found that savings in such areas as snow removal and bridge repair could offset increased cooling and dredging costs. Cities on the Illinois shoreline would also have savings due to reduced winter expenditure.

Table 15-3. Estimated Economic Impacts of Lowerings of the Levels of Lake Michigan Over a 50-Year Period (1990-2040)

Types of Expenses	Cost[a]	
	1.25 meters lower	2.5 meters lower
Recreational harbors	30-50	75-100
Dredging	15	35
Sheeting	20[b]	40[b]
Slips/docks		
Commercial harbors		
Dredging	108	212
Sheeting	38	38
Slips/docks	40[b]	90[b]
Water supply sources		
Extending urban intakes	15	15
Wilmette Harbor Intake	1	2
Beaches		
Facility relocations	1-2	1-2
Outfalls for stormwater		
Extensions and modifications	2	4
Total	$270-292[b]	$512-540

[a] Costs in millions of 1988 dollars to address future lake levels at indicated depths below average (1951-80) levels of Lake Michigan.

[b] Some costs could be partly covered by normal replacement expenditures over the period of changing levels.
Source: Changnon et al. (Volume H).

Ice Cover

Warmer winters would reduce ice cover on the Great Lakes. Some analysts have speculated that ice would be completely eliminated. Assel used a model to estimate the potential extent and duration of ice cover.

Study Design

Assel developed a statistical relationship between temperature and ice cover for this study. The models were developed for the three basins of Lake Erie, for the Lake Superior Western and Eastern Basins, and for Whitefish Bay in Lake Superior. Whitefish Bay was included because it has the longest period of ice cover and acts as a choke point on shipping in and out of Lake Superior. Lakes Superior and Erie represent extremes in terms of air temperature regimes, lake depth, and heat storage capacity, and bound the range of potential ice cover changes.

Limitations

Assel's study did not consider the effects of wind and other variables on ice formation. Implicitly, the analysis assumed that winds stay the same. Stronger winds would make the ice season shorter than estimated, and weaker winds (and calmer waters) would make it longer. The three GCMs estimate that windspeeds over the two lakes drop by 0.0 to 0.3 meters per second (see Croley, Volume A). Inclusion of windspeed changes would have lowered ice cover reduction results. The model was built based on the relatively cool years of the 1960s and 1970s; therefore, the doubled CO_2 scenario temperatures are outside the range of winter temperatures in those years. However, the model simulated ice duration within 3 weeks of actual ice duration for the warm winter of 1982-83.

Results

Assel found that although average ice cover might be significantly reduced, ice would still form on the lakes (Table 15-4). Results for the central basin of Lake Erie are displayed in Figure 15-3. It now averages 83 days of ice cover. In the 1981-2009 transient scenario, ice cover was estimated to be 71 days; in the 2010-2039 scenario, it was estimated to decline to 41 days. Under the doubled CO_2 climate, ice cover could be reduced to a total of 6 to 19 days, and ice formations would be generally limited to near-shore and shallow areas. Whitefish Bay in Lake Superior currently averages about 115 days of ice cover. Under the doubled CO scenarios, ice duration would be reduced to 69 to 86 days. Also, the maximum percentage of Whitefish Bay covered by ice would be reduced from close to 100% to 70-20%.

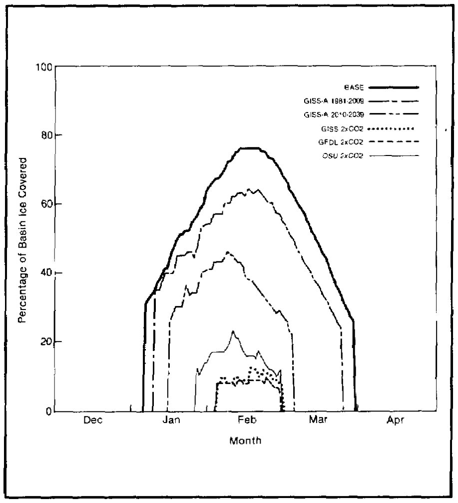

Figure 15-3. Changes in duration and extent of ice cover in central basin of Lake Erie under transient and doubled CO_2 scenarios (Assel, Volume A).

The temperature rise in the scenarios may not be warm enough to eliminate ice cover on the Great Lakes, but many winters could have no ice at all. The Lake Erie Central Basin is estimated to be ice-free from 11 to 22 years out of 30 years, rather than 1 out of 30 years, as estimated for base climate conditions. This result appears to be sensitive to depth, as estimates indicate that the deeper Lake Erie East Basin would be ice-free 60 to 84% of the time, and the shallow West Basin would be ice-free in 7 to 17% of the winters. Since it is colder, Lake Superior would have ice cover in virtually all winters under the scenarios.

Assel found that ice cover reductions during the first 30 years of the transient scenario (model years 1981-2010) may not be significantly different than under current conditions. The length and extent of ice cover noticeably decline, beginning in the second 30 years of the transient scenario (201140). By the last decade of the transient scenario, the 2050s, the extent of ice cover was almost identical to the GISS doubled CO_2 coverage.

Table 15-4. Reduction in Ice Cover in Lakes Erie and Superior (average annual days of cover)

Lake	Base	GISS Transient A		Doubled $_{CO2}$			Analog
	1951-80	1981-2009	2010-2039	GISS	GFDL	OSU	1930s
Erie West	93	84	54	26	23	35	85
Erie Cent	83	71	41	8	6	19	61
Erie East	97	82	43	6	5	13	70
Supr West	112	108	88	46	24	75	106
Supr East	108	103	84	43	19	69	103
Supr WFB	115	109	92	55	26	80	112

Abbreviations:
Supr = Superior; WFB = Whitefish Bay; Cent = Central.
Source: Assel (Volume A).

Croley also found that ice cover would be reduced. His analysis found that average surface temperatures on all the lakes in the winter could be above 0°C. Even if average temperatures are that high, water temperatures in near-shore and shallow areas, the areas to which Assel said ice would be limited, would be sufficiently cold to cause ice formation.

Implications

Ice cover reductions could have positive and negative effects. On the positive side, the shipping season would be extended (see below). Water would flow more freely through rivers and connecting channels, allowing for more hydropower production in the winter. On the other hand, ice protects some aquatic life, such as whitefish, and protects shorelines against the erosive impact of high-energy waves (Meisner et al., 1987).

Shipping

With lower lake levels, ships would have to reduce their cargo, or ports and channels would have to be dredged. However, the shorter duration of ice cover would allow for a longer shipping season. The additional days of transport may make up for the loss of capacity on each voyage.

Study Design

Keith et al. studied the potential impacts of changes in lake levels and ice cover on shipping in six ports: Two Harbors; Duluth/Superior and Whitefish Bays in Lake Superior; and Toledo, Cleveland, and Buffalo in Lake Erie. They used the "ECO Great Lakes Shipping Model," which includes current data on major ports and commercial ships in the Great Lakes, types of cargo, costs of transport, and operating costs. Keith et al. used lake level reductions from Croley and Hartmann to study the change in cargo capacity and costs per ton, and they used the change in cargo capacity to estimate how many days of shipping would be needed to transport the same amount of cargo as transported at present. The latter figure was compared to ice duration reductions estimated by Assel to determine whether the shipping season was sufficiently extended to allow for transport of the same amount of annual cargo as currently transported.

Limitations

The analysis did not consider changes in the composition of the fleet or in the mix and amount of cargo. It also assumed that demand for shipping of goods did not change, even in response to changes in availability of shipping. The analysis did not examine whether goods would shift to or from alternate ports or means of transportation and how changes in the costs of shipping and in the shipping season would affect users. Keith et al. also assumed that channels were not dredged to be deeper. Thus, analysis is useful for estimating the direction and approximate magnitude of change, but quantitative results should be interpreted with caution.

Results

The costs of shipping were estimated to increase as a result of lower lake levels. The effect on the cargo load for ships using the Port of Buffalo are displayed in Figure 15-4. Under drops of 0.7 to 1.0

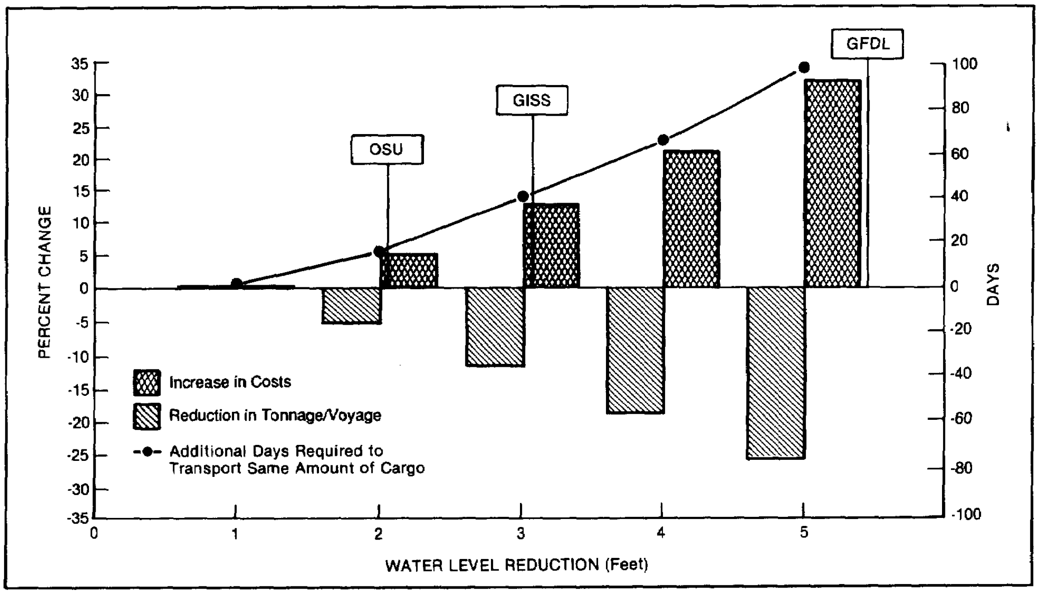

Figure 15-4. Impacts of lower lake levels and reduced ice cover on shipping, cargo capacity, costs, and days of transport for the Port of Buffalo (Keith et al., Volume H).

meter in Lake Erie, which are the lake level reductions estimated by Croley for the OSU and GISS scenarios, cargo capacity would decrease by about 5 to 13%, and costs per ton would rise by the same amount. Croley's estimate from the GFDL scenario was that Lake Erie would fall 1.65 meters (5.4 feet), but the shipping model does not include lake level drops of more than 5 feet. A drop of 5 feet would decrease cargo capacity per voyage by 27% and increase costs by 33%. Thus, the drop in lake levels estimated under the GFDL scenario could increase costs by more than 33%. Since lake levels in Lake Superior were not estimated to fall as much, the corresponding reduction in cargo capacity for ships on those ports would be in the range of 2 to 8%.

Sanderson estimated that lake level reduction of 0.2 to 0.6 meters would increase total Canadian shipping costs by 5%, assuming the current fleet and mix stayed the same. Although results are not directly comparable, since Keith et al. examined U.S. flagships and ports while Sanderson studied Canadian ships and ports, the estimates are of the same magnitude.

Whether the same amount of annual cargo can be transported, assuming no dredging to deepen channels, depends mostly on how much lake levels drop. If the drop is sufficiently large, annual tonnage could be reduced. The following discussion assumes that lake level declines occur at the same time as ice cover reductions. It is not clear from these studies whether lake levels will respond more slowly to climate change than ice cover. Figure 154 also displays the additional days needed to transport the same amount of cargo as is currently shipped through Buffalo. Under the approximate 2-to 3-foot drop of the wetter and relatively cooler OSU and GISS scenarios, another 15 to 40 days of shipping would be needed. Assel estimated that under those scenarios, ice duration in eastern Lake Erie would be reduced by 84 to 91 days. Thus, under these scenarios, even with reduced capacity per voyage, there would be enough additional days of travel to transport even more goods. If lake levels fell 5 feet, which is less than estimated by GFDL, an additional 100 days of transport would be needed to handle the same amount of cargo. Ice duration in eastern Lake Erie could be reduced by 92 days under this scenario, which would not allow enough time to transport the same amount of cargo, assuming the current fleet and demand for transport. The results appear to be more sensitive to changes in lake levels than to reductions in ice cover.

Keith and Willis used current dredging costs to estimate the cost of dredging the ports to restore current channel depths. The total costs of dredging the three ports in Lake Erie range from $7 to $31 million per port (1987 dollars). Current annual dredging costs for those ports range from $800,000 per year in Buffalo to $2.5 million per year in Toledo (J. Hasseler, U.S. Army Corps of Engineers Buffalo District, 1988, personal communication).

Implications

Reduction in the tonnage per voyage or increased costs for dredging would raise shipping costs. However, with a longer shipping season, users of shipping such as powerplants would not have to carry large inventories to last through the winter and own enough land to store those inventories. Besides reducing costs, this could allow current lakefront storage areas to be used for other purposes. Whether these savings would offset higher shipping costs was not examined.

Dredging the ports and channels could degrade the water quality of the lakes. The sediments in many of these ports are toxic, and disposal of the sediments could be complicated by their toxicity and by the reduced disposal areas resulting from lower lake levels.

Water Quality

Two studies estimated the temperatures and thermal structures of southern Lake Michigan and the Lake Erie Central Basin. The Lake Erie study estimated biological activity, such as algal production and changes in dissolved oxygen levels. The Michigan and Erie analyses were used by Magnuson et al. to study changes in the thermal habitats of fish.

Thermal Structure of Southern Lake Michigan

Study Design

McCormick used a one-dimensional thermal structure model (Garwood, 1977) to estimate the heat content and structure of a site in south-central Lake Michigan. The model has been successfully applied to oceans and inland seas and was used by McCormick to analyze a site 150 meters (500 feet) deep. GCM data for windspeed, temperature, humidity, solar radiation, and cloud cover were applied to hourly data from 1981 to 1984.

Limitations

McCormick used the years 1981-84 as his base case because hourly water temperature data are not available for 1951-80. Three years provide very limited baseline climate variability, although these years include cold and warm periods. The results are most sensitive to changes in windspeed. Since the scenario may underestimate reductions in windspeed from the GCMs (see the discussion of the limitations of the lake level study), this analysis may overestimate wind-driven mixing in the upper layer and underestimate changes in the length of time and degree of stratification. On the other hand, if the intensity of summer storm increases, then stratification may be weakened and shortened. The analysis assumed there was no change in the frequency of storms. More summer storms may weaken stratification, while fewer storms could strengthen stratification.

Results

McCormick estimated that the length of the stratified season could increase under all three scenarios. Figure 15-5 displays the mixed-layer depth over an average year. The higher heat content may cause the lake to begin to thermally stratify, on average, about 2 months earlier than in the base case (in April as opposed to June). The stratified layers were estimated to begin to deepen around late fall, as under current climate conditions.

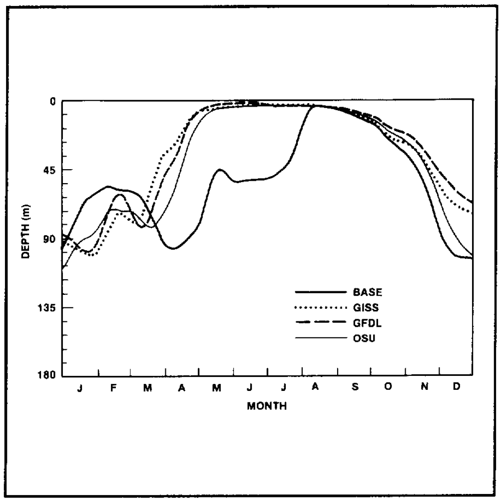

Figure 15-5. Average annual mixed-layer depth in southern Lake Michigan (McCormick, Volume A).

Surface lake temperatures were estimated to be up to several degrees higher than in the base case. The increase in surface temperatures was greater than the increase in subsurface temperatures. There appears to be a larger warming of the entire water column in the winter, about 2 to 3°C, than in the summer, which has a warming of about 2°C. The warmer lake temperatures are consistent with the studies of Croley and Assel, which suggest that midlake water would generally be ice-free. The earlier onset of stratification, reduced inds in the scenarios, and greater temperature differences between lake layers could yield stronger density differences between upper and lower layers.

McCormick detected a significant decrease in the frequency of complete mixing of the lakes. The surface layer could be warmer and more buoyant, making it more difficult for entrainment and mixing to occur. Temperatures were too warm in the winters of some years to allow the lake to become isothermal (the mixed layer would stay above the bottom of the lake all year), leading to a year-long stratification. This result is consistent with Croley's analysis.

Implications

Reduced turnover of the lakes could have serious implications for aquatic species in the lakes. Mixing of oxygen and nutrients could be disrupted, possibly affecting the abundance of life in the lower and upper layers of the lakes.

Eutrophication of the Lake Erie Central Basin

Nutrient loadings have made many areas of the shallow Lake Erie eutrophic at times. The shallow western and central basins of the lake are particularly vulnerable to eutrophication. Installation of pollution controls in recent years has improved water quality. Blumberg and DiToro analyzed whether climate change would have an effect on eutrophication in the Lake Erie Central Basin.

Study Design

Blumberg and DiToro modeled the thermal structure of the Lake Erie Central Basin. They developed a thermal model for the basin, using a modeling framework previously designed by Blumberg (Blumberg and Mellor, 1983). This model is similar to the one used by McCormick for southern Lake Michigan.

Blumberg and DiToro then examined the direct effects of changes in the thermal structure on aquatic life in the basin. The outputs from the thermal model were fed into a eutrophication model that had been previously developed by DiToro (DiToro and Connolly, 1980). The latter model estimates what would happen to dissolved oxygen levels in the lakes by simulating the interactions between nutrient availability and biological (e.g., plankton) activity.

The models were run using only two base years, 1970 and 1975. In 1970, the thermocline (density gradient between the upper and lower layers) was deep, and over 60% of the hypolimnion (lower level) in the Lake Erie Central Basin was anoxic (depleted of oxygen). In 1975, the thermocline was shallow, and less than 10% of the lower layer was anoxic (DiToro et al., 1987).

Limitations

Although the two base years encompass a wide range of baseline anoxic conditions, they do not represent a full range of climate variability. In addition, as in the Lake Michigan study, the scenario assumed no change in the frequency of storms. More summer storms would weaken stratification and increase dissolved oxygen levels, while fewer storms would have the opposite effect. The analysis did not incorporate the actual reduction in nutrient loadings from the base years, or the estimated drop in lake levels from Croley's work. Lower lake levels would reduce the volume of the lower layer in Lake Erie, possibly increasing eutrophication. The models were not run for the winter, but Blumberg and DiToro tested the sensitivity of results to higher water column temperatures (due to warmer winter air temperatures) in the spring and found no significant difference in results. Blumberg and DiToro used the vector wind estimates from the GCMs, which may overestimate mixing in the upper layer.

Pollution loadings in 1970 and 1975 were much higher than they are today. Use of current pollution loadings would have resulted in higher estimates of dissolved oxygen levels and lower estimates of the area of the basin that could become anoxic. The direction of change estimated by Blumberg and DiToro would not have been affected.

Results

Blumberg and DiToro estimated that the Lake Erie Central Basin could remain stratified about 2 to 4 months longer than under current conditions, with the stratified season starting 2 to 6 weeks sooner and ending 2 to 7 weeks later. The temperature differences between the upper and lower layers of the basin were estimated to be greater under all scenarios, leading to less exchange of nutrients across the thermocline. The depth of the thermocline appears to be most sensitive to estimated changes in windspeeds. In two scenarios, GISS and GFDL, windspeeds were generally lower, and the thermocline was estimated to be about 2 meters higher than current depths. Under the OSU scenario, windspeeds were estimated to increase and the thermocline was estimated to be approximately 1 meter deeper than current levels. A lowering of the thermocline depth by 2 meters in the 25-meterdeep Lake Erie Central Basin can reduce the volume of the lower layer by 20%, limiting total oxygen availability.

All three scenarios generally led to decreases in dissolved oxygen levels compared with base case conditions despite differences in thermocline depth. The increase in area of the Lake Erie Central Basin that was estimated to become anoxic is shown in Figure 15-6. Dissolved oxygen levels were estimated to increase only in the July 1970 case, and this occurred because the levels were near zero to begin with. Blumberg and DiToro concluded that the difference in oxygen content was caused by warmer lake temperatures, which raise biological activity enough to increase oxygen demand.

The enhanced biological activity was combined with a more intense and longer stratified season to further lower dissolved oxygen levels. Lower thermocline depths, such as in the OSU scenario, result in even greater decreases in dissolved oxygen levels. The estimated changes in the thermal structure of Lake Erie are comparable to McCormick's results for southern Lake Michigan. Both estimated that average temperatures in the water column would rise, that there would be greater differences in temperature between the epilimnion and hypolimnion, and that stratification would last longer. One major difference in the results is that stratification begins earlier and lasts longer in Lake Erie and begins earlier and breaks up at the same time as the present stratification in Lake Michigan. It is not clear whether this difference is attributable to different lake depths, to surface meteorology used to force the models, or to surface boundary conditions in the calculations.

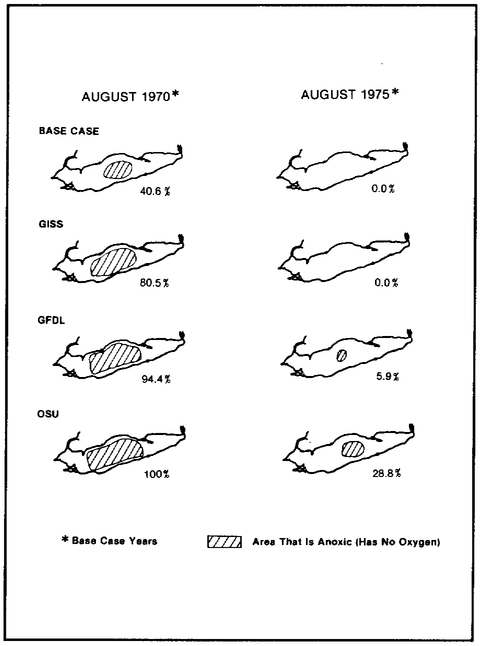

Figure 15-6. Area of central basin of Lake Erie that becomes anoxic (Blumber and DiToro, Volume A).

Implications

Decreased dissolved oxygen levels could make the Lake Erie Central Basin less habitable for finfish and shellfish during the summer. This could reduce recreational uses of the lake such as swimming, fishing, and boating. It also could put more pressure on reducing sources of pollutants, especially such nutrients as phosphorous, from point and nonpoint sources.

