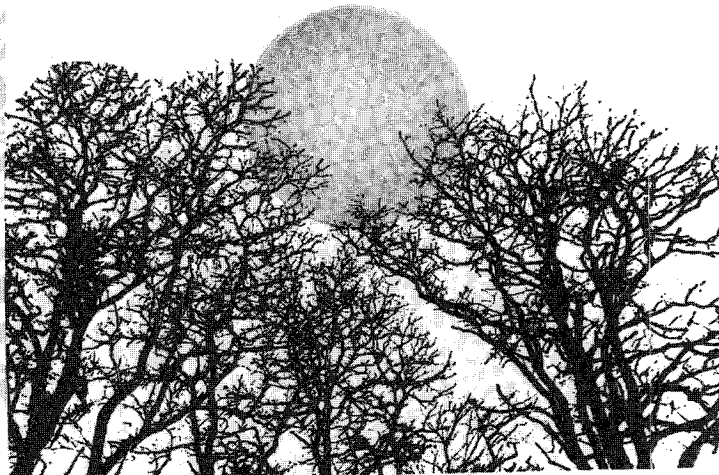


S E N S I T I V I T Y  
O F  
W A T E R  
R E S O U R C E S  
I N T H E  
D E L A W A R E  
R I V E R  
B A S I N



T O  
C L I M A T E  
V A R I A B I L I T Y  
A N D  
C H A N G E

soil characteristics were determined from more than 100 representative areas of the basin. The parameters for the model were chosen for each run at random from the range of actual characteristics, and a large number of runs then could produce a representative sample of hydrologic characteristics for the basin. The same procedure of sampling a range of basin climatic, topographic, and soil parameter values was followed in all analyses involving TOPMODEL that are referenced later in this report; hence, all sensitivity experiments are comparable and incorporate parameter values representative of all the source areas of basin streamflow.

Data on basin topography, soil properties, and daily precipitation and temperature are required to run TOPMODEL. The topographic parameter, a measure of hillslope steepness and shape, was derived from gridded, digitized elevation data from 1:250,000-scale maps. Soil parameters (saturated hydraulic conductivity, depth to bedrock, and field capacity) were estimated from digitized soil-survey maps at 1:250,000 scale. Daily average temperature and total precipitation were derived from a stochastic climate model of the basin (Wolock and others, 1989) based on data from 28 first-order National Weather Service meteorological stations in and near the basin. The daily stochastic climate model incorporates the spatial differences in intensity and duration of daily precipitation.

One hundred 5-year simulations were run, each simulation starting with a different randomly selected set of climatic, topographic, and soil parameter values. The following hydrologic characteristics were calculated for each 5-year simulation: mean daily depth to water table, mean daily evapotranspiration, mean daily streamflow, maximum daily streamflow, 7-day low flow, and the ratio of surface runoff to total runoff. Rank correlation coefficients between the basin parameters (climatic, topographic, and soil) and the hydrologic characteristics were calculated from the set of 100 simulations. The magnitude of the correlation coefficient indicates the degree of association between the basin parameter and the hydrologic characteristic.

The ranges of correlation coefficients ( $r$ ) derived from the 100 simulations indicate that simulated maximum daily flow ( $r = 0.61$  to  $0.83$ ), mean daily flow ( $r = 0.74$  to  $0.94$ ), and 7-day low flow ( $r = 0.65$  to  $0.77$ ) correlated better with precipitation parameters than with other basin parameters. The ratio of surface runoff to total runoff correlated

best with the topographic parameter ( $r = 0.72$ ). Simulated evapotranspiration correlated best with average daily temperature ( $r = 0.92$ ). Simulated moisture deficit for saturated soil correlated best with depth to bedrock ( $r = 0.72$ ).

Grouping the correlation results into the general categories of climate, topography, and soil indicates that climate has the greatest effect on maximum daily flow, mean daily flow, evapotranspiration, and 7-day low flow. Topography has the greatest effect on the ratio of surface runoff to total runoff. Soil has the greatest effect on depth to water table. On the basis of these results, the differences in most of the hydrologic characteristics for small basins in the Delaware River basin are due to differences in climate from one part of the basin to another. Only differences in depth to water table and flow path are not due to differences in basin climate.