<u>Fisheries</u>

The Blumberg and McCormick studies show that climate change would probably raise lake temperatures and reduce oxygen levels in certain areas. To get an initial sense of what these changes might mean for Great Lakes fish, Magnuson et al. examined the potential ecosystem, organism, and population responses to warmer temperatures.

Study Design

Magnuson et al. estimated changes in fish habitat, growth, prey consumption, and population for sites in Lakes Erie, Michigan, and Superior. The work used several approaches and models to examine the following:

- Changes in ecosystem activity, such as changes in phytoplankton populations, were estimated by using a community "Q_{10}" rule (Ruttner, 1931), which approximates the higher biological activity associated with higher temperatures.

- Magnuson et al. used the Blumberg and McCormick thermal structure studies to estimate the potential effects on thermal habitats -- the niche in which temperatures are optimum for fish. To estimate changes in habitats, the study used laboratory estimates of the temperature regimes preferred by fish (Magnuson et al., 1979; Crowder and Magnuson, 1983) and assumed that the lower layer of the Lake Erie Central Basin is uninhabitable. In addition, using a thermal model for streams (Delay and Seaders, 1966), the study calculated the change in habitat for brook trout in a southern Ontario river.

- Magnuson et al. used a food consumption and conversion model (Kitchell et al., 1977) to estimate the changes in annual growth and prey consumption at three near-shore sites in Lakes Superior, Michigan, and Erie. This analysis assumed that consumption rates increase with climate warming. Growth simulation for Lake Michigan using water temperature scenarios from McCormick assumed that prey availability did not increase. This study assumed that fish migrate to habitable sites when inshore temperatures are too warm.

Limitations

The study did not examine the combined effects of reduced habitat and greater need for forage in the summer, which would combine to intensify species interactions. The analysis did not incorporate impacts resulting from lower lake levels, such as possible loss of wetlands, and it did not analyze the aquatic effects of the potential reduction in the frequency of lake turnover or the impacts of a reduction in ice cover. The introduction of new species, which could have negative impacts on existing fish, was not examined.

Any uncertainties associated with the McCormick and Blumberg studies would be carried over into the analysis on habitat. These changes in the lakes and littoral systems may have negative impacts on Great Lakes fish. These uncertainties could reverse the direction of results and lead to more declines in fish populations than indicated here.

Results

Phytoplankton production, zooplankton biomass, and maximum fishery yields were estimated to increase 1.3- to 2.7-fold, with the largest increase in phytoplankton production (1.6to 2.7-fold) (Figure 15-7). The larger increases in biological activity were generally associated with larger temperature increases. The increase in phytoplankton provides more forage for zooplankton, which, in turn, provides more forage for fish. The increase in phytoplankton can also enhance eutroplucation, as was estimated by Blumberg and DiToro.

Magnuson et al. found that the average annual thermal habitat for all fishes would increase. This was especially apparent for lake trout, which is a coldwater fish with a preference for very cold water, and which could have more than a 100% increase in habitat (see Figure 15-8). The major reason for the increase in habitat is that more habitable waters would be found in the fall, winter, and spring. On the other hand, hotter temperatures could decrease summer habitats for certain species by 2 to 47%, depending on the temperature rise and species. The length of stream suitable for brook trout in the summer could be reduced by 25 to 33% because of higher temperatures.

Fishes were generally estimated to have increased body size under the scenarios. Cool and cold coldwater fishes could have 20 to 70% more growth, and warmwater fishes in warm areas could have 220 to 470% more growth. This assumes that prey availability increases. If prey availability does not increase, fish growth would also decrease owing to an inability to compensate for the increased metabolic costs of living in higher temperatures. Magnuson et al. calculated that if prey availability does not increase, fish growth in Lake Michigan could decrease by 10 to 30%. Warmwater fish would have larger decreases if prey did not increase. Furthermore, the increased demand for forage may intensify species' interactions and alter the food web structure.

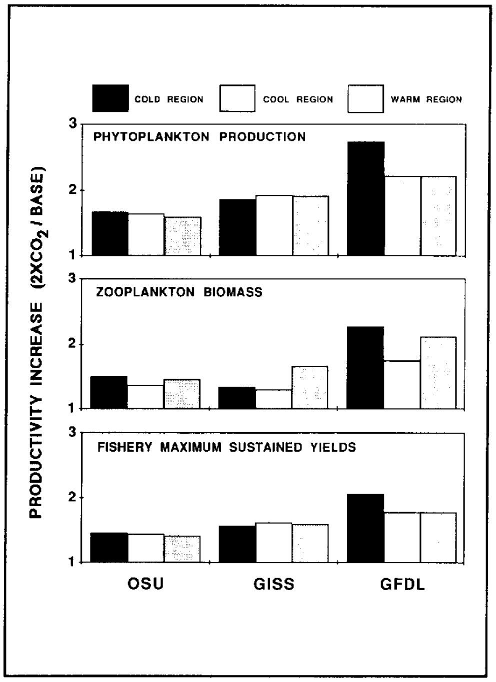

Figure 15-7. Increases in Great Lakes aquatic productivity (Magnuson et al., Volume E).

The effects of reduced ice cover and possible reduction in wetlands on Great Lakes fishes was not investigated, although Freeberg (1985) suggests that a reduction in ice cover would reduce whitefish recruitment, and Meisner et al. concluded that loss of wetlands due to lower lake levels could reduce spawning, nursery, and feeding grounds for fish in shallow areas, reducing fish populations (Meisner et al., 1987).

Implications

Fish populations could increase, with beneficial implications for commercial and recreational fishing, although certain species, such as brook trout in streams, may be reduced. A net increase in fisheries would lead to more employment in commercial fishing and tourism industries, but would increase the need for maintaining water quality in the lakes. Increased demand on the forage base by predators and the introduction of new species and reduced ice cover could have negative effects, but these cannot be predicted and must be considered as surprises of unknown probability.

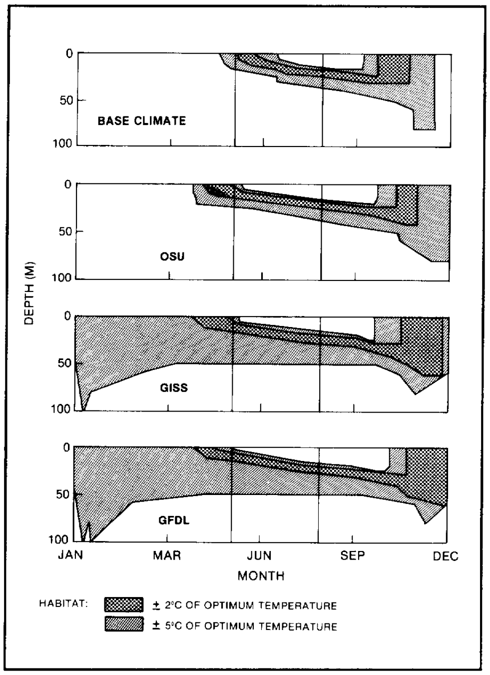

Figure 15-8. Increase in lake trout habitat (Magnuson et al., Volume E).

Forests

Climate change could affect the distribution and abundance of forests in the Great Lakes region. Overpeck and Bartlein examined the equilibrium range shift of forests, Botkin et al. studied transitional impacts on composition and abundance, and Zabinski and Davis analyzed the ability of trees to migrate along with a rapidly changing climate.

Potential Range Shifts

Study Design

Overpeck and Bartlein studied the potential shifts in ranges of forest types over eastern North America. This analysis suggests where trees are likely to grow in equilibrium doubled CO_2 climate conditions after allowing for migration of tree species to fully catch up with climate change (see Forest Migration). It indicates only the approximate abundance of different species within a range, not what the transitional effects of climate on forests might be, or how fast trees will be able to migrate to the new ranges. (For a discussion of the study's methodology and limitations, see Chapter 5: Forests.)

Results

Under all three doubled CO_2 scenarios, the range of spruce, a major component of the boreal forests, could shift almost entirely out of the region. Northern hardwoods, such as birch and northern pine species, would shift to the north but may still be in the region. Oak trees, which are mostly found in the southern part of the region, would be found all over the region in the warmer conditions. The abundance of prairie forbs (shrubs) would increase in the region, and southern pines could eventually migrate to the southern part of the region.

Transitional Effects

In contrast to Overpeck and Bartlein, Botkin et al. examined the transitional effect of climate change on forests as well as doubled CO_2 effects.

Study Design

Botkin et al. used a model of forest species growth and competition to estimate the effects of climate change on Great Lakes forests (Botkin et al., 1972, 1973). This model, which is known as a stand simulation model, can be used to estimate the transitional changes in composition and abundance of forest species in response to environmental changes such as higher temperature and precipitation.

Botkin et al. studied two diverse sites in the Great Lakes region. The first is in Mt. Pleasant, Michigan, a heavily settled area dominated by northern hardwoods and oaks, where commercial forests are an important resource. The other site is in Virginia, Minnesota, an undeveloped area dominated by boreal forests that have commercial and recreational uses.

Limitations

The model includes all dominant tree species in the northern United States and assumes that seeds from all these trees are universally available throughout the region. Species with predominantly southern distributions are not included; therefore, the model does not estimate whether they could grow in the region under the warmer climate. (Overpeck found that southern pines may migrate into the southern part of the region.) Thus, the stand simulation model does not accurately estimate migration of trees, either within the region or from other areas. Furthermore, the results do not assess whether transplantation by humans of more southern species would be successful. In addition, the model does not account for fertilization effects of CO_2, although CO_2 may not have positive effects in the competitive environment of unmanaged ecosystems (see Botkin et al., Volume D). Botkin et al.'s analysis did not account for introduction of new pests into the region, for the possibility of increased frequency of fires, or for the combined impact of changes in tropospheric air pollution levels and UV-B radiation.

Results

Botkin et al. estimated the doubled CO_2 climate would cause major changes in forest composition throughout the region. Results from the Mt. Pleasant site indicate that tree biomass at dry sites, which now have oak and sugar maple, could be reduced by 73 to 99% and could convert to oak savannas or even prairies. Relatively wet soil sites might be converted from sugar maple to mostly oak woodlands with some red maple. Biomass at these sites could be reduced by 37 to 77%.

In the Minnesota site, the boreal forests could be replaced by northern hardwood forests, now characteristic of areas to the south (see Figure 159). Relatively dry areas, such as the Boundary Waters Canoe Area where balsam fir dominates, and upland areas where white birch and quaking aspen dominate, could be replaced by forests consisting mainly of sugar maples. Where currently saturated soils in these upland areas become drier and better sites for tree growth, wood production may increase. However, bogs that now contain white cedar could become treeless. This is because no species that could tolerate warmer bog conditions are currently in the region. It is possible that more southern species could be transplanted to these

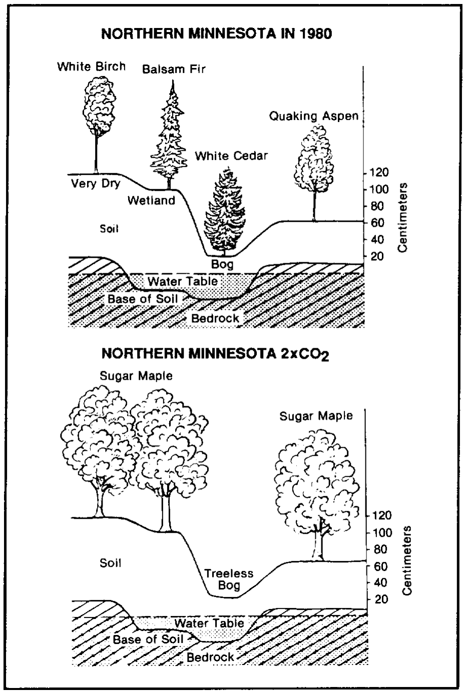

Figure 15-9. Changes in composition of northern Minnesota forests (Virginia, Minnesota; soil depth = 1.0 meter; water table depth = 0.8 meter) (Botkin et al., Volume D).

sites, although this was not studied.

In both sites, the biggest decline is seen in the hotter and drier GFDL scenario. Decreased soil moisture, which is a result of higher temperatures and reduced rainfall, appears to be the most significant factor reducing biomass.

Botkin et al. found that the abundance of species could significantly change in three to six decades. Figure 15-10 displays results from the transient scenarios for balsam fir and sugar maple at the Minnesota site. The basal area of balsam fir could start to decline in three to six decades. Potential declines in several decades are also seen in simulations of white cedar and white birch in the Minnesota site. Sugar maple, which has negligible basal area in the current climate, was estimated to start to exhibit significant growth within three decades in both transient scenarios.

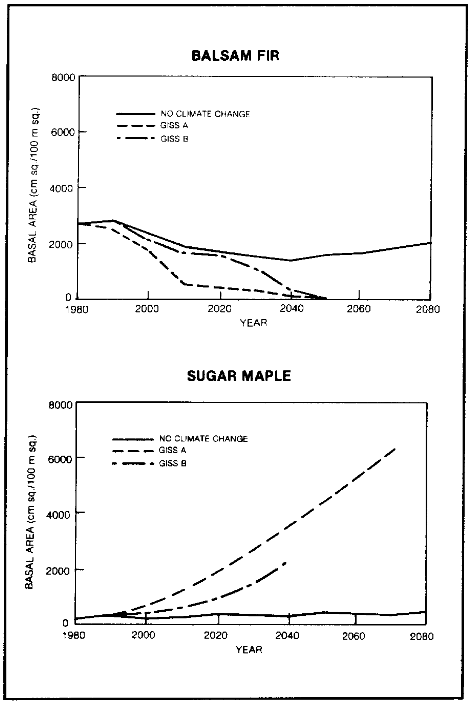

Figure 15-10. Change in forest composition during the next century for a deep, wet, sandy soil in northern Minnesota (Botkin et al., Volume D).

Forest Migration

Both Overpeck and Botkin assumed that trees would be able to migrate to new locations (although Botkin did not assume southern species would be able to migrate into the Great Lakes region). Zabinski and Davis examined the potential range shifts of sugar maple, yellow birch, hemlock, and beech currently found in the Great Lakes region and compared that shift with potential rates of migration.

Study Design

Zabinski and Davis assumed that tree species grow only in climates with temperatures and precipitation identical to their current range. They determined the location of potential species ranges under the GISS and GFDL scenarios. The climate values were determined by extrapolating between gridpoints. Zabinski and Davis examined the potential migration of the species by assuming that the doubled CO_2 climate would not occur until 2090, and that these species could migrate into new regions at the rate of 100 kilometers (62 miles) per century.

Limitations

The study did not consider human transplantation of seedlings to speed migration. The analysis did not consider competition among species or whether migratory routes would be blocked. It also did not analyze whether species could survive in the soil conditions, nutrient availability, sunlight, and other relevant factors in northern areas. Doubled CO_2 climate conditions could occur sooner than 2090, resulting in greater range reductions. The rate of forest migration used is double the maximum rate ever recorded for temperate trees. A faster warming and slower migration would make it more difficult for forests to keep up with shifts in range attributable to climate change. Zabinski and Davis did not consider whether higher atmospheric CO_2 concentrations would mitigate the decline of forests along southern boundaries of their ranges.

Results

Under the wetter GISS scenario, the potential ranges of sugar maple, yellow birch, hemlock, and beech move markedly northward to central Canada. The results for hemlock and sugar maple are displayed in Figure 15-11. The stippled area shows the potential range, and the black area shows how far the trees could migrate by 2090. Zabinski and Davis found that hemlock, yellow birch, and sugar maple could become much less abundant in the parts of Wisconsin and Michigan where they currently grow. Beech may be completely eliminated from the lower peninsula of Michigan where it is presently abundant. In addition, the rate of migration would be slower than the climate change. The trees would not migrate as far as the northern boundary of the climate range (the stippled area). The southern boundary would be driven northward by climate change. Since the shift in climate zones is faster than the assumed rate of migration, the southern boundary would move north faster than the northern migration rates. The total range of all four species would be reduced.

Under the GFDL scenario, which is the hottest and driest, all four species are eliminated from the Great Lakes region. Northern hardwood tree species might be replaced by trees characteristic of more southern latitudes or by prairie or scrubland. Since the southern range of the trees moves farther north than in GISS, the inhabited range would be much smaller than under GISS. Zabinski and Davis found that all four tree species would be confined to an area in eastern Canada having a diameter of only several hundred kilometers. The ability of the four species to survive in more northern latitudes may depend on whether they could adapt to different day lengths and soils.

<u>Implications of Forest Studies</u>

All three studies, through different analytic approaches, agree that the scenarios of climate change would produce major shifts in forest composition and abundance. Boreal forests would most likely no longer exist in the region. Northern hardwood forests might still be present, especially in the north. Uncertainty exists concerning whether forests in the southern part of the region will die back leaving grasslands or whether new species will be able to migrate or will be transplanted and flourish. The rapid rate of climate change, coupled with the presence of urban areas and extensive farmland in the southern Great Lakes States, may impede migration of southern species into the region. Such a shift could result in increased soil erosion and decreased water quality. In addition, higher tree mortality and drier soils could increase fire frequency. There also may be an increase in pathogen-related mortality in trees. Shifts in forest composition and abundance may have implications for wildlife in the region.

This shift in species also could have significant impacts on the commercial forest industry in the region. The industry currently harvests softwoods for production of pulp, paper, and construction materials. These species would decline and would be replaced by oaks and maples, which are useful for furniture but take longer to become fully grown. Red maple, which may be more abundant in the southern area, is not currently used commercially. Changes in forest abundance may also affect tourism and recreation.

Agriculture

The agriculture studies combined analyses of impacts on the region and across the country. Ritchie et al. studied the potential impacts of climate change on crop yields in the region. Adams et al. then used the results from this study and other regional crop yield

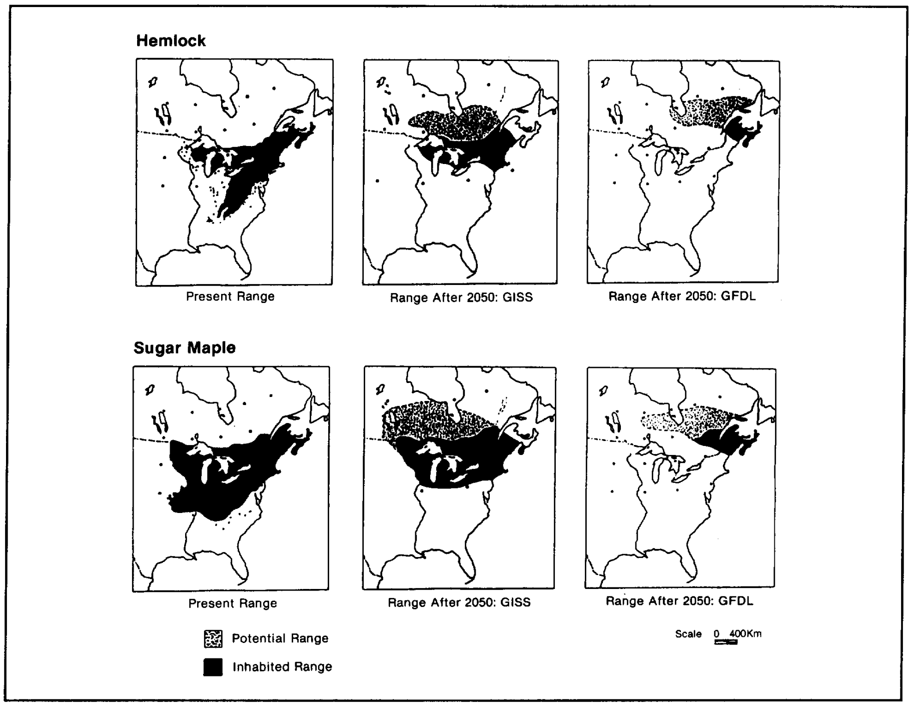

Figure 15-11. Shifts in range of hemlock and sugar maple (Zabinski and Davis, Volume D).

analyses to estimate economic adjustments by farmers. Easterling studied how a typical Illinois corn farmer would try to adapt to climate change.

Crop Yields

Study Design

Ritchie et al. used crop growth models to estimate the impacts of climate change on yields for corn and soybeans in the Great Lakes States (Jones and Kiniry, 1986; Wilkerson, 1983). The two physiological models examine the direct effects of temperature and precipitation on crop yields. Ritchie et al. also used simple estimates of increased photosynthesis and decreased transpiration to conduct a sensitivity analysis of the combined impacts of change in weather and CO_2 fertilization on crop yields. In addition, they studied whether crop varieties currently in southern areas may mitigate climate effects.

Limitations

The direct effects of CO_2 in the crop modeling study results may be overestimated for two reasons. First, experimental results from controlled environments may show more positive effects of CO than would actually occur in variable, windy, and pest-infested (weeds, insects, and diseases) field conditions. Second, because other radiatively active trace gases, such as methane (CH_4) also are increasing, the equivalent warming of a doubled CO_2 climate may occur somewhat before an actual doubling of atmospheric CO_2. A level of 660 ppm CO_2, was assumed for the crop modeling experiments, while the CO_2 concentration in 2060 is estimated to be 555 ppm Hansen et al., 1988).

All the scenarios assumed that by having low salinity and no compaction, soils would be relatively favorable for crops, and there were would be no limits on the supply of all nutrients. In addition, the analysis assumed farmers would make no technological adjustments to improve crop yields or introduce new crops. Possible negative impacts due to changes in storm frequency, droughts, and pests and pathogens were not factored into this study. The results could be significantly affected by such changes. The percentage changes for Duluth are very large because current yields are very low relative to other sites.

Results

Ritchie et al. found that temperature and precipitation changes alone could reduce crop yields everywhere in the region, except in the northernmost latitudes, such as Duluth, where yields could increase depending on rainfall availability. Results from selected sites are displayed in Table 15-5. Corn yields could decrease from 3 to 60%, depending on climate and water regime (dryland or irrigated). However, Duluth, the most northern site, could see increases of 49 to 86%. Current dryland and irrigated corn yields are lower in Duluth than in the more southern sites. Dryland yields in Duluth under climate change could be equal to other sites, and irrigated yields could exceed the other locations.

Dryland soybean yields are estimated to drop by 3 to 65% in the region, except in the north. There, dryland yields may decrease by 6% under GFDL but increase by 109% under the wetter GISS. Under irrigated scenarios, soybean yields in the north increase by 96 to 153%. Even with the increase in output, the soybean yields in Duluth may still be lower than in areas to the south.

The reduction in yields in the south would be due mainly to the shorter growing period resulting from extreme summer heat. Production in the north is currently limited by the long winter, so a longer frost-free season results in increased yields.

Ritchie found that the demand for irrigation would rise between 20 and 173% under the GFDL scenario and up to 82% under GISS, although some sites under GISS were estimated to have reductions in demand of up to 21%.

The combined effects of higher concentrations of CO_2 and climate change could increase yields if sufficient rainfall is available. If it is not, yields could rise or fall. Dryland corn and soybean yields may rise up to 135% under the GISS scenario and up to 390% in Duluth. In the dry GFDL scenario, however, yields could fall up to 30% or rise up to 17%, again except for Duluth, which has an increase of 66 to 163%. Irrigated yields for corn rise and fall under both scenarios, but irrigated soybean yields could rise 43 to 72% in the south and up to 465% in Duluth. The combined effects lead to an estimated reduction in demand for irrigation for corn of 26 to 100% under both scenarios, whereas irrigation needs for soybeans under GFDL rise by 65 to 207% and range in GISS from a reduction of 10% to an increase of 32%.

Ritchie found that use of a longer season corn variety could reduce the negative effects of climate alone, under the GFDL scenario, but would still result in net losses.

It is not clear whether crop yields would rise or fall in the region. Among other factors, this will depend upon how CO_2 and climate change combine to affect crop growth and on how hot and dry the climate becomes. Yields and the potential demand for irrigation appear to be quite sensitive to rainfall, being higher under relatively drier scenarios. If climate change is severe enough, as under the GFDL scenario, yields could fall. In general, irrigation demand would rise, but some significant exceptions exist.

Implications

The potential shifts of agriculture northward are discussed below. Since the demand for irrigation is generally higher, it could become a more attractive option for farmers in the region. Whether more irrigation is actually used will depend on its costs and the price of crops.

Regional Shifts

Ritchie et al.'s analysis only estimates changes in potential yields for the Great Lakes region. How much farmers actually grow will depend in part on what happens elsewhere. If the relative productivity of agriculture rises, farmers will probably increase output. If relative productivity falls, they would most likely cut back. Adams et al. examined how different regions of the United States may react to potential productivity changes. Results are presented here for the Great Lakes region only.

Adams et al. modeled potential nationwide shifts in crops using the Great Lakes analysis and analyses of shifts in other regional crop yields. He did the analysis for yields attributable to climate change alone, and for the combined effects of climate and enhanced CO_2 concentrations. Adams et al.'s analysis did not account for the effects of climate on agriculture

Table 15-5. Effects of Climate Change Alone on Corn and Soybean Yields for Selected Sites in Great Lakes States (ranges are GISS-GFDL and are % change from base)

Site	Corn		Soybeans	
	Dryland	Irrigated	Dryland	Irrigated
Duluth, MN	+49 to -30	+86 to +36	+109 to -6	+153 to +96
Green Bay, WI	-7 to -60	-3 to -44	-3 to -65	+3 to -26
Flint, MI	-17 to -48	-14 to -38	-6 to -51	+6 to -11
Buffalo, NY	-26 to -47	-18 to -38	-21 to -53	+6 to -6
Fort Wayne, IN	-11 to -51	-15 to -48	-2 to -58	0 to -19
Cleveland, OH	-26 to -50	-19 to -43	-16 to -59	-1 to -14
Pittsburgh, PA	-22 to -55	-19 to -45	-13 to -59	0 to -13

Source: Ritchie et al. (Volume C).

in other countries. How U.S. and regional agriculture respond to climate change may be strongly influenced by changes in relative global productivity and demand. The study did not consider introduction of new crops such as citrus. (For a discussion of the study's design and limitations, see Chapter 6: Agriculture.)

Results

Adams et al.'s estimates of acreage changes for the Great Lakes States are shown in Table 15-6. It appears that land devoted to agriculture in the Great Lakes region would not change significantly in response to climate change. The results indicate a slight tendency to increase acreage in the northern Great Lakes States, although only by small amounts. Results for the Corn Belt States are inconclusive.

Table 15-6. Percentage Change in Acreage for Great Lakes States After Doubled CO_2 Climate Change (Corn Belt States include Iowa and Missouri)

Area	Climate change alone		Climate and CO_2	
	GISS	GFDL	GISS	GFDL
Lake States	+3	0	+1	+10
Corn Belt	+2	-6	-1	-6

Implications

The results of Adams et al. and Ritchie et al. suggest that northern regions could become more attractive for agriculture, although more extensive analysis is needed to confirm this result. The presence of thin, glaciated soils may limit this expansion. If it occurs, such an expansion could have significant implications for development of the north. Additional acreage could be converted from current uses, such as forests, to agriculture. Increased erosion and runoff from this additional acreage would pollute groundwater and streams and lakes in relatively pristine areas. Enhanced agriculture may increase the need for more shipping as lower lake levels raise shipping costs.

Adjustments by Illinois Corn Producers

Farmers may make many adjustments to climate change such as planting different crop varieties, planting earlier in the season, irrigating, and using different fertilizers. Easterling examined how a typical corn farmer in Illinois would react to climate change.

Study Design

Easterling presented several professional crop consultants with the GISS and GFDL climate change scenarios and with estimates of corn yields and prices for climate effects alone from the Ritchie et al. and

Adams et al. studies. Based on the interviews, a set of decision rules was established to estimate how a typical Illinois corn farmer would alter farming practices in response to the climate and agriculture scenarios.

Limitations

The climate change scenarios involve climate conditions not experienced by the experts. Their estimates of how farmers would respond are not based on experience with similar conditions but on speculation. The results of the combined climate and CO_2 sensitivity analyses were not presented to the experts. The analysis is specifically for Illinois corn farmers and cannot be extrapolated to other areas or crops.

Easterling found that the degree of adjustment depends on how much climate changes. Under the wetter GISS scenario, farmers could make adjustments to help mitigate the impacts of higher temperatures. Such adjustments could include planting earlier in the spring to avoid low soil moisture levels in the summer, using full-season corn varieties for earlier planting, and changing tillage practices and lowering planting densities to better conserve soil moisture. Under the hotter and drier GFDL scenario, corn production might not be feasible. Farmers would likely install irrigation systems; switch to short-season corn, soybeans, and grain sorghum; and perhaps remove marginal lands from production. This last conclusion is consistent with the Adams et al. study.

Implications

Although farmers have a variety of adjustment options to help cope with climate change, they may have great difficulty coping with extreme changes such as the dry climate implied by the GFDL scenario. Use of more irrigation would have negative implications for water quality, although this would be partly counterbalanced by any retirement of marginal lands.

Electricity Demand

Study Design

Linder and Inglis used the GISS transient scenarios to estimate the national changes in demand for electricity for the years 2010 and 2055. The temperature change for 2055 is almost as high as the GISS doubled CO_2 estimate of 4.2°C. They first estimated the change in electricity demand due to gross national product (GNP) and population growth, and then factored in demand changes based on change in climate. The results for the Great Lakes States are displayed here in terms of the percentage change from the non-climate-related growth. The Great Lakes analysis did not consider any reductions in hydropower production resulting from drops in lake levels. (For a description of the study's design and limitations, see Chapter 10: Electricity Demand.)

Results

Estimates of changes in annual demand induced by climate change are displayed in Table 15-7. The results for 2010 are a range based on GISS transient scenarios A and B, and the results for 2055 are just for GISS A. A latitudinal difference exists within the Great Lakes region. In the northern states of Minnesota, Wisconsin, Michigan, northern Ohio, and upstate New York, annual demand falls. The reduced demand for winter heating apparently offsets the increased demand for summer cooling. This is true in 2010 and 2055, when scenario temperatures are, respectively, 1 and 4°C higher than the base case. Annual demand in the southern part of the region (in Illinois, Indiana, southern Ohio, and Pennsylvania) was estimated to rise because increased cooling needs are apparently greater than reductions in heating.

Although annual demand could fall in some areas, new generation capacity requirements for all utilities in the region would be higher than they are now because of increased summer cooling needs. New generation capacity requirements needs are estimated to rise by 3 to 8% in 2010 and by 8 to 11% in 2055. Whether costs would rise in the next two decades is not clear. Linder and Inglis estimated that under the gradual warming of GISS B, cumulative capital costs in the region would be reduced by $1.3 billion, while under the more rapid warming of GISS A, costs would increase by $300 million. By 2055, costs would rise to $23 to $35 billion under GISS A. However, Linder and Inglis estimated that the cost to build additional capacity to meet GNP and population growth without climate change would be $488 to $715 billion.

Table 15-7. Estimated Changes in Electricity Demand Induced by Transient Climate Change Scenarios for Great Lakes Utilities (%)

Utility	Annual (2010)	Annual (2055)
Minnesota	-0.2 to -0.3	-1.2
Wisconsin	0.4 to -0.5	-2.3
Michigan	-0.2 to -0.3	-1.2
Upstate New York	-0.2 to -0.5	-1.3
Ohio, north	-0.2 to -0.3	-1.3
Ohio, south	0.4 to -0.5	2.1
Pennsylvania	0.4 to -0.5	2.2
Illinois	0.5	2.0
Indiana	0.4	1.9
Total	Negligible	<1

Source: Linder and Inglis (Volume H).

Implications

Increased capacity requirements could place additional stress on the region. Fossil fuel plants could add more pollutants to the air. The lake level analysis indicates that hydropower production from the lakes would be reduced, further increasing the demand for energy from other sources.

POLICY IMPLICATIONS

Climate change could raise many issues to be addressed by policymakers in the region. Fundamentally, decisionmakers may have to cope with water use, water quality, and land management issues. They could have to respond to a decline in water availability, increased demand for water, poorer water quality, and shifts in land use, including the possibility of expanded agriculture in the north.

Most likely, many of the decisions in response to climate change, especially issues concerning water management, would be made on an international basis. Both Canada and the United States oversee the regulation of the lakes, water quality, and diversions of water out of the basin.

Water Supply Issues

Lake Regulation

One important issue to be faced by both countries may be regulation of the lakes. Lower lake levels may require altering regulation plans for Lakes Superior and Ontario. This would involve tradeoffs among the needs of shippers, hydropower, shoreline property owners, and infrastructure, and downstream needs, in deciding how high to keep the lakes and rivers. For example, maintaining highwater levels in the lakes to support shipping, hydropower, consumption, and improved water quality would be at the expense of shipping, hydropower, municipal and industrial consumption, and water quality in the St. Lawrence River. Additional structures to control the flow on the lakes may be an option. The International Joint Commission should begin to consider in its long-term planning the potential impacts of climate change on lake regulations.

Withdrawals

Even without climate change, population growth would increase demand for water for municipal and industrial consumption and power generation. Climate change would most likely intensify the demand for withdrawals from the lakes for even more uses within and outside the basin. Municipal consumption would rise (Cohen, 1987b), and farmers in the region may need more water for irrigation.

Others outside the Great Lakes may demand diversion of water from the basin. The 1986 Water Resources Development Act prohibits such diversion without the agreement of all Great Lakes governors and prohibits the federal government from studying this issue. Increased diversion through the Chicago Ship Canal was requested in the summer of 1988 to raise water levels on the drought-starved Mississippi River. The U.S. Army Corps of Engineers rejected the request. Policy-makers will have to balance these demands with the needs of people in the basin.

Shipping

Any response to the potential impacts on the shipping industry may be costly. Possibilities include dredging of both ports and connecting channels. Dredging could cost tens, if not hundreds, of millions of dollars. In addition to the high capital costs of dredging, substantial environmental costs could be incurred in disposing of dredge soils contaminated with toxic chemicals. If dredging were not undertaken, cargo loads would be lower and would possibly impair Great Lakes commerce.

Pollution Control

Climate change could lead to stricter pollution control to maintain water quality. Reduced riverflow, lower lake levels, changed thermal structure, and potentially reduced groundwater supplies may necessitate stricter standards and additional controls on sources of pollution. A need may exist for better management of nutrient runoff from farms into shallow areas, such as the Lake Erie Western and Central Basins. Many pollution control institutions, such as EPA and state and local water quality agencies, would have the authority to impose appropriate controls on polluters.

The water quality problems directly caused by climate change could be exacerbated by other responses to climate change. Intensified agriculture in the region could increase runoff, necessitating more control of nonpoint sources of pollution. If agriculture in northern areas expands, surface and groundwater quality in relatively pristine areas may be degraded. Pollution control authorities such as the U.S. EPA may need to impose more comprehensive controls for those areas and should consider this in their long-term planning.

Fisheries

Although the analysis on fisheries indicates that fish populations in the Great Lakes would generally increase, maintaining fisheries may require intensive management. In productive areas, the possibility of introduction of new species could mean major changes in aquatic ecosystems. Fisheries management may be needed to maintain commercially and recreationally valuable species.

The Great Lakes Fishery Commission may wish to consider the possible implications of climate change on valuable fisheries and management strategies to handle these possible changes. Additional pollution controls may be needed to help maintain fisheries in such areas as western and central Lake Erie.

Land Use

Shorelines

The potential changes in land availability and uses present opportunities and challenges. Lower lake levels would open up new beaches and potential areas for recreation and development, although high capital costs may be associated with developing them. These lands could be kept undeveloped to serve as recreational areas and as protection against fluctuating lake levels and erosion. Conversely, they could be developed to provide more housing and commercial uses. Building structures closer to the shorelines would make them more vulnerable to short-term rises in lake levels.

How these lands will be used will be decided by local and state governments as well as private shoreline property owners. Under the Coastal Zone Management Act, states may identify coastal zone boundaries and define permissible land (and water) uses (Baldwin, 1984). Thus, the act could be used to help manage the use of exposed shorelines.

Lower lake levels and less ice cover may also increase shoreline erosion, decreasing the value of shorelines and degrading water quality. The Great Lakes Basin is not included in the U.S. coastal barrier system, a program that denies federal funds for development of designated erosion or floodprone coastal barriers (Ray et al., Volume J).

Forestry

The potential decline in forests and northward shift in Great Lakes agriculture raise many land-use issues. One important issue may be how to manage potentially large and rapid shifts in forest composition. To speed northward colonization, plantings of the species might be recommended along the advancing front of suitable climate. However, unsuitable soils and day lengths shorter than the species can tolerate might limit the success of such plantings. The forestry industry may consider growing different types of species and producing wood for different uses, such as for furniture rather than for pulp and paper.

Agriculture

Although forests may decline, demand for more land for agriculture in northern areas may grow; however, Adams et al. indicated this demand may be small and will depend on market forces and policies. Federal and state land managers as well as local zoning laws may need to consider that the demand for land use may change. Rules on these lands could have a major influence on how, if at all, the north is developed.

Demographic Shifts

This report did not study the demographics associated with climate change and cannot say whether people will migrate north along with warmer climates. A workshop on climate change and the Great Lakes region, conducted by Ray et al. and attended by government representatives, academics, and citizens group representatives who have studied climate-related Great Lakes resources, concluded that populations from other regions of the United States could migrate to the Great Lakes. The region could have a more favorable climate than more southern areas. Although lake levels may fall, the lakes will still contain a large amount of freshwater while other areas have more severe water availability problems. Consequently, the Great Lakes region may be relatively more attractive than other regions.

Like lower lake levels, an in-migration could present opportunities and challenges. Such a migration could revitalize the region, reversing population and economic losses of recent decades. However, it also could exacerbate some of the problems associated with climate change. More people and industries would require more water and add more pollution, further stressing water supplies and quality. Population growth could increase pressure to develop exposed shorelines along the lakes.

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CHAPTER 16
SOUTHEAST

by James G. Titus

FINDINGS

Global climate change could diminish the extent of the region's forests, reduce agricultural productivity and increase the abandonment of farms, diminish fish and shellfish populations, and increase electricity demand. Approximately 90% of the national coastal wetland loss and two-thirds of the national shoreline protection costs from sea level rise could occur in the Southeast. The impacts on rivers and water supplies are uncertain.

Agriculture

- Southeastern agriculture is generally more vulnerable to heat stress than to freezing, so the adverse impacts of more hot days would more than offset the beneficial impact of a longer growing season.

- As a result of climate change alone, yields of soybeans and corn would vary from no change in the cooler regions to up to a 91% decrease in warmer areas, even if rainfall increases.

- A preliminary assessment suggests that when the direct effects of CO 2 are included, yields might increase in parts of the region if climate also becomes wetter. If climate becomes drier, yields could decrease everywhere in the region. However, our understanding of the direct effects of CO_2 fertilization is less certain than our understanding of the impacts of climate change. Increased CO_2 could also affect weeds, but these impacts were not analyzed.

- If rainfall decreases, irrigation will become necessary for farming to remain viable in much of the region.

- The range of such agricultural pests as potato leafhoppers, sunflower moths, and black cutworms could move north by a few hundred kilometers. This would most likely result in increased use of pesticides.

- Considering various scenarios of climate change and CO_2, the productivity of southeastern agriculture could decline relative to northern areas, and 10 to 57% of the region's farmland could be withdrawn from cultivation. This analysis did not consider whether new crops would be introduced. The decline in cultivated acreage may tend to be concentrated in areas where farming is only marginally profitable today. A reduction in agriculture could hurt farm-related employment and the regional economy.

Forests

- There may be a significant dieback in southern forests. Higher temperatures and drier soils may make it impossible for most species to regenerate naturally and may cause forests to convert to shrub terrain or grassland. The decline in the forests could be noticeable in 30 to 80 years, depending on the site and scenario. Southern noncoastal areas, such as Atlanta and Vicksburg, may have particularly large reductions. The moist coastal forests and the relatively cool northern forests may survive, although with some losses.

- The forest industry, which is structured around currently valuable tree species, would have to either relocate or modify its planting strategies.

- Historically, abandoned farms have generally converted to forests. If large portions of the Southeast lose the ability to naturally generate forests, much of the region's landscape may gradually come to resemble that of the Great Plains.

Water Supplies

Because the winter accumulation of snow plays a negligible role in determining riverflow, our inability to predict whether rainfall will increase or decrease makes it difficult to say whether riverflows will increase or decrease.

- The limited number of hydrologic studies conducted in the Southeast further prevents us from making any definitive statement about the regionwide implications for rivers.

- Decreases in rainfall could disrupt navigation, drinking water availability, recreation, hydropower, powerplant cooling, and dilution of effluent, while increased rainfall could exacerbate the risk of flooding.

- For the scenarios used in this report, changes in operating rules for managed water systems would allow current water demands to be met in most instances.

- The Southeast generally has ample groundwater supplies. The potential implications of increased irrigation on groundwater need to be examined.

Sea Level Rise

- A 1-meter rise in sea level by the years 2100 would inundate 30 to 90% of the region’s coastal wetlands and flood 2,600 to 4,600 square miles of dryland, depending on the extent to which people erect levees to protect dryland from innundation. If current river management practices continue, Louisiana alone would account for 40% of national wetland loss, and developed areas could be threatened as soon as 2025.

- Holding back the sea by pumping sand or other measures to raise barrier islands, and protecting mainland areas with bulkheads and levees, would cost approximately $42 to $75 billion through the year 2100 for a 1-meter rise.

Marine Fisheries

- Gulf coast fisheries could be negatively affected by climate change. A loss of coastal wetlands due to sea level rise could eliminate the critical habitats for shrimp, crab, and other commercially important species. Temperatures in the gulf coast estuaries may exceed the thermal tolerances for commercially important finfish and shellfish, such as shrimp, flounder, and oysters. Oysters and other species could be threatened by the increased salinity that will accompany sea level rise. Some species, such as pink shrimp and rock lobster, could increase in abundance.

Electricity Demand

The annual demand for electricity in the Southeast could rise by 14 to 22 billion kilowatthours (kWh), or 2 to 3%, by 2010 and by 100 to 197 billion kWh, or 7 to 11%, by 2055 as a result of increased temperature.

By 2010, approximately 7 to 16 gigawatts (GW) could be needed to meet the increased demand, and by 2055, 56 to 115 GW could be needed -- a 24 to 34% increase over baseline additions that may be needed without climate change. The cumulative costs could be $77 to $110 billion by 2055.

Policy Implications

- Federal laws constrain the U.S. Army Corps of Engineers and other water resource managers from rigorously considering tradeoffs between may nonstatutory objectives of federal dams in the Southeast, including recreation, water supply, and environmental quality. Increased flexibility would improve the ability of these agencies to respond to and prepare for climate change.

- Given the potential withdrawals of acreage from agriculture, the potential for growing tropical crops needs to be examined.

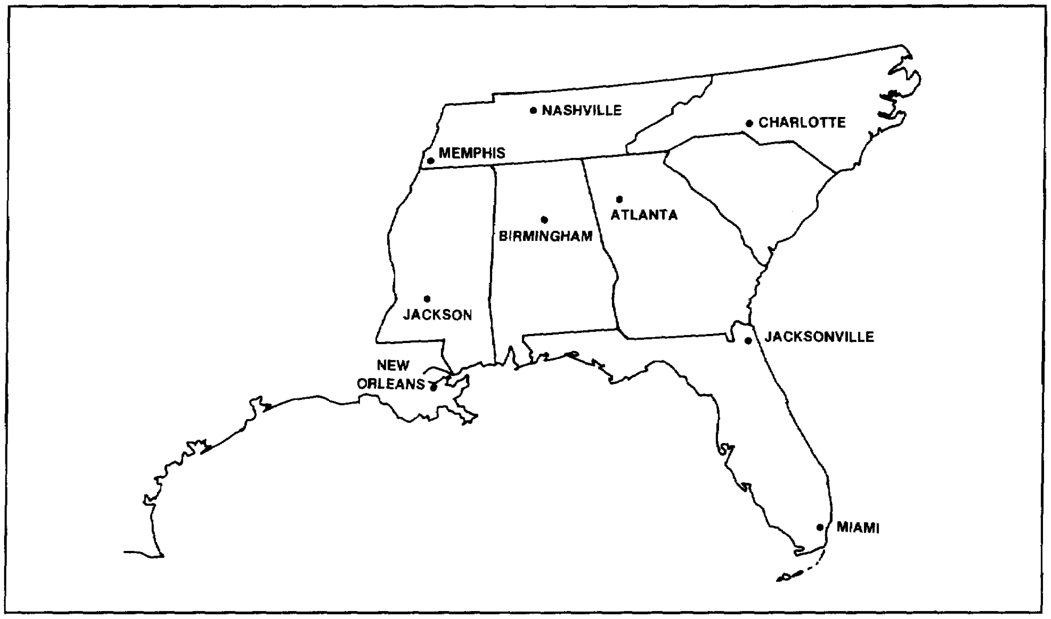

Figure 16-1. Southeast region.

- Strategies for now being evaluated by the Louisiana Geological Survey and the U.S. Army Corps of Engineers to address coastal wetland loss in Louisiana should consider a possible sea level rise of 0.5 to 2.0 meters. measures that would enable this ecosystem to survive would require major public works and changes in federal navigation and riverflow policies. Because of the decades required to implement necessary projects and the prospect that much of the ecosystem would be lost by 2030 even without climate change, these programs need to proceed expeditiously.

- Given the potentially important impacts on forests, private companies as well as agencies such as the U.S. Forest Service and state agencies may wish to assess the potential for large losses of southern forests and the implications for research and management strategies.

CLIMATE AND THE SOUTHEAST

The climate and the coastal zone of the Southeast are among the chief factors that distinguish the southeastern United States from the rest of the nation[1]. The warm temperatures, abundant rainfall, and generally flat terrain gave rise in the 17th century to a strong agricultural economy with a distinctive regional culture. The combination of a benign climate and 60% of the nation's ocean beaches continues to attract both tourists and new residents to the southeastern coastal plain. Florida, for example, is the nation's fastest growing state and will be the third largest by the year 2000 (Meo et al., Volume J).

CLIMATE-SENSITIVE RESOURCES OF THE SOUTHEAST

Water Resources

When statewide averages are considered, each of the seven states in the Southeast receives more rainfall than any other state in the continental United

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[1] Except for the discussion of the economic implications for agriculture, the term "Southeast" refers to the study area shown in Figure 16-1: North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Tennessee, and the coastal zones of Louisiana and Texas.

States (although parts of some western states receive more). Moreover, the rivers of the Southeast drain over 62% of the nation's lands; the Mississippi River alone drains 38% of the nation (Geraghty et al., 1973).

The Southeast supports 50,000 square miles of bottomland hardwood forests (Mitch and Gosselink, 1986)[2], which are periodically flooded areas that offer winter habitat for migratory birds such as ducks, geese, and songbirds. Bass, catfish, and panfish are found in the slow-moving rivers, and trout inhabit the fast-moving mountain streams.

Dams have been constructed along most of the region's major rivers. Although private parties have built a few dams, most of the major projects were built by the U.S. Army Corps of Engineers, the Tennessee Valley Authority, and other federal agencies. In general, the statutory purposes of these reservoirs have been to ensure a sufficient flow of water during droughts, to prevent floods, and to generate electricity. The non-statutory objectives of environmental quality, recreation, and water supply also are considered in the operation of dams.

Dam construction has created large lakes along which people have built houses, hotels, and marinas. These dams generate 22.2 billion kilowatthours (kWh) per year, approximately 7% of the region's power requirements (Edison Electric Institute, 1985). In general, the reservoirs have sufficient capacity to retain flood surges and to maintain navigation flows during the dry season. The one notable exception is the Mississippi River: levees and land-use regulations are the main tools for preventing flood damages; although the Mississippi's base flow usually is sufficient to support navigation, boats ran aground on many stretches of the river during the drought of 1988.

In Florida, which accounts for 45% of water consumption in the Southeast, groundwater supplies about half the water used by farms and 85% of the water used for residential and industrial purposes. For the rest of the Southeast, groundwater supplies most water for agricultural and rural uses but only 30% for public supplies (see Meo et al., Volume J).

Atlanta and some other metropolitan areas obtain their water supplies from federal reservoirs; however, even the many cities that do not still may benefit from federal and federal/state water management. For example, New Orleans obtains its water from the Mississippi River. Without the Old River Control Structure in Simmesport, Louisiana, which prevents the river from changing its course to the Atchafalaya River, the New Orleans water supply would be salty during droughts. Although Miami obtains its water from the Biscayne Aquifer, some coastal wells would be salty without the efforts of the U.S. Army Corps of Engineers and the South Florida Water Management District to recharge the aquifer with supplemental freshwater from canals and Lake Okeechobee.

The various uses of water often conflict with each other. Hydroelectric power generators, lakefront residents, and boat owners benefit when water levels are maintained at high levels. However, high water levels make flood control more difficult, and municipal uses, navigation, hydropower, and environmental quality require that water be released during the dry season, which adversely affects recreation.

Estuaries

Over 43% of the fish and 70% of the shellfish harvested in U.S. waters are caught in the Southeast (NOAA, 1987). Commercially important fishes are abundant largely because the region has over 85% of the nation's coastal wetlands; over 40% are in Louisiana alone.

Most of the wetlands in the Southeast are less than 1 meter above sea level. The wetlands in Louisiana are already being lost to the sea at a rate of 50 square miles per year because of the interaction of human activities and current rates of relative sea level rise resulting from the delta's tendency to subside 1 centimeter per year. (This problem is discussed in greater detail below.)

Summer temperatures in many of the gulf coast estuaries are almost as warm as crabs, shrimp, oysters, and other commercially important fishes can tolerate (Livingston, Volume E). Winter temperatures along the gulf coast are almost warm enough to support mangrove swamps, which generally replace marshes

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[2] This measure includes Mississippi, Arkansas, Louisiana, Texas and Virginia.

once they are established; mangroves already dominate the Florida coast south of Fort Lauderdale.

Beach Erosion and Coastal Flooding

The Southeast has 1,100 miles of sandy ocean beaches, many of which are found on low and narrow barrier islands. The Atlantic coast is heavily developed, while much of the gulf coast is only now being developed. In part because of their vulnerability to hurricanes, none of Mississippi's barrier islands has been developed, and only one of Louisiana's barrier islands is developed at present. Because much of Florida's gulf coast is marsh, it is still largely undeveloped.

All eight coastal states are experiencing coastal erosion. Along developed coasts, recreational beaches have narrowed, increasing the vulnerability of shorefront structures to storms. In Louisiana, some undeveloped barrier islands are eroding and breaking up. Elsewhere, narrow barrier islands are keeping pace with sea level rise by "overwashing" (i.e., rolling over like a rug) in a landward direction, while wide islands and mainland coasts have simply eroded. The coastal states of the Southeast are responding by holding back the sea in some areas and by adapting to erosion in others.

The two greatest natural disasters in U.S. history resulted from floods associated with hurricanes in Galveston, Texas, and Lake Okeechobee, Florida, in which over 8,000 people drowned. After the Mississippi River overflowed its banks and inundated most of coastal Louisiana in the 1930s, Congress directed the U.S. Army Corps of Engineers to initiate a major federal program of flood control centered around the Southeast. Nevertheless, flood waters often remain over some low areas in Louisiana and Florida for several days after a major rainstorm.

Hurricanes continue to destroy recreational development in at least a few ocean beach communities almost every year in the Southeast. The region presently experiences the majority of U.S. coastal flooding and probably would sustain the worst increases in flooding as a result of global warming. Unlike the Northeast and Pacific coasts, this region has wide low-lying coastal plains and experiences several hurricanes annually. Florida, Texas, and Louisiana account for 62% of the $144 billion of private property insured by the Federal Flood Insurance Program (see Riebsame, Volume J).

Agriculture

In the last few years, droughts and heat waves have caused crop failures in many parts of the Southeast. Unlike much of the nation, cold weather generally is not a major constraint to agricultural production, except for Florida's citrus industry.

Although cotton and tobacco were once the mainstays of the Southeast's economy, agriculture now accounts for only 1% of the region's income (U.S. Department of Commerce, 1986). Since World War II, substantial amounts of farmland have been withdrawn from agriculture, and much of thus land has been converted to forest. The cotton crop has been largely lost to the irrigated Southwest, and although tobacco remains profitable, it is grown on only 500,000 acres. However, in the last few decades, southeastern farmers have found soybeans to be profitable; this crop now accounts for 45% of all cultivated land in the Southeast. Corn continues to account for 5% of southeastern agriculture U.S. Department of Commerce, 1982). Table 16-1 compares annual revenues by state for various crops.

Forests

The commercial viability of southeastern forests has increased greatly since World War 11, primarily as a result of the increased use of softwoods, such as pines and firs, for plywood and for applications that once required hardwood. Because this transition coincided with lower farm prices and declining soils in the piedmont foothills of the Southeast, many mountain farms have been converted to forests. However, in the last 10 years, 7 million acres of coastal plain forests have been converted to agriculture (Healy, 1985).

Approximately 45% of the nation's softwood (mostly loblolly pine) and 50% of its hardwood are grown in the region. Forests cover 60% of the Southeast, and 90% of forests are logged. Oak-hickory covers 35%, and pine covers another 33% of commercial forests. Only9% of the southeastern forests are owned by federal and state governments, and 18% are owned by the forest industry. In contrast, 73% of the forests are owned by farmers and other private parties (Healy, 1985).

Table 16-1. Annual Revenues by State for 33% of commercial forests. Only 9% of the Various Crops (thousands of 1986 southeastern forests are owned by federal and state dollars)

Crop	Value
Corn for grain	
Alabama	856,550
Florida	31,493
Georgia	203,931
Mississippi	22,600
North Carolina	324,789
South Carolina	104,333
Tennessee	193,687
Cotton	
Alabama	145,540
Florida	8,112
Georgia	97,325
Mississippi	449,630
North Carolina	30,944
Tennessee	109,610
Sugarcane for sugar and seed	
Florida	369,899
Tobacco	
Florida	NA
Georgia	NA
North Carolina	NA
South Carolina	NA
Tennessee	NA
Peanuts for nuts	
Alabama	133,930
Florida	48,600
Georgia	472,645
North Carolina	122,941
South Carolina	5,882
Soybeans	
Alabama	140,719
Florida	31,036
Georgia	179,676
Mississippi	365,018
North Carolina	196,673
South Carolina	125,214
Tennessee	230,373

NA= Not Available.

Source: U.S. Department of Agriculture (1987).

Indoor and Outdoor Comfort

The southeast is one of the few areas that spends as much money on air-conditioning as heating. Figure 16-2 shows temperatures throughout the Southeast for the months of January and July. Even in January, about half the region experiences average temperatures above 50°F. Thus, with the possible exception of the cool mountains of Tennessee and North Carolina, a global warming would increase the number of days during which outdoor temperatures would be unpleasantly hot much more than it would reduce the number of unpleasantly cold days.

PREVIOUS STUDIES OF THE IMPACTS OF CLIMATE CHANGE ON THE SOUTHEAST

Most studies examining the impact of global warming on the Southeast have focused on sea level rise. Recent efforts have addressed other topics. Several dozen researchers presented papers on other global warming impacts on the Southeast at a 1987 EPA conference held in New Orleans (Meo, 1987). Their papers suggested that agricultural yields would decline, forest species would shift, and that coastal and water supply officials should start to plan for the consequences of global warming.

Flooding

Leatherman (1984) and Kana et al. (1984) applied flood-forecasting models to assess potential increases in flooding in Galveston, Texas, and Charleston, South Carolina. For the Galveston area, a 90-centimeter (3-foot) rise would increase the 100-year floodplain by 50%, while a 160-centimeter (5.2-foot) rise would enable the 100-year storm to overtop the seawall erected after the disaster of 1900. For the Charleston area, a 160-centimeter rise would increase the 10-year floodplain to the area currently covered by the 100year floodplain.

Gibbs (1984) estimated that the economic impact of a 90-centimeter rise by 2075 could be as great as $500 million for Galveston and over $1 billion for Charleston. However, he also estimated that the adverse impacts of flooding and land loss could be cut in half if the communities adopted measures in anticipation of sea level rise. Titus (1984) focused on decisions facing

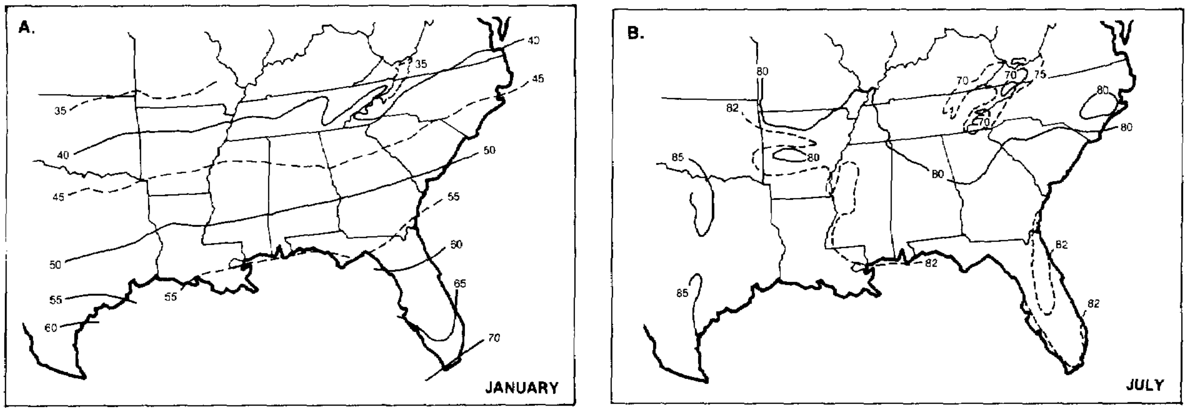

Figure 16-2. Typical temperatures in the Southeast: (A) January, (B) July.

Sullivans Island, South Carolina, in the aftermath of a storm. He concluded that rebuilding $15 million in oceanfront houses after a storm would not be economically sound if future sea level rise is anticipated, unless the community is prepared to continuously nourish its beaches.

Wetlands

Kana et al. (1986) surveyed marsh transects and estimated that 90- and 160-centimeter (3.0- and 5.2-foot) rises in sea level would drown 50 and 90%, respectively, of the marsh around Charleston, South Carolina. Armentano et al. (1988) estimated the Southeast would lose 35 and 70% of its coastal wetlands for respective rises of 1.4 and 2.1 meters, assuming that developed areas are not protected.

Infrastructure

The Louisiana Wetland Protection Panel (1987) concluded that a rise in sea level might necessitate substantial changes in the ports and shipping lanes of the Mississippi River to prevent the loss of several thousand square miles of coastal wetlands. Titus et al. (1987) showed that a reconstructed coastal drainage system in Charleston should be designed for a 1-foot rise in sea level if the probability of such a rise is greater than 30%. Linder et al. (1988) found that warmer temperatures would require an electric utility company to substantially increase its generating capacity.

CLIMATE CHANGE STUDIES IN THIS REPORT

Table 16-2 and Figure 16-3 illustrate the studies undertaken as part of this effort. Few resources had previously been applied to examining the various impacts of climate change for the Southeast. Models of coastal erosion, coastal wetland loss, agricultural yields, forest dynamics, and electricity consumption were sufficiently refined, so that it was possible to inexpensively apply them to numerous sites and develop regional assessments. Louisiana, which accounts for half of the region's wetlands, has been the subject of previous studies. It is discussed following the studies for this report.

By contrast, the impacts on water resources and ecosystems required more detailed site-specific studies, and it was not possible to undertake such case studies for a large number of watersheds or ecosystems. Therefore, our analysis was limited to representative case studies. For water resources, we picked (1) the Tennessee Valley, because it is the largest managed watershed in the region; and (2) Lake Lamer, because it serves Atlanta, the region's second largest city. In both cases, we were able to identify researchers who were already familiar with the area. The sole aquatic ecosystem studied in depth was Apalachicola Bay, picked because the estuary had already been the subject of the most comprehensive data collection effort in the Southeast.

Table 16-2. Studies of the Southeast

Regional Studies

- Impacts on Runoff in the Upper Chattahoochee River Basin - Hains, C.F. Haines, Hydrologist, Inc. (Volume A)
- Projected Changes in Estuarine Conditions Based on Models of Long-Term Atmospheric Alteration - Livingston, Florida State University (Volume E)
- Policy Implications of Global Climatic Change Impacts Upon the Tennessee Valley Authoriy Reservoir System, Apalachicola River, Estuary and Bay and South Florida - Meo, Ballard, Deyle, James, Malysa, and Wilson, University of Oklahoma (Volume J)
- Potential Impacts on Climatic Change on the Tennessee Valley Authority Reservoir System -Miller and Brock, Tennessee Valley Authority (Volume A)
- Impact of Climate Change on Crop Yield in the Southeastern U.S.A. - Peart, Jones, and Curry, University of Florida (Volume C)
- Methods for Evaluating the Potential Impacts of Global Climate Change - Sheer and Randall, Water Resources Management, Inc. (Volume A)
- Forest Response to Climate Change: A Simulation Study for Southeastern Forests - Urban and Shugart, University of Virginia (Volume D)

National Studies That Included Southeast Results

- The Economic Effects of Climate Change on U.S. Agriculture: A Preliminary Assessment - Adams, Glyer, and McCarl, Oregon State University (Volume C)
- National Assessment of Beach Nourishment Requirements Associated with Accelerated Sea Level Rise - Leatherman, University of Maryland (Volume B)
- The Potential Impacts of Climate Change on Electric Utilities: Regional and National Estimates -Linder and Inglis, ICF Inc. (Volume H)
- The Effects of Sea Level Rise on U.S. Coastal Wetlands -Park and Trehan, Butler University and Mausel and Howe, Indiana State University (Volume B)
- Potential Effects of Climatic Change on Plant-Pest Interactions - Stinner, Rodenhouse, Taylor, Hammond, Purrington, McCartney, and Barrett, Ohio Agricultural Research and Development Center (Volume C)
- Assessing the Responses of Vegetation to Future Climate Change: Ecological Response Surfaces and Paleoloocal Model Validation - Overpeck and Bartlein, Lamont-Doherty Geological Observatory (Volume D)
- An Overview of the Nationwide Impacts of Rising, Sea Level - Titus and Greene, U.S. Environmental Protection Agency (Volume B)
- The Cost of Defending Developed Shorelines Along Sheltered Waters of the United States from a Two Meter Rise in Mean Sea Level - Weggel, Brown, Escajadillo, Breen, and Doheny, Drexel University (Volume B)

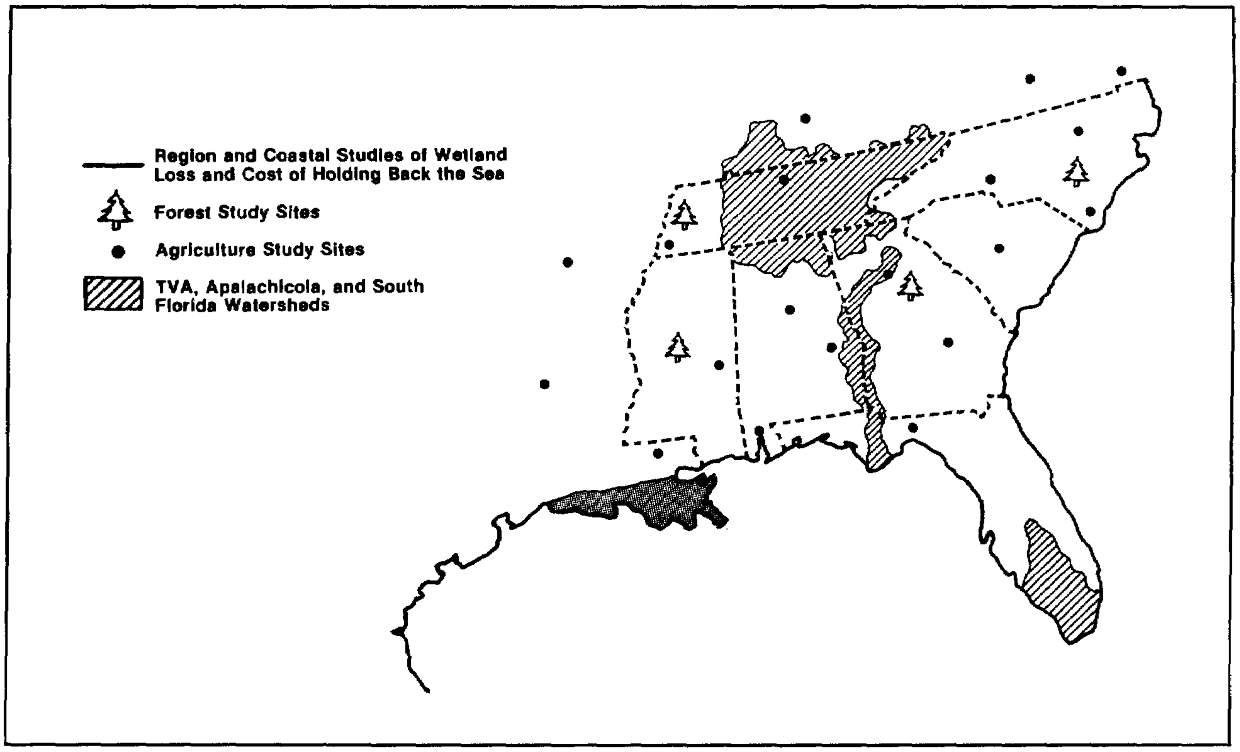

Figure 16-3. Overview of studies of the Southeast.

SOUTHEAST REGIONAL CLIMATE CHANGE SCENARIOS

Figure 16-4 illustrates the scenarios of future climate change from general circulation models. Table 16-3 shows the more detailed seasonal changes.

Table 16-3 illustrates how the frequency of mild days during the winter and the frequency of very hot days during the summer might change under the Goddard Institute for Space Studies (GISS) doubled CO$_2$ scenario. As explained in Chapter 4: Methodology, these estimates used average monthly changes in temperature and assumed no change in variability. Under this scenario, the number of days per year in which the mercury would fall below freezing would decrease from 34 to 6 in Jackson, Mississippi; from 39 to 20 in Atlanta; and from 41 to 8 in Memphis. The number of winter days above 70°F would increase from 15 to 44 in Jackson, from 4 to 14 in Atlanta, and from 5 to 24 in Memphis.

Of the nine cities shown, only Nashville has summer temperatures that currently do not regularly exceed 80°F. However, the number of days with highs below 80°F would decline from 60 to 34. Elsewhere, the heat would be worse. The number of days per year above 90°F would increase from 30 to 84 in Miami, from 17 to 53 in Atlanta, and from 55 to 85 in New Orleans. Memphis, Jackson, New Orleans, and Jacksonville, which currently experience 0 to 3 days per year above 100°F, would have 13 to 20 such days (Kalkstein, Volume G).

RESULTS OF SOUTHEASTERN STUDIES

Coastal Impacts

A number of national studies for the report presented results for the effects of climate change on the southeastern coast. Leatherman estimated the cost of maintaining recreational beaches. Park et al. and Weggel et al. examined the impacts on wetland loss and shoreline defense, and used their results to estimate the regionwide cost of raising barrier islands. The projected

Table 16-3. The GISS Doubled $_{CO2}$ Scenario: Frequency of Hot and Cold Days (°F)

Location	Number of winter days with:				Number of summer days with:					
	Daily low <32		Daily high >70		Daily high <80		Daily high >90		Daily high >100	
	HIST[a]	$2x_{CO2}$	HIST[a]	$2x_{CO2}$	HIST[a]	$2x_{CO2}$	HIST[a]	$2x_{CO2}$	HIST[a]	$2x_{CO2}$
Atlanta, GA	38.3	20.5	4.2	13.6	10.0	2.2	17.1	53.3	0.6	4.2
Birmingham, AL	35.5	8.1	7.1	30.7	4.5	0.4	34.1	72.5	1.5	10.7
Charlotte, NC	42.1	23.8	3.4	9.9	11.9	3.7	23.1	56.5	0.1	5.9
Jackson, MS	33.5	5.9	15.3	43.5	0.8	0.2	55.1	83.1	2.0	19.5
Jacksonville, FL	9.3	1.7	34.6	49.6	2.3	0.3	46.4	81.3	0.6	14.1
Memphis, TN	41.2	8.1	5.2	23.6	4.9	0.7	50.5	74.8	2.6	19.1
Miami, FL	0.2	0.0	72.9	82.7	0.6	0.0	29.8	83.5	0.0	2.5
Nashville, TN	42.5	15.4	0.3	8.6	60.4	33.7	10.5	20.2	0.3	3.5
New Orleans, LA	14.9	3.5	24.9	39.5	0.9	0.1	55.4	84.9	0.3	13.5

HIST[a] = Historic.
Source: Kalkstein (Volume G).

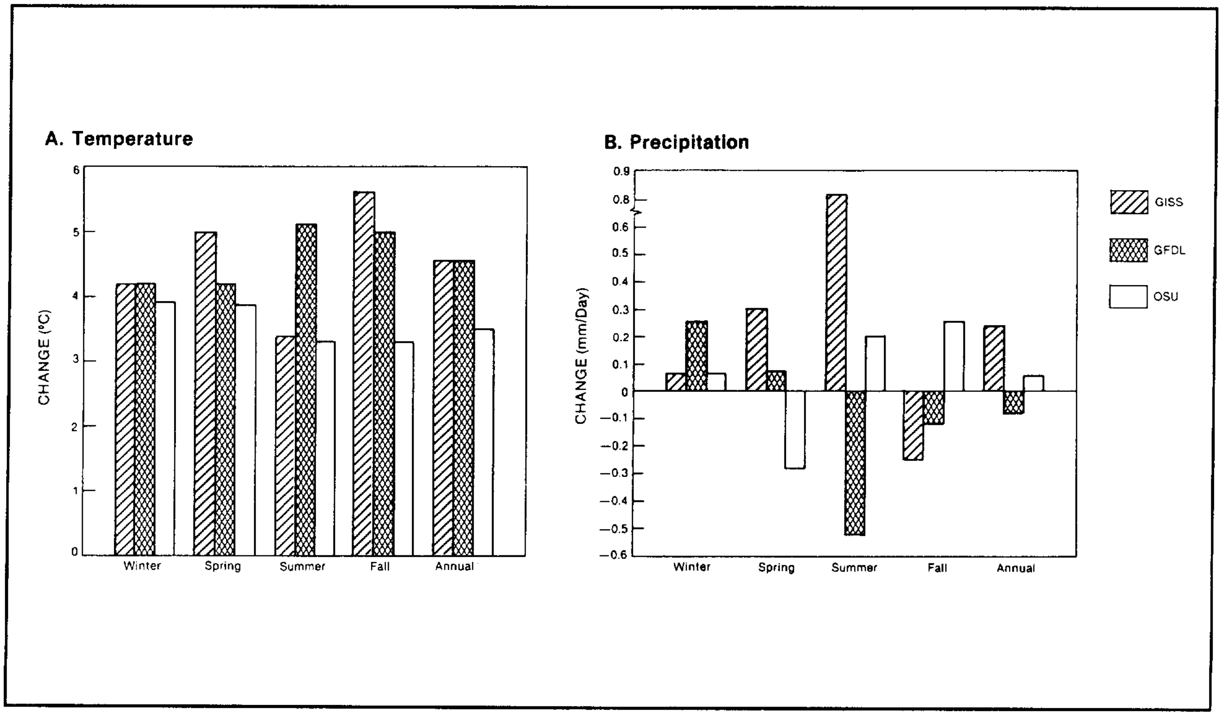

Figure 16-4. $2xCO_2$ less $1XCO_2$ climate scenarios for the Southeast: (A) temperature, and (B) precipitation..

rise in sea level would cause shorelines to retreat, exacerbate coastal flooding, and increase the salinity of estuaries, wetlands, and aquifers. (For a discussion of the rationale, methods, and nationwide results of these studies, see Chapter 7: Sea Level Rise.)

Coastal Wetlands

Park et al. (Volume B) examined 29 southeastern sites to estimate the regionwide loss of coastal wetlands for a variety of scenarios of future sea level rise. Their analyses included such societal responses as providing structural protection for all shorelines (total protection), protecting areas that are densely developed today (standard protection), and allowing shorelines to adjust naturally without coastal protection (no protection).

Figure 16-5 illustrates their estimates for the year 2100 for the various scenarios of sea level rise and coastal defense. Even if current sea level trends continue, 25% of the Southeast's coastal wetlands will be lost, mostly in Louisiana. Excluding Louisiana:

- current trends imply a loss of 15%;
- a 50-centimeter rise could result in a loss of 35 to 50%, depending on how shorelines are managed;
- a 100-centimeter rise could result in losses of 45 to 68%; and
- a 200-centimeter rise implies losses of 63 to 80%.

Park et al. estimated losses of 50, 75, and 98% for Louisiana under the three scenarios. However, they did not consider the potential for mitigating the loss by restoring the flow of river water into these wetlands; no model exists that could do so (Louisiana Wetland Protection Panel, 1987). Titus and Greene estimated statistical confidence intervals illustrated in Table 16-4.

Total Coastal Land Loss

Park et al. also estimated total land loss, including both wetlands and dryland. Most of the land loss from a rise in sea level would occur in Louisiana. A 50-centimeter (20-inch) sea level rise would result in the loss of 1,900 to 5,900 square miles of land, while a 200-centimeter rise would inundate 10,000 to 11,000 square miles.

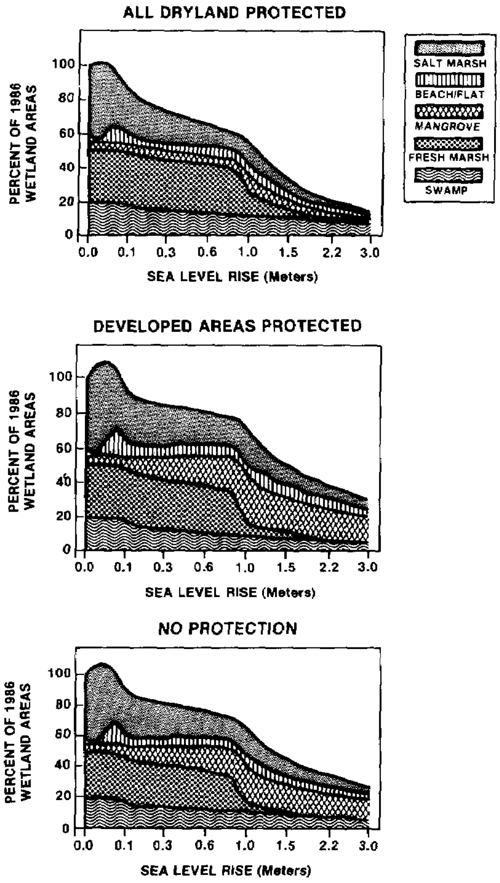

Figure 16-5. Wetlands loss in the Southeast for three shoreline protection options (Park et al., Volume B). (NOTE: These numbers are different from those in Table 16-4 because they include nonvegetated wetlands, i.e., beaches and flats.)

Cost of Protecting Recreational Beaches

In Volume B, Leatherman notes that the projected rise in sea level would threaten all developed recreational beaches. Even a 1-foot sea level rise would erode shorelines over 100 feet throughout the Southeast. Along the coasts of North Carolina and Louisiana, the erosion would be considerably greater. Because the distance from the high tide line to the first building is rarely more than 100 feet, most recreational beaches would be lost, unless either the buildings were removed or coastal protection measures were undertaken.

Table 16-4 illustrates Leatherman's estimates of the cost of protecting recreational beaches by pumping sand from offshore locations. (See Table 7-3 for state-by-state results). A 1-meter rise in sea level could imply almost $20 billion in dredging costs, with Texas spending $8.5 billion and Florida and Louisiana each spending over $3 billion.

Using constant unit costs (except for Florida), Leatherman estimated that a 2-meter rise could only double the total cost to $43 billion. Titus and Greene estimated that if the unit costs of sand increased, 1- and 2-meter rises could cost $30 and $74 billion, respectively. They also estimated that the respective costs of rebuilding roads and utilities on barrier islands could be $5 to 9 billion, $10 to 40 billion, and $60 to 75 billion for the three scenarios.

Cost of Protecting Calm-Water Shorelines

While Leatherman focused only on the open ocean coast, Weggel et al. estimated the regionwide costs of holding back the sea in developed sheltered and calm-water areas. Weggel et al. estimate that about $2 billion would be spent to raise roads and to move structures, and $23 billion would be spent to erect the necessary levees and bulkheads for a 2meter rise. Table 16-4 shows confidence intervals estimated by Titus and Greene, which imply a total cost of $42 to 75 billion for a 1- meter rise. The combined cost is $68 to 83 billion. These estimates do not include the costs of preventing flooding or of protecting water supplies.

Table 16-4. Summary of Results of Sea Level Rise Studies for the Southeast (billions of dollars)

Response	Baseline	50-cm rise	100-cm rise	200-cm rise
Developed areas are protected				
Land lost				
Dryland lost (mi^2)	1,300-3,700	1,900-5,500	2,600-6,900	4,200-10,100
Wetlands lost (%)[a]	11-22	24-50	34-77	40-90
Cost of coastal defense		19-28	42-75	127-174
Open coast				
Sand	3	10-15	19-30	44-74
Elevated structures	negligible[b]	5-9	10-40	60-75
Sheltered shores	negligible[b]	2-5	5-13	9-41
All shores are protected				
Land lost				
Dryland lost (mi^2)				
Wetlands lost (%)[a]	0	0	0	0
No shores are protected	0	38-61	47-90	68-93
Land lost				
Dryland lost (mi^2)	N/A	2,300-5,900	3,200-7,600	4,800-10,800
Wetlands lost (%)[a]	N/A	22-48	30-75	37-88

[a] “Wetlands” refers to vegetated wetlands only; it does not include beaches or tidal waves.

[b] Costs due to sea level rise are negligible.

Source: Titus and Greene (Volume B).

Tennessee Valley Authority Studies

The Tennessee Valley Authority (TVA) was created in 1933 to spur economic growth in an area previously considered to be one of the nation's poorest. Geographically isolated by the Appalachian Mountains, the region lacked electricity and roads, and the Tennessee River could not provide reliable transportation because it flooded in the spring and dried to a trickle during the summer. By creating the TVA, Congress sought to remedy this situation by harnessing the river to provide electricity, to prevent the flooding that had plagued Chattanooga, and to ensure sufficiently stable riverflows that would permit maintenance of a 9-foot-deep navigation channel.

The region administered by the TVA covers 40,000 square miles and includes parts of seven states. In the last half century, the TVA has coordinated the construction of 43 major dams along the river and its tributaries, many of which are shown in Figure 16-6. The system provides power to over 7 million people and contains 675 miles of navigable waterways with annual commercial freight of 28 million tons. The lakes created by the dams have over 10,000 miles of shorelines, which generate 75 million visits each year and along which people have invested $630 million, boosting the region's annual economy by $400 million (Miller and Brock, Volume A).

To assess the potential impacts of climate change, Miller and Brock conducted a modeling study of the water resource implications, and Meo et al. examined the policy implications for the TVA.

TVA Modeling Study

Methods

Miller and Brock used the TVA's "Weekly Scheduling Model," which the Agency currently uses in setting the guidelines for its operations, to assess the impacts of climate change. This linear programming model selects a weekly schedule for managing each reservoir in the TVA system by sequentially satisfying the objectives of flood control, navigation, water supply, power generation, water quality, and recreation. Miller and Brock used this model to simulate reservoir levels, riverflows, and hydropower generation for wet and dry scenarios, derived from the runoff estimates from the GISS doubled CO_2 model run.

TVA was unable to use a hydrologic model to estimate runoff for this study. Instead, they sought to use the runoff estimates from general circulation models. Unfortunately, the OSU and GFDL models estimate that there is no runoff today, which would not permit derivation of a scenario. Therefore, the GISS runoff estimates were used as the "wet scenarios." Based on Rind (1988), the dry scenario simply assumed that the change in runoff would be the inverse of the change assumed in the wet scenario. Therefore, a TVA study should be viewed as an assessment of the system's sensitivity to climate change, not as the literal implications of particular general circulation models.

Miller and Brock assessed the potential impacts of climate change on flood levels in Chattanooga, Tennessee, using a model that had been developed to estimate the constraints on weekly tributary releases. They also estimated the potential implications for water quality in the Upper Holston Basin of the valley, using a reservoir water quality model, a riverflow model, and a water quality model that TVA has used in the past to determine the environmental constraints affecting riverflow.

Limitations

Because the riverflow scenarios were not based on hydrologic analysis, conclusions cannot be drawn regarding the sensitivity of riverflow to climate change; a more thorough study should apply a basinwide hydrologic model to the region. A key limitation for the flood analysis was that EPA assumed that every storm in a given month would result in a change in riverflow proportional to the change in monthly runoff rather than incorporating potential changes in flood frequency and intensity. (For climate change scenarios, see Chapter 4: Methodology.) Finally, the study assumed that TVA would not mitigate impacts by changing its operating rules for the reservoirs in response to climate change.

Results

Reservoir levels

Figure 16-7 shows the estimates of the changes in reservoir levels in the Norris Reservoir for the wet and dry scenarios. Currently, water levels are typically

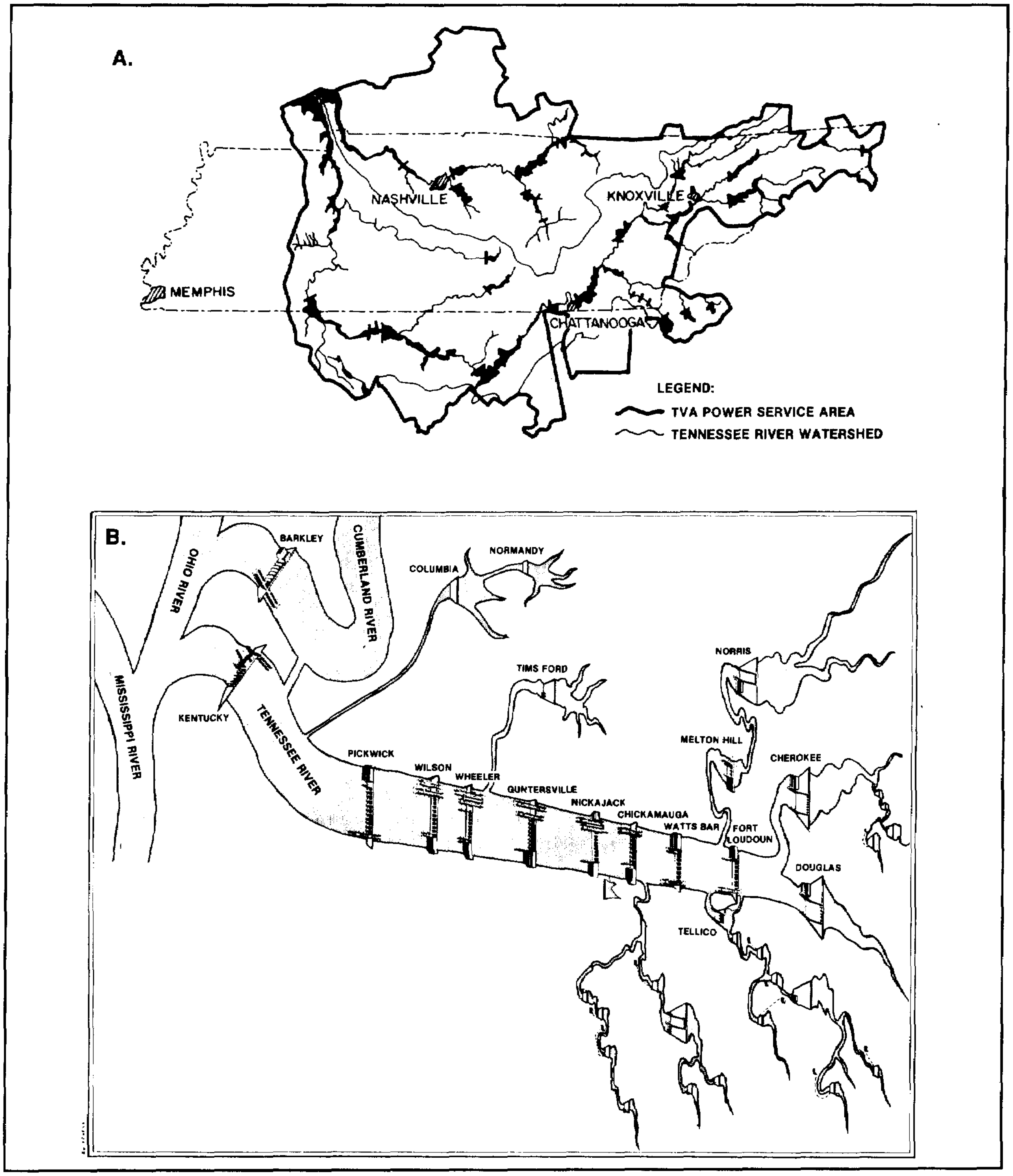

Figure 16-6. (A) Map of the TVA region, and (B) schematic of the TVA reservoir system (Miller and Brock, Volume A).

above 1,010 feet (NGVD) from early May to early August. Under the wet scenario, the water would generally be above this level from early April to early September; during the driest years (1%), the water levels would be similar to the current normal level between May and October. In the dry scenario, water levels would never exceed 1,005 feet in a typical year, and even during the wettest years (1%) they would barely exceed the current normal condition between April and September.

Changes in lake levels of this magnitude would have important implications for recreation in the Tennessee Valley, which is supported by facilities worth over $600 million. Even today, recreation proponents are concerned with reservoir levels dropping during some summers. Miller and Brock found that the wet scenario would largely eliminate current problems with low lake levels; in contrast, the dry scenario would make these problems the norm.

Water Quality

Miller and Brock found that a drier climate could also create environmental problems. Lower flows would reduce the dilution of municipal and industrial effluents discharged into the river and its tributaries. Moreover, because water would generally remain at the bottom of reservoirs for a longer period of time, the amount of dissolved oxygen could decline; this would directly harm fish and reduce the ability of streams to assimilate wastes. Miller and Brock concluded that the water supplies from TVA would probably be sufficient, but that TVA could experience operational difficulties and customer dissatisfaction due to degraded water quality. During extended low-flow conditions, wastes would have increased opportunities to backflow upstream to water supply intakes.

Flooding

Although a drier climate could exacerbate many current problems facing TVA, a wetter climate could create difficulties, particularly the risk of flooding, in matters that are currently under control. Miller and Brock found that in the wet scenario, during exceptionally wet years, storage would be inadequate at the tributary reservoirs; this condition could result in uncontrolled spillage over dams. A high probability of flooding would also exist at Chattanooga. Miller and Brock examined the levels of the five worst floods of the last 50 years at Chattanooga, which did not overflow the banks of the Tennessee River or flood the city. However, under the wet scenario, two of the floods would overtop the banks. The worst flood could reach a level of 56.3 feet and cause over $1 billion in damages; the second worst could reach a level of 46 feet and cause over $200 million in damages (see Figure 16-8).

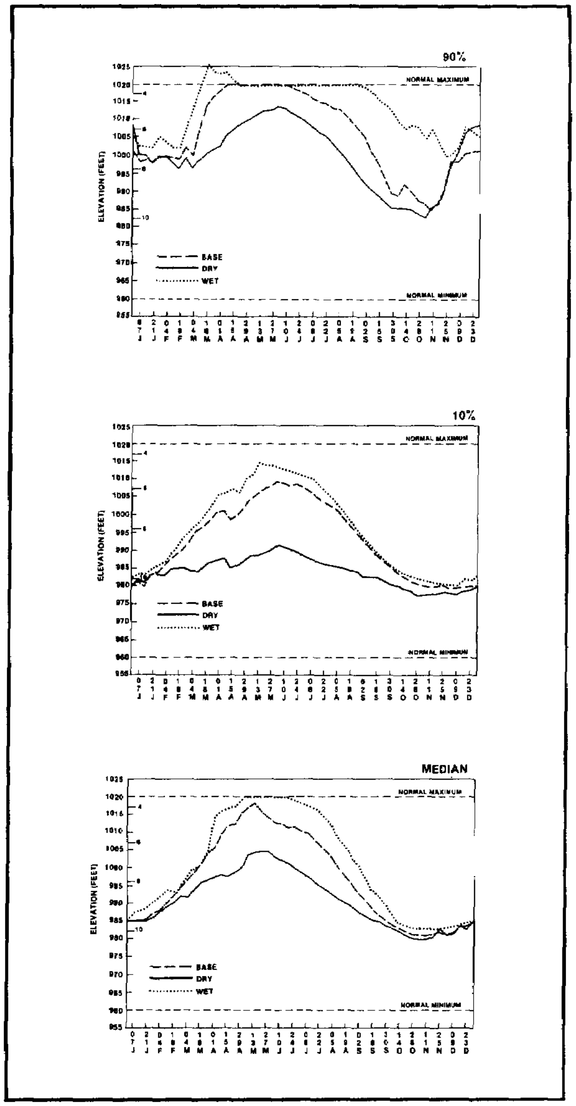

Figure 16-7. Water levels in Norris Reservoir under climate scenarios: (A) 10% wet test years; (B) median; and (C) 10% driest years (adapted from Miller and Brock, Volume A).

Flooding could be reduced if operating rules were modified to keep water levels lower in reservoirs on tributaries (although this would diminish the hydropower benefits from a wetter climate). However, changes in operating rules would not be sufficient to protect Chattanooga from being flooded during a repeat of the worst storm, because rainfall would be largely concentrated over the "mainstem" reservoirs, which do not have substantial flood-control storage.

Power Generation

Miller and Brock calculated that the wet and dry scenarios imply, respectively, an annual increase of 3.2megawatt-hours (16%, $54 million per year) and a decrease of 4.6 megawatt-hours (24%, $87 million per year), given current capacity and operating rules.

Climate change could also have an impact on fossil-fuel powerplants. If river temperatures become warmer, they will require additional dilution water. Although sufficient water would be available if the climate became wetter, meeting minimum flow requirements would be more difficult if climate became drier. Miller suggested that the most feasible operational change would be to cut back power generation at fossil-fuel powerplants during periods of low flow. However, hydropower production would also be reduced during periods of low flow, so cutting back production might not be acceptable. One alternative would be to construct cooling towers, which would eliminate discharges of hot water, at a capital cost of approximately $75 million.

<u>Tennessee Valley Policy Study</u>

Meo et al. (Volume J) analyzed the history, statutory authority, and institutional structure of the TVA to assess the ability of the organization to respond to climate change. Their analysis relied both on the available literature and on interviews with a few dozen officials of TVA and states within the region. They divided the possible responses of TVA into two broad categories: (1) continuing the current policy of maximizing the value of hydroelectric power, subject to the constraints of flood control and navigation; and (2) modifying priorities so that power generation would be subordinated to other objectives if doing so would yield a greater benefit to the region. They concluded that if the climate became wetter, current policies would probably be adequate to address climate change because the only adverse effect would be the risk of additional flooding, which is already a top priority of the system.

If climate became drier, on the other hand, existing policies might be inadequate, because they require power generation to take precedence over many of the resources that would be hardest hit. Although they expect that the TVA will be more successful at addressing future droughts, Meo et al. found that during the 1985-86 drought, falling lake levels impaired recreation and reduced hydropower generation, forcing the region to import power while five powerplants sat idle. Meo et al. point out that groundwater tables are falling in parts of the region, in part because numerous tributaries recharge the aquifers whenever water is flowing but are allowed to run dry when water is not being released for hydropower. They suggest that even without climate change, the deteriorating groundwater quality and availability are likely to lead a number of communities to shift to surface water supplies in the coming decades, adding another use that must compete for the water that is left over when the demands for power have been met. Even with current climate, they contend, the TVA should assess whether other uses of the region's water resources would benefit the economy more. If climate becomes drier, the need for such a reevaluation will be even more necessary.

Studies of the Impacts on Lake Lanier and Apalachicola Bay

Figure 16-9 shows the boundaries of the 19,800-square-mile Chattahoochee- Flint Apalachicola River Basin. The U.S. Army Corps of Engineers and others who manage the Chattahoochee River as it passes through Lake Lamer on its way to the Apalachicola estuary and the Gulf of Mexico face many of the same issues as those faced by the TVA. However, they also are managing the water supply of Atlanta, the second largest city in the Southeast, and the flow of water into an estuary that supports the most productive fishery in Florida (U.S. Department of Commerce, 1988).

A number of researchers were involved in EPA's assessment of the potential implications of climate change for this watershed. A study of Lake Lamer and a study of the implications for the fish in Apalachicola Bay are discussed in the following sections of this chapter.

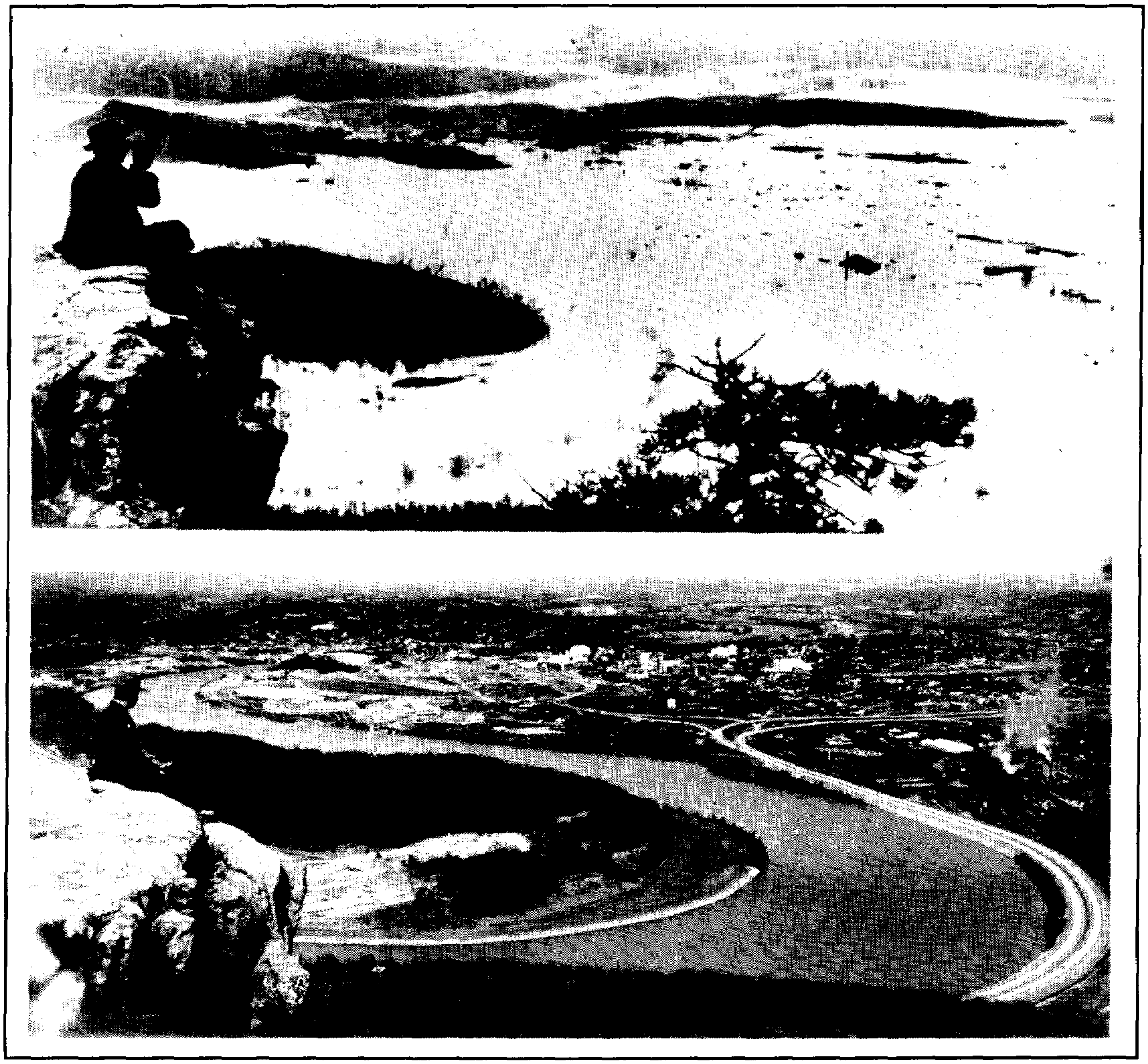

Figure 16-8. Chattanooga was vulnerable to flooding until the TVA system of dams was constructed. The upper photo shows the 1867 Flood, with water levels similar to those projected by the Miller and Brock under the wet scenario (Miller and Brock, Volume A).

Lake Lanier

Lake Lanier, located 30 miles northeast of Atlanta, is a source of water for the city and nearby jurisdictions. Federal statutes require the U.S. Army Corps of Engineers to manage Lake Lanier to provide flood control, navigation, and hydropower. Nevertheless, the lake is also managed to meet nonstatutory objections such as recreation, minimum flows for environmental dilution, and water supply.

Since Lake Lanier was dammed in 1957, the statutory objectives of flooding and navigation have been met; annual hydropower generation has been 134

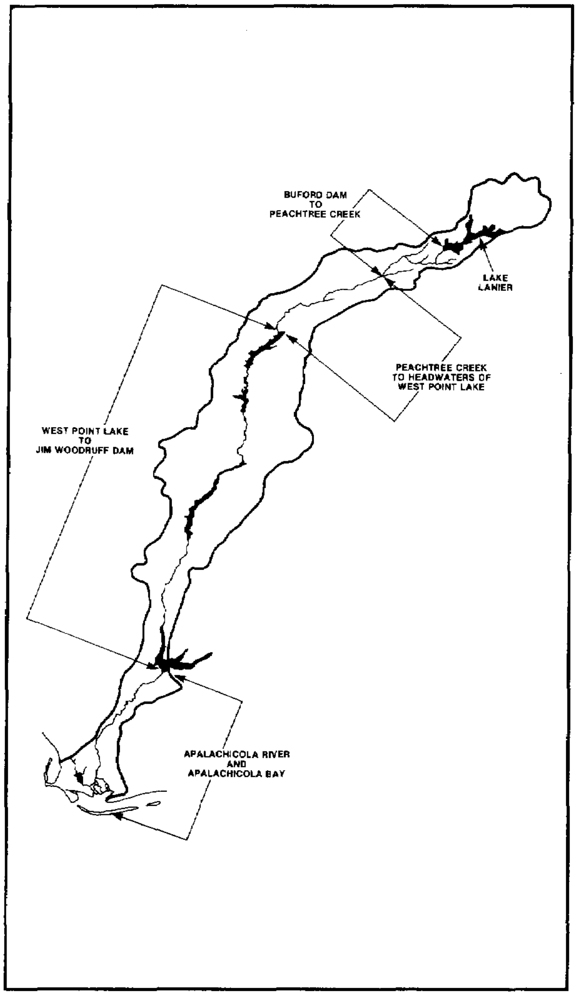

Figure 16-9. Drainage area of the Apalachicola-Chattahoochee-Flint River system.

MWH[3], equal to 2% of today's power requirements for Atlanta; and the releases of water have fulfilled the additional minimum flow needed to dilute the effluents from sewage treatment plants.

During the last two decades, the lake's shoreline has been substantially developed with marinas, houses, and hotels. To a large degree, the residents have become accustomed to the higher water levels that prevailed from the 1970s through 1984. Droughts from 1985 to the present, however, have lowered lake levels, disrupting recreation. In the summer of 1986, navigation for recreational boats located downstream of the lake was curtailed because of minimal releases from the lake. In 1988, Atlanta imposed water-use restrictions, with the objective of cutting consumption by 10 to 20%. A bill has been introduced to add recreation to the list of statutory purposes (HR-4257).

Runoff in the Chattahoochee River Basin

Study Design. Hains estimated runoff in the Chattahoochee River Basin and the flow of water into Lake Lanier for the three scenarios. He calibrated the Sacramento hydrology model developed by the National Weather Service (Burnash et al., 1973) to the conditions found in the watershed of the upper Chattahoochee River. He then generated scenarios of riverflow for the baseline climate and the GCM scenarios.

Limitations. The Sacramento model was designed primarily for flood forecasting, not base flow. In addition, the model was calibrated using the data on evaporation of water from pans, which is not perfectly correlated with evapotranspiration, and these data came from a nearby watershed.

Since the analysis was based on scenarios of average monthly change, it did not consider potential changes in variability of events such as floods. The analysis did not incorporate changes in vegetation, which could affect runoff.

Results. As with the Tennessee River, the major climate models disagree on whether the Chattahoochee watershed would become wetter or drier with an effective doubling of greenhouse gases. Hains estimated that under the wetter GISS scenario, the average annual riverflow of the Chattahoochee River would increase by 13%; the drier OSU and GFDL models imply declines of 19 and 27%, respectively, as shown in Figure 16-10. The GISS scenario implies slight decreases in winter flow and increases the rest of the year. Under the GFDL scenario, these substantial decreases were estimated throughout the year, with almost no flow in late summer. The OSU scenario also shows reductions, but the reduction is greatest during the flood season (February to May) and negligible

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[3] Personal communication from Harold Jones, Systems Engineer, Southeast Power Administration, Department of Energy, September 12, 1988.

during the dry season (late summer/early fall).

Management of Lake Lanier

Study Design. Sheer and Randall (Volume A) examined the implications for water management of the riverflow changes estimated by Hains. They modified a monthly water balance model/operations model previously applied in southern California for the lake, based on current operating rules for the reservoir. For the first set of runs, the model assumes that (1) minimum flows are maintained for navigation and environmental dilution at all times, (2) lake levels are kept low enough to prevent flooding, (3) historic rates of consumption continue, and (4) peak hydropower generation is maximized. To ensure that the assumptions adequately reflect the actual decision rules used by water managers, Sheer and Randall reviewed the rules with local officials from the U.S. Army Corps of Engineers, the Atlanta Regional Council, and others responsible for managing the water supply. In a second set of runs, they examined the impacts of climate change under alternative operating rules that assume recreation is also a statutory objective.

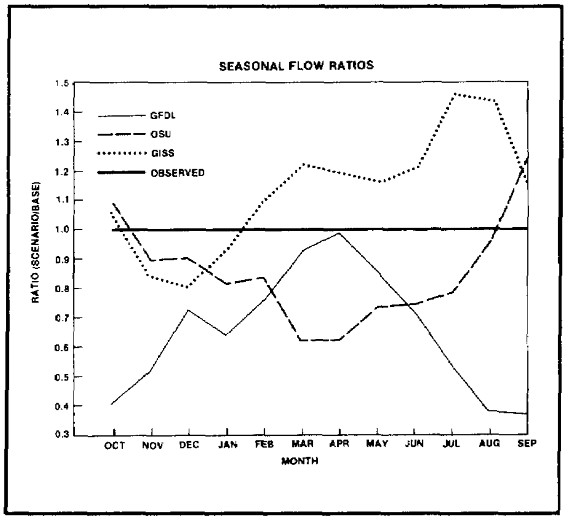


Figure 16-10. Ratios of flow under doubled CO_2 scenarios to base case in Upper Chattahoochee River.

Limitations. Sheer and Randall did not consider changes in demand for water due to climate change or population growth; thus, it produces high estimates of future water availability under all scenarios. Moreover, the results were not compared with historic lake levels.

Results. Figure 16-11 shows the Sheer and Randall estimates of lake levels; Figure 16-12 shows quarterly hydropower production. Under the relatively wet GISS scenario, annual power production could increase by 9%. The higher streamflows in this scenario would still be well below those that occasionally occurred before Lake Lamer was closed; hence, no significant threat of flooding would exist for a repeat of the climate of 1951-80. Under the relatively dry GFDL scenario, however, power production could drop 47%, and lake levels would be likely to drop enough to substantially disrupt recreation. This scenario assumes that Atlanta would continue to take as much water as it does currently (allowing for growth would increase water supply problems).

Sheer and Randall also examined the implications of making recreation a statutory objective. Although it would be possible to maintain lake levels, Atlanta's water supply would be threatened. With the current climate, strict enforcement of such a policy would result in Lake Lanier supplying no water to metropolitan Atlanta for 8 months of every 30 years. Although under the GISS scenario this would be reduced to 1 month, under the dry GFDL scenario, Atlanta would have to use an alternative source of water 1 to 3 months each summer.

Implications. Climate change combined with population growth may require water managers to reexamine the tradeoffs between the various uses of the Chattahoochee River and Lake Lanier. A number of local water officials who met with Sheer suggested that an appropriate response to changing water availability might be to relax minimum flow requirements for navigation and environmental quality. They reasoned that minimum flows for environmental purposes are based on the assumption that sewage treatment plants are discharging at their maximum rates and that temperatures are high, conditions that are usually not met. They also argued that little is accomplished by maintaining minimum flows for navigation because ship traffic is light in the lower Chattahoochee. Others argued, however, that it would be unwise to assume that minimum flows could be decreased because future growth may increase the need for dilution of effluents, and warmer temperatures would speed biological activity. The likely impacts of climate change on Apalachicola Bay may also increase the need to

Figure 16-11. Lake Lanier elevation (September) under doubled CO_2 scenarios (Sheer and Randall, Volume A).

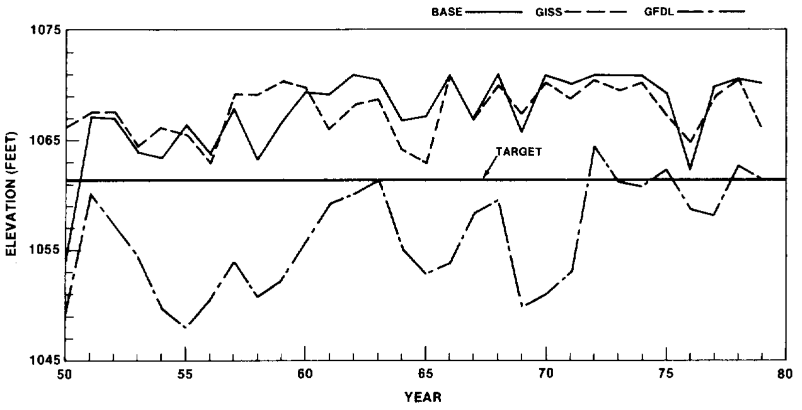
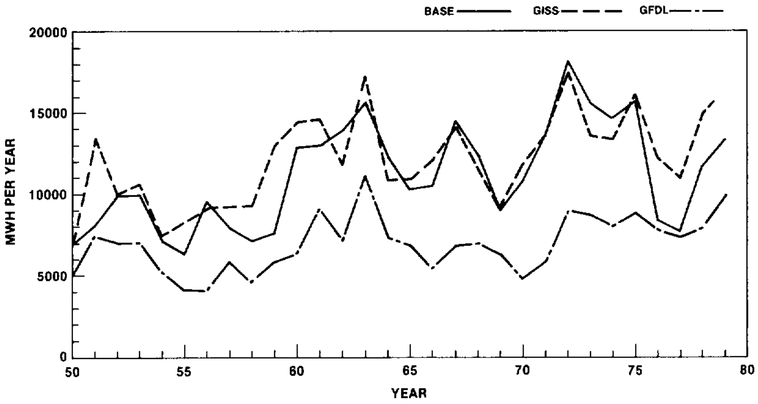


Figure 16-12. Lake Lanier power generation under doubled CO_2 scenarios (Sheer and Randall, Volume A).



maintain minimum flows.

Apalachicola Bay

Apalachicola Bay supports hundreds of commercial fishermen; over 80% of Franklin County earns a livelihood from the bay (Meo et al. Volume J). The contribution of fishing to the area was estimated at $20 million for 1980, representing 90% of Florida's oyster harvest and 10% of its shrimp harvest. This figure is projected to grow to $30 to $60 million by 2000.

Although the state has purchased most of the land that is not part of a commercial forest, economic pressures on forestry companies to sell land for coastal development are increasing. In 1979, the National Oceanic and Atmospheric Administration created the Apalachicola National Estuarine Sanctuary to prevent development from encroaching into this relatively pristine estuarine environment.

The biology of the Apalachicola Bay estuary may be affected by higher temperatures, higher sea levels, and different flows of water into the Apalachicola River. Hains estimated the flow of the Apalachicola River, and Park et al. estimated wetland loss due to sea level rise. Livingston used both of these results and the temperature change scenarios to evaluate the potential impacts on the bay's fish populations.

Sea Level Rise

The methods of Park et al. for estimating wetland loss are described in Chapter 7: Sea Level Rise.

They estimated that a 1-meter rise in sea level would inundate approximately 60% of the salt marshes in Apalachicola Bay, and that mangrove swamps, which are rarely found outside southern Florida today, would replace the remaining salt marsh. Table 16-5 illustrates their estimates.

Apalachicola Riverflow

Study Design. Hains estimated the impact of climate change on riverflow, using a regression model, which is simpler than the Sacramento model he used for the Chattahoochee River analysis. The regression expressed the logarithm of riverflow as a function of the logarithms of precipitation and evapotranspiration for a few weather stations located in the basin.

Limitations. Hains' procedure greatly oversimplified the relationships between the causal variables and riverflow, ignoring the impacts of reservoir releases and the failure of the relationships to fit the simple log-linear form. These results should be interpreted as an indication of the potential direction of change.

Results. Figure 16-13 illustrates Hains' estimates of average monthly flows for the Apalachicola estuary. Annual riverflow would decrease under all scenarios, although it would increase in the summer and fall for the GISS and OSU scenarios, respectively.

Figure 16-13. Doubled CO_2 flow into Apalachicola Bay (Hams, Volume A).

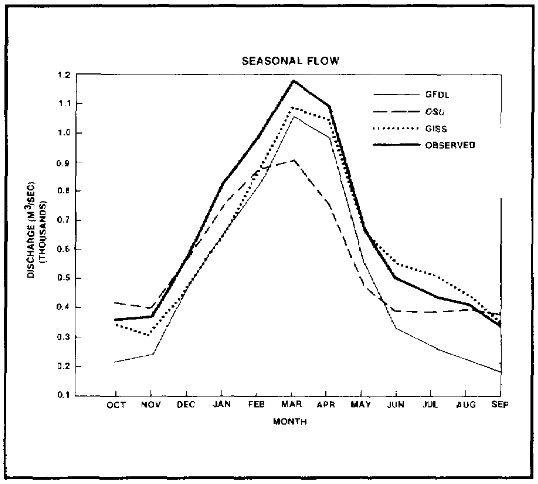


Table 16-5. Remaining Coastal Wetlands in Apalachicola Bay in the Year 2100 (hectares)

Area	1987	Current area sea level rise	50-cm rise	100-cm rise	200-cm rise
Swamps	9.46	6.71	6.26	5.47	4.16
Fresh marsh	1.46	1.27	1.17	1.00	0.25
High marsh	1.19	0.37	0.04	0.04	0.02
Low marsh	3.42	2.33	0.39	0.06	0.03
Mangrove	0	0	3.06	2.13	1.80
Total wetlands	15.53	10.68	10.92	8.70	6.26

Source: Park et al. (Volume B).

Fish Populations in Apalachicola Bay

Study Design. Using data from the literature on the tolerance of various species to warmer temperatures, Livingston estimated the number of months in a typical 30-year period during which the estuary would be too hot for these species and extrapolated this information to estimate reductions in populations.

Hydrologic modeling was not used to estimate the combined impacts of sea level rise and changing riverflow on salinity. Instead Livingston used historic data to estimate regression equations relating riverflow to salinity and salinity to populations of some commercially important seafood species.

Limitations. There is no historical record by which to estimate the impact of warmer temperatures on the Apalachicola (or any other) estuary. Livingston did not model the relationships between various aquatic species or how they would change. He did not consider how finfish and shellfish might adapt to climate change, and he was unable to estimate the impact of wetland loss on populations of finish and shellfish.

The limitations in Hains' estimates of riverflow do not significantly affect the results of Livingston's study because riverflow was only one of several variables to be considered. The uncertainties surrounding changes in rainfall probably dwarf any errors due to Hains' simplified hydrology, and higher temperatures and sea level rise appear to be more important.

Results. The results of this study suggest a dramatic transformation of the estuary from subtropical to tropical conditions.

Warmer temperatures. Livingston concluded that warmer temperatures would have a profound effect on seafood species in the estuary because many species cannot tolerate temperatures much above those that currently prevail. Figure 16-14 compares the number of months in a 6-year period (based on 1971-76) in which temperatures exceed a particular level for the current climate and the GISS and GFDL scenarios, with known thresholds for major commercial species.

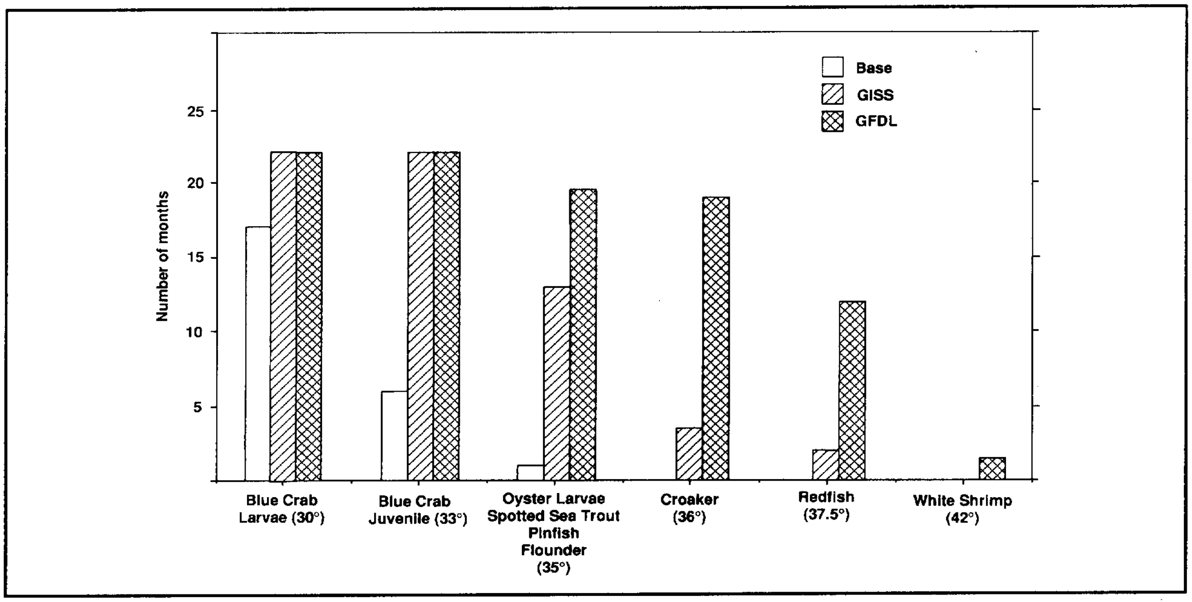


Figure 16-14. Months in a 6-year period during which temperatures (°C) would be too high for selected species under doubled $_{CO2}$ scenarios (Livingston, Volume E).

Livingston concluded that crabs, shrimp, oysters, and flounder could not survive in the estuary with the warming estimated in the GISS and GFDL scenarios, which imply close to 100% mortality for blue crab larvae and juveniles. The GFDL scenario could cause over 90% mortality for spotted sea trout, oyster larvae, panfish, and flounder. The mortality under the milder GISS scenario would be only 60%.

Although Livingston concludes that the oysters would probably be eliminated, he cautions that shrimp and other mobile species might adapt by fleeing the estuary for cooler gulf waters during the summer. However, such a flight would leave them vulnerable to predators.

Increased salinity. Although sea level rise and warmer temperatures seem likely to substantially reduce the productivity of the estuary, the probable impact of precipitation changes is less clear. If riverflow in the Chattahoochee declines, it would combine with sea level rise to increase salinity concentrations in the estuary. Livingston concluded that oysters are the most vulnerable to increases in salinity because oyster drill and other predators, as well as the disease MSX, generally require high salinities. Livingston estimated losses of 10 to 35% for oysters, blue crabs, finfish, and white shrimp under the GFDL scenario because of salinity increases alone.

Sea level rise. Livingston also concluded that the loss of wetland acreage would have important impacts on the estuary. Table 16-6 shows Livingston's estimates of losses in particulate organic carbon, the basic source of food for fish in the estuary. Sea level rise between 50 and 200 centimeters would reduce available food by 42 to 78%. A proportionate loss in seafood populations would not necessarily occur, since organic carbon food supplies are not currently the constraining factor for estuarine populations. However, wetlands also are important to larvae and small shrimp, crabs, and other species, serving as a refuge from predators. A rise in sea level of a meter or more could lead to a major loss of fisheries.

Despite the adverse impacts on shellfish and flounder, a number of species might benefit from global warming. For example, Livingston points out that pink shrimp could become more prevalent. Moreover, some finfish spend their winters in Apalachicola Bay and occasionally find the estuary too cold. Other species such as rock lobster that generally find the waters too cold at present may also be found in the estuary in the future.

Implications. Based on Livingston's projections, Meo et al. (Volume J) used current retail prices of fish to estimate that the annual net economic loss to Franklin County could be $5 to $15 million under the GFDL scenario, $1 to $4 million under GISS, and $4 to $12 million under the OSU scenario.

Livingston's results should not be interpreted to mean that fishing will be eliminated from Apalachicola Bay. The extent to which commercially viable tropical species could replace the species that are lost was not estimated.

Table 16-6. Projected Changes of the Net Input of Organic Carbon (metric tons per year) to the Apalachicola Bay System for Various Scenarios of Sea Level Rise

Factor	Fresh wetlands	Seagrass	Salt marshes	Phytoplankton	Total
Current scenario for 2100	30,000	27,200	46,905	233,280	337,385
Baseline sea level rise	26,100	28,700	23,500	144,640	222,940
0.5-meter rise	24,000	28,800	4,690	71,450	128,940
1.0-meter rise	21,300	30,100	940	58,790	111,130
2.0-meter rise	4,980	31,035	780	15,160	51,955

Source: Livingston (Volume E).

Agriculture

Agriculture in the Southeast will be affected directly by changes in climate and indirectly by changes in economic conditions and pests. This section presents results from a crop modeling study of yield changes by Peart et al., and regional results from national studies of agricultural production shifts by Adams et al. (Volume C) and of impacts of changes in pest populations by Stinner et al. (Volume C).

Crop Modeling Study

Study Design

Peart et al. (Volume C) used the crop models CERES-Maize (Jones and Kiniry, 1986) and SOYGRO (Wilkerson et al., 1985) to estimate the impacts of climate change on yields of corn and soybeans for 19 sites throughout the Southeast and adjacent states. Agricultural scientists have used these models for several years to project the impacts of short-term climatic variations. They incorporate the responses of crops to solar radiation, temperature, precipitation, and soil type, and they have been validated over a large range of climate and soil conditions in the United States and other countries.

The major variable not considered by these and other existing agricultural models is the direct "fertilization effect" of increased levels of atmospheric carbon dioxide. Peart et al., therefore, modified their models to consider both the increased rate of photosynthesis and the increased water-use efficiency that corn and soybeans have exhibited in field experiments (see Chapter 6: Agriculture).

Limitations

The analysis of combined effects is new research and will need further development and refinement. The model runs use simple parameters for CO effects, assume higher atmospheric concentration of CO 2 than are predicted, and probably overestimate the beneficial impact on crop yields. The direct effects of CO_2 in the crop modeling study results may be overestimated for two reasons. First, experimental results from controlled environments may show more positive effects of CO_2 than would actually occur in variable, windy, and pest-infested (weeds, insects, and diseases) field conditions. Second, because other radiatively active trace gases, such as methane, also are increasing, the equivalent warming of a doubled CO 2 climate may occur somewhat before an actual doubling of atmospheric CO_2. A level of 660 ppm CO_2 . was assumed for the crop modeling experiments, while the CO_2 concentration in 2060 is estimated to be SSS ppm Hansen et al., 1988) (see Chapter 6: Agriculture).

The study assumed that soils were relatively favorable for crops, with low salinity or compaction, and assumed no limits on the supply of all nutrients, except nitrogen. The analysis considers neither change in technology nor adverse impacts due to changes in storm frequency, droughts, and pests and pathogens.

Results

Soybean Yields. Table 16-7 illustrates the results of the soybean model for 13 nonirrigated sites in the study area, as well as Lynchburg, Virginia, a colder site included for comparison purposes.

The relatively wet GISS and relatively dry GFDL scenarios imply very different impacts on yields. In the GISS scenario, the cooler sites in Georgia and the Carolinas mostly show declines in soybeans yields of 3 to 25%, and the other sites show declines of 20 to 39%, ignoring CO_2 fertilization. When the latter effect is included, the Atlantic Coast States were estimated to experience gains of 11 to 39%, and the other states could vary from a 13% drop in Memphis to a 15% gain in Tallahassee. (Tennessee fares worse than the North Carolina sites at similar latitudes because its grid cell does not receive as favorable an increase in water availability.)

By contrast, the dry GFDL scenario results in very large drops in soybean productivity, with all but one site experiencing declines greater than 50% and eight sites losing over 75%, considering only the impact of climate change. Even when CO_2 fertilization is considered, all but four sites experience losses greater than 50%.

Corn Yields. The two scenarios differ in a similar fashion for nonirrigated corn. However, in the case of irrigated corn, where the analysis primarily reflects the impact of temperature increases, the two scenarios show more agreement. When CO_2 fertilization was not considered, drops of 13 to 20% were estimated

Table 16-7. Impacts of Doubled CO_2 Climate Change on Soybean Yields for Selected Southeastern Sites for Climate Change Alone and for Climate Change and CO_2 Fertilization (percentage change in yield)[a]

Site	Climate change only		Climate change and CO_2 fertilization	
	GISS	GFDL	GISS	GFDL
Memphis, TN	-38	-88	-13	-70
Nashville, TN	-30	-52	+4	-81
Charlotte, NC	-7	-92	+32	-88
Raleigh, NC	-3	-87	+39	-76
Columbia, SC	-20	-78	+18	-62
Wilmington, NC	-11	-62	+25	-41
Atlanta, GA	-11	-78	+27	-67
Macon, GA	-25	-91	+11	-82
Tallahassee, FL	-20	-51	+15	-17
Birmingham, AL	-31	-54	0	-29
Mobile, AL	-34	-43	-8	error
Montgomery, AL	-39	-84	-10	-68
Meridian, MS	-37	-78	-9	-66
Lynchburg, VA	+1	-74	+49	-55

[a] The impacts of Cow fertilization cannot be quantified as accurately as climate change only. The climates shown here overstate the beneficial impact of CO_2 because Peart et al. assume that CO_2 has doubled. Because other gases contribute to the global warming, CO_2 will have increased by a smaller fraction.

[b] Peart et al. investigated the cumber of sites in states adjacent to the Southeast. Lynchburg is included to permit comparison of results for the Southeast with a colder site.

Source: Peart et al. (Volume C).

in the GISS scenario, and drops of 20 to 35% were calculated for the GFDL scenario. When CO_2 fertilization was included, the GISS scenario implied declines of less than 8% for all sites, and the GFDL model showed similar declines for two sites and respective declines of 17 and 27% for Charlotte, North Carolina, and Macon, Georgia.

Irrigation. The two scenarios show more agreement for agricultural fields that are already irrigated. Since the changes in water availability are irrelevant here, the impacts are dominated by the increased frequency of very hot days.

The results are mixed on whether currently dry land areas would be shifted to irrigation. Table 16-8 shows the percentage increases in yields that would result from adding irrigation for particular scenarios. All but four sites could increase yields today by 50 to 75% by irrigating. Under the wetter GISS scenario, irrigation would increase yields only 7 to 53% (compared with not irrigating under the GISS scenario). However, under the dry GFDL scenario, irrigation would increase yields by 50 to 493% -- that is, it would mean the difference between crop failure and a harvest slightly above today's levels in most years. Even without CO_2 fertilization, 75% of the nonirrigated southeastern sites could gain more from irrigation than they would lose from the change in climate resulting from the GFDL scenario.

A farmer's decision to irrigate, shift to other crops, or remove land from production would depend to a large degree on what happens to prices of both crops and water. Even though water is plentiful today, the capital costs of irrigation prevent most farmers in the

Table 16-8. Increases in Corn Yields from a Shift to Irrigation (percent, assuming no CO_2 fertilization)[a]

Site	Current climate	GISS	GFDL
Memphis, TN	70	50	270
Nashville, TN	65	49	205
Charlotte, NC	64	43	486
Raleigh, NC	51	28	444
Columbia, SC	58	47	386
Wilmington, NC	16	8	50
Atlanta, GA	15	7	79
Macon, GA	61	33	489
Birmingham, AL	6	9	61
Mobile, AL	36	41	91
Montgomery, AL	72	39	493
Meridian, MS	62	53	323
Lynchburg, VA	56	37	361

[a] Estimates represent change in yields, given particular scenario, from shifting to irrigation.

[b] Peart et al. investigated a number of sites in states adjacent to the Southeast. Lynchburg is included to permit comparison with Southeast results with those for a colder site.

Source: Column 1 from Peart et al. (Volume C); Columns 2 and 3 derived from Peart et al. and Column 1

Southeast from taking advantage of the potential 50% increases in yields. But if crop failures due to drought became as commonplace as Peart et al. project for the dry GFDL scenario, a major increase in irrigation probably would be necessary. Although groundwater is currently plentiful in the Southeast, no one has assessed whether there would still be enough water if the climate became drier and irrigation increased. Furthermore, climate change may increase the demand for water for nonagricultural uses.

Shifts in Production

Adams et al. (Volume C) examined the impacts of changes in crop yields on farm profitability and cultivated acreage in various regions of the United States. (The methods for this study are discussed in Chapter 6: Agriculture.) Their results suggest that the impact of climate change on southeastern agriculture would not be directly proportional to the impact on crop yields (Table 16-9).

Considering only the impact of climate change, Adams et al. found that the GISS and GFDL scenarios would reduce crop acreage by 10 and 16%, respectively. When CO_2 fertilization is considered, however, Adams et al. project respective declines in farm acreage of 57 and 33% for the GISS and GFDL scenarios. As yields increase, prices decline. Adams et al. estimate that most areas of the nation would lose farm acreage. However, they estimate that the Southeast would experience the worst losses: wlvle the Southeast has only 13% of the cultivated acreage, it would account for 60 to 70% of the nationwide decline in farm acreage. This result is driven by the increased yields that the rest of the nation would experience relative to the Southeast.

When the CO_2 fertilization effect is ignored, the reductions in acreage would be much smaller, although the Southeast would still account for 40 to 75% of the nationwide loss. The general decline in yields would boost prices, which could make it economical for many farmers to irrigate and thereby avoid the large losses associated with a warmer and possibly drier climate.

Agricultural Pests

The modeling and economic studies of agriculture do not consider the impact of pests on crop yields. However, Stinner et al. (Volume C) suggest that global warming would increase the range of several agricultural pests that plague southeastern agriculture. (For details on the methods of this nationwide study, see Chapter 6: Agriculture.) They point out that the northern ranges of potato leafhoppers, sunflower moths, black cutworms, and several other southeastern pests are limited by their inability to survive a cold winter. Thus, milder winters would enable them to move farther north, as illustrated in Figure 16-15. Stinner et al. also note that increased drought frequency could increase the frequency of pest infestations.

Implications of Agriculture Studies

Agriculture appears to be at least as vulnerable to a potential change in climate in the Southeast as in any other section of the country. Unlike many of the

Table 16-9. Impact of Climate Change on Cultivated Acreage in the Southeast' (figures in parentheses are percentage losses)

Region	Baseline	With Direct CO_2		Without Direct CO_2	
		GISS	GFDL	GISS	GFDL
Acreage (millions)					
SE coast	12.5	8.7(30)	7.8(38)	11.5(8)	11.2(10)
Appalachia	15.5	2.8(82)	7.4(52)	14.1(9)	12.9(17)
Delta	19.9	9.3(53)	16.7(16)	17.7(11)	16.2(19)
Total	47.9	20.8(57)	31.9(33)	43.3(10)	40.3(16)

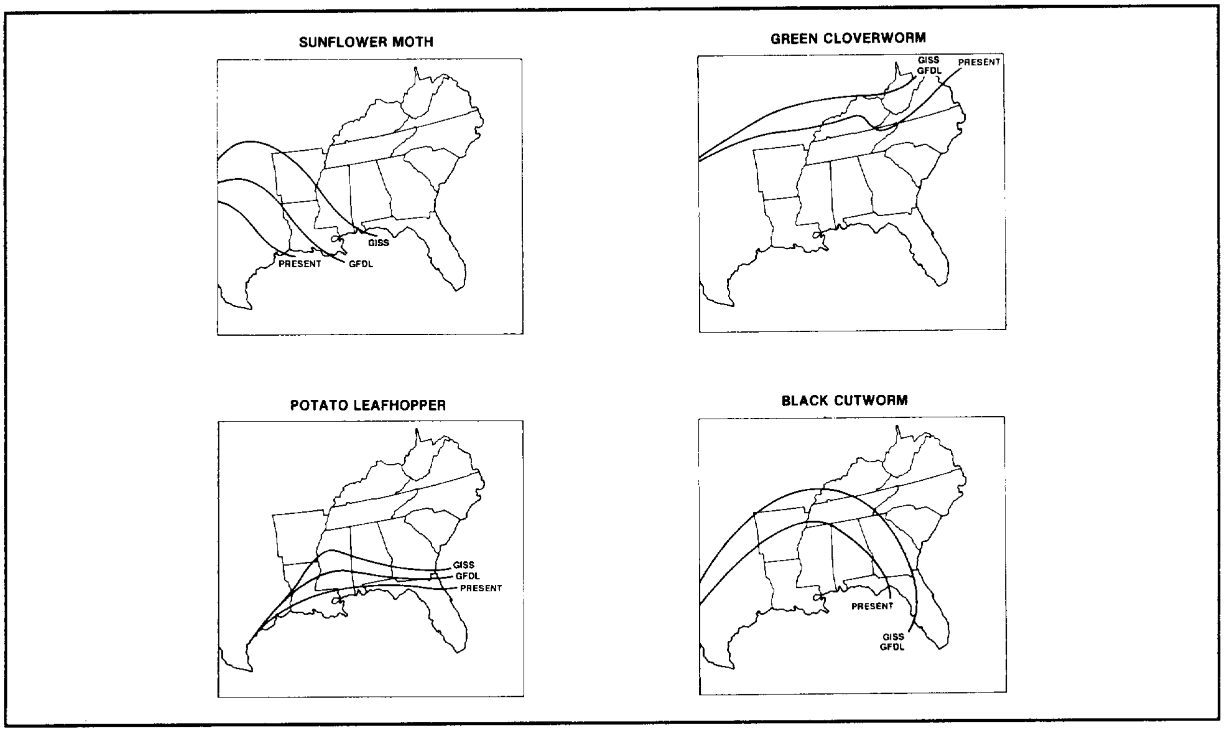


Figure 16-15. Present and predicted northern ranges of various agricultural pests (Stinner et al., Volume C).

colder regions, the benefits of a longer growing season would not appreciably offset the adverse impacts of warmer temperatures in the Southeast, where cold weather generally is not a major constraint to agricultural production.

Florida may present an important exception to the generally unfavorable implications of climate change for crop yields. Although Florida is the warmest state in the Southeast, its agriculture appears to be harmed by cold temperatures more than the agriculture of other states in the region. In recent years, hard freezes have destroyed a large fraction of the citrus harvest several times. As a result, the industry is moving south into areas near the Everglades, and sugarcane, which also thrives in warm temperatures, is expanding into the Everglades themselves. Global warming could enable the citrus and sugarcane areas to include most of the state. Warmer temperatures also would help coffee and other tropical crops that are beginning to gain a foothold in the state. This study, however, did not examine how the frequency of extreme events, such as the number of days below freezing in Florida, would change.

Although Florida's relative abundance of water may make it the exception, the current situation there highlights an important aspect of climate change: Within the context of current prices and crop patterns, the impact of climate change appears to be unfavorable. However, warmer temperatures may present farmers with opportunities to grow different crops whose prices would justify irrigation or whose seasonal cycles would conform more closely to future rainfall patterns.

Forests

Potential Range Shifts

Study Design

Overpeck and Bartlein (Volume D) used two independent methods to study the potential shifts in ranges of forest types over eastern North America. These analyses suggest where trees are likely to grow in equilibrium doubled CO_2 climate conditions after allowing for migration of tree species to fully catch up with climate change. The study only indicates the approximate abundance of different species within a range, not what the transitional effects of climate on forests might be, or how fast trees will be able to migrate to the new ranges. (For a discussion of the study's methodology and limitations, see Chapter 5: Forests.)

Results

Three GCM scenarios and two vegetation models yielded similar results. The abundance of deciduous hardwood populations (e.g., oak), which currently occupy the entire modeled eastern region from the Great Lakes region to the gulf coast, would shift northward away from the gulf coast and almost entirely out of the study region. Because the stand simulation model did not include subtropical species, it was unable to simulate any vegetation along the gulf coast under the very warm doubled CO_2 climate. The results for southern pine were less conclusive but generally show the upper border of the species range moving northward while the southern border remains stable. Growing conditions along the gulf coastal region, however, would also be favorable to subtropical species in a doubled CO_2 environment, but since the models used in the study had no data on such species, it is unclear how southern pine might fare under competition with subtropical varieties.

Transitional Effects

Study Design

Urban and Shugart (Volume D) applied a forest simulation model to a bottomland hardwood forest along the Chattahoochee River in Georgia and to upland sites near Knoxville, Tennessee, Macon, Georgia, Florence, South Carolina, and Vicksburg, Mississippi. Their study considered the OSU, GFDL, and GISS scenarios for doubled CO_2, as well as the GISS transient A scenario through the year 2060.

The model these researchers used was derived from FORET, the "gap" model originally developed by Shugart and West (1977). The model simulates forest dynamics by modeling the growth of each tree in a representative plot of forest land. It keeps track of forest dynamics by assigning each of 45 tree species optimal growth rates, seeding rates, and survival probabilities, and by subsequently adjusting these measures downward to account for less than optimal light availability, temperature, soil moisture, and soil fertility. In the case of the bottomland hardwood site, the model also considers changes in river flooding, based on the flows in the lower Chattahoochee calculated in the Lake Lanier study. The researchers applied the model to both mature forests and the formation of a new forest from bare ground.

Limitations

The results should not be taken literally owing to a number of simplifying assumptions that Urban and Shugart had to make. First, they assumed that certain major species, such as loblolly pine, could not tolerate more than 6,000 (cooling) degree-days per year. These species are not currently found in warmer areas, but the southern limits of their range are also limited by factors other than temperature, such as the Gulf of Mexico and the dry climate of Texas and Mexico. Although the 6,000 degree-day line coincides with these species' southern boundary across Florida, the peculiar environmental conditions of that state make it impossible to confidently attribute an estimate of thermal tolerance to that observation alone. This caveat does not apply to most of the oaks, hickories, and other species found in the cooler areas of the Southeast.

Another important caveat is that the model does not consider the potentially beneficial impact of CO_2 fertilization on photosynthesis, changes in water-use efficiency, or leaf area. Nor did the analysis consider introduction of new species into the region. Thus, there is more confidence about the fate of species currently in the region than about what may replace those species.

Results

The simulations by Urban and Shugart call into question the ability of southeastern forests to be generated from bare ground, particularly if the climate becomes drier as well as warmer. For the Knoxville site, the dry GFDL scenario implies that a forest could not be started from bare ground, while the GISS and OSU doubled CO_2 scenarios estimate reductions in biomass of 10 to 25%. For the South Carolina site, only the GISS climate would support a forest, albeit at less than 50% of today's productivity. The Georgia and Mississippi sites could not generate a forest from bare ground for any of the scenarios. Thus, even with increased rainfall, some sites would have difficulty supporting regeneration.

The transient analyses suggest that mature forests could also be lost -- not merely converted to a different type -- if climate changes. Figure 16-16 shows that none of the forests would decline significantly within 50 years; however, all would decline substantially before the end of the transient run in 80 years. The Mississippi forest would mostly die within 60 years, and the South Carolina and Georgia forests within 80 years. Only the relatively cool Tennessee site would remain somewhat healthy, although biomass would decline 35%.

Although the simulation results suggest that southeastern forests are unlikely to benefit from the global warming, the impact on forests may not be as bad as the model suggests, if new species move in or if loblolly pine can tolerate more than 6,000 degree days per year. Nevertheless, major shifts in forest types are almost certain to occur from the warmer temperatures alone.

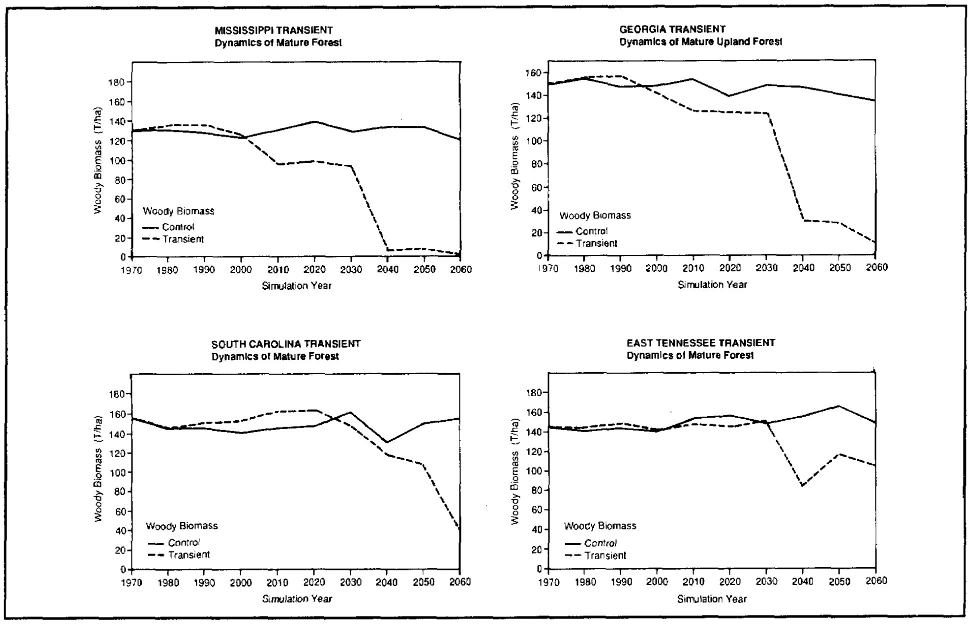


Figure 16-16. Response of southeastern forests to GISS transient scenarios of climate change (Urban and Shugart, Volume D).

Electric Utilities

Linder and Inglis (Volume H) examined the impact of global warming on the demand for electricity throughout the Southeast for the two GISS transient scenarios. (For additional details on the methods and limitations of this study, see Chapter 10: Electricity Demand.) Because their study was limited to electricity, it did not consider the reduced consumption of oil and gas for space heating that would result from warmer temperatures.

Table 16-10 shows the percentage changes in electric power requirements for various areas in the Southeast. Along the gulf coast, annual power requirements could increase 3 to 4% by 2010 and 10 to 14% by 2055; elsewhere, the increases could be somewhat less. Because peak demand for electricity generally occurs during extremely hot weather, peak demand would rise more than annual demand. (This result is also sensitive to changes in variability.)

Linder and Inglis compared increases in electric capacity required by climate change with those necessitated by economic growth. They estimated that through 2010, climate change could increase the expected capital costs of $137 billion by 6 to 9%; through 2055, it could increase expected requirements of $350 to $500 billion by as much as 20%.

COASTAL LOUISIANA

The sediment washing down the Mississippi River has formed the nation's largest delta at the river's mouth, almost all of which is in Louisiana. Composed mostly of marsh, cypress swamps, and small "distributary” channels that carry water, sediment, and nutrients from the river to these marshes and swamps, Louisiana's wetlands support half of the nation's shellfish, one-fourth of its fishing industry, and a large trapping industry. They also provide flood protection for metropolitan New Orleans and critical habitats for bald eagles and other migratory birds.

Water management and other human activities of the last 50 years are now causing this delta to disintegrate at a rate of about 100 square kilometers per year. Sediment that used to replenish the delta now largely washes into the deep waters of the gulf because flood-control and navigation guide levees confine the flow of the river. Thus, the delta is gradually being submerged, and cypress swamps are converting to open-water lakes as saltwater penetrates inland. If current trends continue, almost all the wetlands will be lost in the next century.

Table 16-10. Percentage Increases in Peak and Annual Demand for Electricity by 2010 and 2055 as a Result of Climate Change

Area	GISS A (2010)		GISS B (2010)		GISS A (2055)	
	Annual	Peak	Annual	Peak	Annual	Peak
North Carolina, South Carolina, Georgia	1.6	7.3	1.3	2.4	5.9	24.4
Florida	2.7	4.9	2.7	3.6	9.3	20.0
Eastern Tennessee	1.6	3.7	1.3	1.2	5.9	12.2
Alabama, Western Tennessee	1.9	3.8	2.2	5.7	6.8	13.5
Mississippi	3.8	7.6	4.4	11.4	13.6	6.9
Louisiana	2.9	7.6	2.7	6.6	10.2	23.4
East Texas	3.1	7.9	2.8	6.6	11.3	25.3

Source: Linder and Inglis (Volume H).

A rise in sea level would further accelerate the rate of land loss in coastal Louisiana. As shown in Figure 16- 17, even a 50-centimeter rise in sea level (in combination with land subsidence) would inundate almost all of the delta and would leave New Orleans, most of which is below sea level and only protected with earthen levees, vulnerable to a hurricane.

Strictly speaking, the entire loss of coastal Louisiana's estuaries should not be attributed to global warming because the ecosystem is already being lost. However, major efforts are being initiated by the U.S. Army Corps of Engineers, the U.S. Fish and Wildlife Service, the Louisiana Geological Survey, several local governments, and other federal and state agencies to curtail the loss, generally by erecting structures to provide freshwater and sediment to the wetlands. Technical staff responsible for developing these solutions generally fear, however, that a 1-meter rise in sea level could overwhelm current efforts, and that if such a rise is ultimately going to take place, they already should be planning and implementing a much broader effort (Louisiana Wetland Protection Panel, 1987).

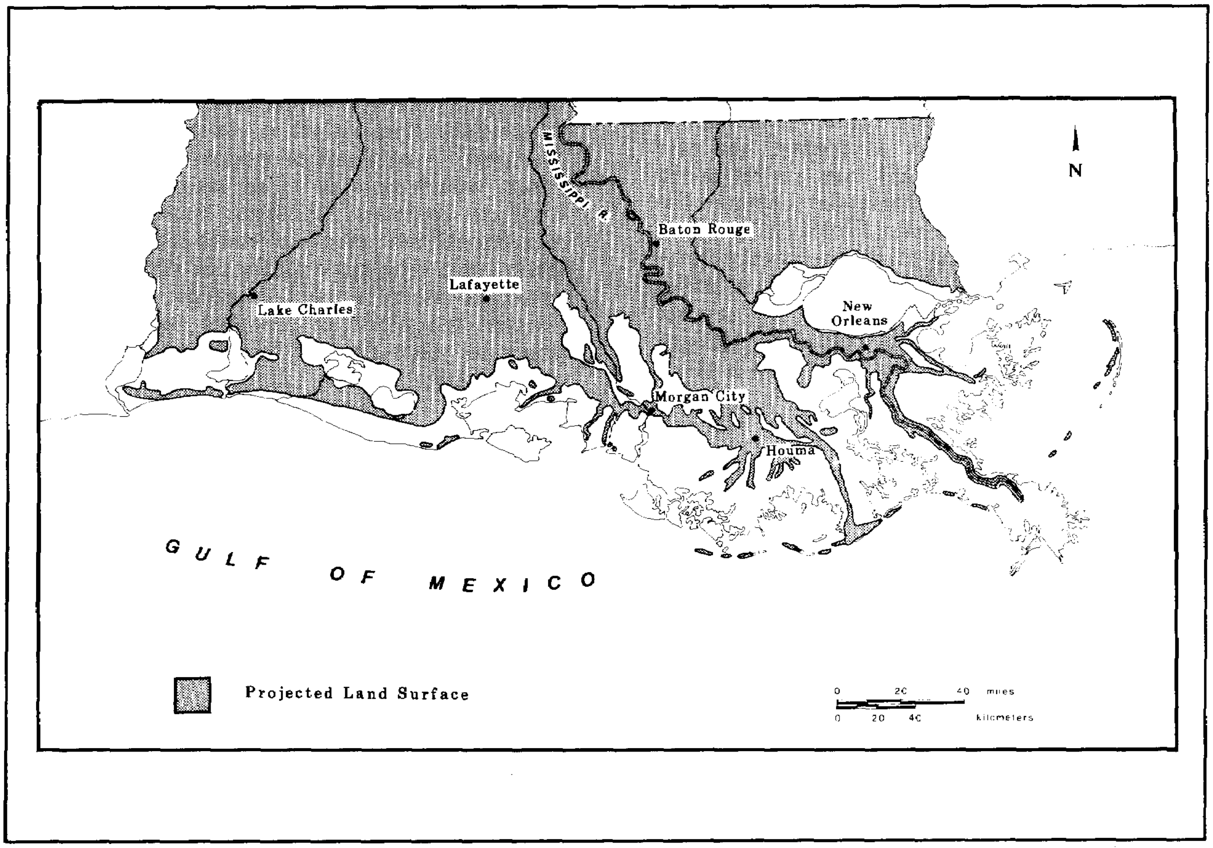


Figure 16-17. Projected future coastline of Louisiana for the year 2033, given a rise in sea level of 55 cm as predicted in the high scenario (Louisiana Wetland Protection Panel, 1987).

POLICY IMPLICATIONS

Agriculture and Forests

Climate change could have a major impact on land use in the Southeast. The estimated abandonment of 10 to 50% of the farmland in the Southeast and large declines in forests raise the an important question: How will this land be used?

In the past, forests have been cleared for agriculture, and when abandoned, they have been converted to forest again. But the forest models suggest that the impact of climate change on the generation of new forests from bare ground would be even more adverse than the impact on existing forests. If the forest simulations are correct, the abandoned fields would become grasslands or would become overgrown with weeds, and the Southeast could gradually come to resemble the scenery found today in the Great Plains.

However, no one has systematically investigated the extent to which human infrastructure might stabilize these changes. Changes in crops might enable more farms to stay in business than Adams et al. project, and new varieties of trees may find the region more hospitable. Because the commercial forests in the Southeast generally have short rotation cycles, it may be easier to respond to climate change there than in other regions. To a large degree, the ability of human intervention to maintain the present landscape would depend on international prices of agricultural and forest products, estimation of which is outside the scope of this report.

Water Resources

The water resource problems faced by the Southeast are not likely to be as severe as the problems faced by other regions of the country. Rainfall and runoff were estimated to increase in the GISS scenario. Although most other assessments suggest that runoff would decline, the magnitude of the decline does not appear to threaten the availability of water for municipal, industrial, or residential use. However, the nonconsumptive uses for hydropower, navigation, environmental quality, and recreation could be threatened. Although sufficient time exists to develop rational strategies to implement the necessary tradeoffs, current federal statutes constrain the ability of water managers to do so.

Impacts of Wetter Climate

Although most water resource problems have been associated with too little water, it does not necessarily follow that a wetter climate would be generally beneficial. The designs of water management infrastructure and the location of development along lakes and rivers have been based on current climate. Hence, shifts in either direction would create problems.

The chief problem from a wetter climate would be more flooding, particularly in southern Florida and coastal Louisiana, where water often lingers for days and even weeks after severe rainstorms and river surges. Inland communities, such as Chattanooga, also might face flooding if wetter periods exceed the ability of dams to prevent flooding.

Impacts of Drier Climate

A drier climate, on the other hand, would exacerbate current conflicts over water use during dry periods. Hydropower would decline, increasing the need to use fossil or nuclear power, both of which would require more water for cooling. Conflicts between municipal water users and recreational interests also would intensify. Lake levels could drop more during the summer, even if municipal use of water did not grow. However, warmer temperatures probably would increase municipal water demand for cooling buildings and watering lawns.

These conflicts could be further exacerbated if farmers increase the use of irrigation. Groundwater is available in reasonably shallow aquifers that drain into rivers. Any consumptive use of water from these aquifers would reduce, and in some cases reverse, the base flow of water from aquifers into these rivers. Water also could be drawn directly from rivers for irrigation in some areas.

A decline in riverflows could be important for both navigation and environmental quality. For the Tennessee, as well as the Chattahoochee and other small rivers, adequate reservoir capacity exists to maintain flows for navigation, if this use continues to take precedence over water supply and recreation. However, the 1988 drought has graphically demonstrated that there are not enough dams to guarantee navigation in the Mississippi. If this situation became more commonplace, the economic impact on New Orleans could be severe. On the other hand, traffic on the Tennessee and Ohio Rivers might use the Tennessee-Tombigbee Canal as an alternative, which would benefit the Port of Mobile.

Lower flows also would reduce the dilution of municipal and industrial effluents discharged into rivers and would decrease the level of dissolved oxygen. This would directly harm fish populations and would cause indirect harm by reducing the abilities of streams to assimilate wastes. Reduced flows also would threaten bottomland hardwood and estuarine ecosystems. To prevent these problems, factories and powerplants might have to erect cooling towers or curtail their operations more frequently.

Is Current Legislation Adequate?

The same issues that face the TVA and Lake Lanier would likely face decisionmakers in other areas. Federal laws discourage water managers in the Southeast from rigorously evaluating the tradeoffs between the various uses of water. Most dams are more than sufficient to meet the statutory requirements for navigation and flood safety and to continue generating substantial hydropower on demand. Consequently, there has been little need to analyze the tradeoffs between these factors. For example, a literal application of the law would not allow the U.S. Army Corps of Engineers to cut hydropower production or navigation releases to ensure a supply of water for Atlanta. Therefore, agencies have not analyzed the allocation of water that best serves the public for various levels of water availability (although the TVA is beginning to do so).

At a practical level, federal water managers have shown flexibility, as in the case of cutting navigation along the Chattahoochee instead of further cutting Atlanta's water supply. If climate changes and more than a modest level of flexibility is necessary, water resource laws could be changed; the physical infrastructure is largely in place to address water problems of the Southeast. But until the laws are changed, the federal agencies in the Southeast often would be forced to allocate water inefficiently. Moreover, people making decisions concerning siting of recreational and industrial development, long-term water supply sources, powerplant construction, and other activities sensitive to the availability of water would risk basing their decisions on incorrect assumptions regarding the future allocation of water.

Estuaries

Coastal plants and animals across the Southeast may have difficulty surviving warmer temperatures. For example, along the northern coast of the Gulf of Mexico, several types of fish spend at least part of their lifetimes in estuaries that are already as hot as they can tolerate. If climate became warmer, however, migrating north would not be feasible. While these species could escape the summer heat by fleeing to the cooler waters of the gulf, such a flight would make them vulnerable to larger fish.

In addition to the direct effect of climate change on estuaries, human responses to climate change and sea level rise also could hurt coastal estuaries. Besides the impacts of flood control, increased reservoir construction would decrease the amount of sediment flowing down the river and nourishing the wetlands. If the climate becomes drier, irrigation could further reduce freshwater flow into estuaries.

To a large extent, the policy implications for wetland loss in the Southeast are similar to those facing the rest of the U.S. coastal zone. Previous studies have identified several measures to reduce the loss of coastal wetlands in response to sea level rise (e.g., Titus, 1988). These measures include the following:

- increase the ability of wetlands to keep pace with sea level;
- remove impediments to landward creation of new wetlands; and
- dike the wetlands and artificially maintain water levels.

All these measures are being employed or actively considered.

Congress has authorized a number of freshwater and sediment diversion structures to assist the ability of Louisiana's wetlands to keep up with relative sea level rise. These structures are engineered breaches in river levees that act as spillways into the wetlands when water levels in the river are high.

Although decisions on where to build diversion structures are being based on current climate and sea level, consideration of global warming would substantially change the assumptions on which current analyses are being based and the relative merits of alternative options. More frequent or higher surges in the Mississippi River would increase the amount of water delivered to the wetlands. And if climate change resulted in more soil erosion, more sediment might also reach the wetlands; lower flows could have the opposite effect. Sea level rise might shorten the useful lifetimes of these projects, but because the flood-protection benefits of protecting coastal wetlands would be greater with a higher sea level (Louisiana Wetland Protection Panel, 1987).

Artificially managing water levels also has been proposed for Louisiana, particularly by Terrebonne Parish, whose eastern wetlands are far removed from a potential source of sediment. Such an approach also might be possible for parts of Florida, where wetlands already are confined by a system of dikes and canals, and water levels already are managed. Although no one has yet devised a practical means by which shrimp and other fish could migrate between ocean and estuary, other species spend their entire lifetimes within the estuary, and freshwater species could remain in artificially maintained freshwater wetlands.

A final response would be to accept the loss of existing wetlands, but to take measures to prevent development from blocking the landward creation of new wetlands. This approach has been enacted by the State of Maine (1987) and would be consistent with the proposals to discourage bulkheads that have been widely discussed by coastal zone managers and enacted by the State of South Carolina. Titus and Greene estimate that 1,800 square miles of wetlands in the Southeast could be created if developed areas were not protected. Although this area represents a small fraction of the potential loss, it would increase the remaining areas of wetlands by 30 to 90%, and it would maintain and perhaps increase the proportion of shorelines on which at least some wetlands could be found.

Beach Erosion

The implications of sea level rise for recreational beaches in the Southeast are similar to the implications for the mid-Atlantic and the Northeast. If shore-protection measures are not taken, the majority of resorts will have no beach at high tide by 2025 under the midrange scenario of future sea level rise. The cost of undertaking the necessary measures through 2025 probably would be economically justified for most resorts (see Chapter 7: Sea Level Rise). However, the cost of protecting all recreational beaches through 2100 would be $100 to $150 billion, which would probably lead some of the more vulnerable areas to accept a landward migration much as areas on North Carolina's Outer Banks are facing today, particularly if warmer temperatures also lead to more hurricanes.

The potential responses to global warming should be viewed within the context of current responses to erosion flooding. Florida has a trust fund to nourish its beaches and has received federal assistance for pumping sand onto the shores of Miami Beach. Mississippi has nourished the beaches of Biloxi, Gulfport, and other resort communities that lie on the mainland along the protected waters behind the barriers. Louisiana is rebuilding its undeveloped barrier islands because they protect the mainland from storms. Most states are moving toward "soft engineering" solutions, such as beach nourishment, because of doubts about the effectiveness of hard structures in universal erosion and their interference with recreational uses of the beach.

Land-use measures also have been employed to adapt to erosion. Because of unusually high erosion rates on the Outer Banks, houses along the coast are regularly moved landward. North Carolina requires houses, hotels, and condominiums to be set back from the shore by the distance of a 100-year storm plus 30 years' worth of erosion on the assumption that after 30 years, the house could be moved back. Texas requires that any house left standing in front of the vegetation line after the shore erodes must be torn down.

If a global warming increases the frequency of hurricanes, a number of southeastern communities will be devastated. However, the overall impact of increased hurricane frequency would be small compared with the impact of sea level rise. While a doubling of hurricanes would convert 100-year floodplains to 50-year floodplains throughout much of the Southeast, a 1-meter rise would convert them to 15-year floodplains.

Because the open-coast areas most vulnerable to sea level rise are generally recreational beach resorts, the costs of erosion and flooding should be viewed within the larger context of why people go to the beach. People from the north visit southeastern beaches to escape winter, and residents of the region go to escape the summer heat. As temperatures become warmer, Georgia and the Carolinas may be able to compete with Florida for northerners. Hotter temperatures also may increase the desire of the region's residents to visit the beach.

Thus, it is possible that the cooler communities will reap benefits from a longer and stronger tourist season that are greater than the increased costs for erosion control. Areas that already have a year-round season are less likely to benefit, and in a few areas like Miami Beach, the off-season may be extended.

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