### **Relation of Streamflow to Temperature and Precipitation**

A comparison of mean annual temperature and total annual precipitation with mean annual streamflow in a midbasin watershed (Neshaminy Creek; fig. 17) reveals that year-to-year variability in precipitation largely controls the observed year-to-year variability in streamflow. This relation is true for most hydrologic systems. (The principal exceptions are systems involving extreme snow accumulation, as in mountain glaciers, where temperature determines how much of the precipitation becomes streamflow each year.) Thus, changes in regional precipitation patterns will have a substantial effect on streamflow.

## **SENSITIVITY OF WATER RESOURCES TO CLIMATE VARIABILITY AND CHANGE**

The remainder of this report presents the results of a research project in the Delaware River basin (Ayers and Leavesley, 1988), which illustrate the sensitivity of water resources to potential changes in the humid-temperate climate of the basin. Many examples illustrate how variability and potential changes in temperature, precipitation, and the transpiration rate of vegetation affect the soil moisture, streamflow, drought, and water supply of the basin. The potential effects of sea-level rise on

saltwater intrusion, aquifer recharge, tidal wetlands, and coastal flooding and erosion are also described.

### **Potential Changes in Soil Moisture and Irrigation Demand**

Soil moisture becomes an increasingly important component of the water budget during summer (June, July, August), when the climatic and biological demand (evapotranspiration) for water is highest (McCabe and Ayers, 1989). Low soil moisture usually leads to plant stress, reduced streamflow, and decreased ground-water recharge. Irrigation is necessary to maintain enough soil moisture to produce crops in areas of sandy, well-drained soils in the southern part of the basin.

Estimates of soil-moisture conditions during summer months were calculated by means of a monthly water-balance model (McCabe and Ayers, 1989) for present conditions, for various hypothetical (prescribed) changes in temperature and precipitation, and for three GCM projections (GFDL, GISS, and OSU models). The model used a Thornthwaite water-balance approach (Thornthwaite and Mather, 1955; Mather, 1978) based on average monthly temperature and precipitation for three climate stations in the basin. Results of the model simulations indicate that atmospheric warming will cause an increase in potential evapotranspiration and, unless precipitation increases, a decrease in soil moisture during the summer. Even with a 20-percent increase in precipitation, simulated mean summer soil moisture for the basin would likely decrease for any temperature increases greater than 2°C (McCabe and Ayers, 1989). Simulated increases in stomatal resistance of plants to transpiration also could counteract the effects of a simulated temperature increase, if the net effect of increased CO<sub>2</sub> is reduced plant transpiration.

Effects of reduced soil moisture in summer on simulated streamflow and ground-water recharge would persist into the autumn. More autumn precipitation would be needed to replenish soil-moisture deficits, and thus less water would be available for autumn and early winter streamflow and ground-water recharge.

About 60,000 acres of cropland and 250 golf courses are irrigated each year in the Delaware River basin (R. Limbeck, Delaware River Basin Commission, oral commun., August 1990). Irrigation water use (57 Mgal/d) is not a large part of the

total water use in the basin (0.7 percent of 7,700 Mgal/d; J. Featherstone, Delaware River Basin Commission, written commun., Feb. 1988), but because about 90 percent of irrigation water applied is lost to evapotranspiration, irrigation constitutes a substantial part of consumptive water use in the basin (19 percent of 302 Mgal/d). This percentage does not include consumptive water use for lawn watering, which is a substantial but largely unknown part of commercial and municipal consumptive water use. A warming trend likely would result in a need for more frequent irrigation and, in turn, in an increase in consumptive water use in the basin, unless the irrigated area or application rates decrease accordingly.

In a simulation study by McCabe and Wolock (1992), an irrigation-demand model was developed to define the potential effects and relative sensitivity of long-term changes in climate on mean annual irrigation demand in southern New Jersey. The simulation model was based on a daily Thornthwaite water-balance approach that was driven by a stochastic model of daily temperature and precipitation. The climate-change scenarios consisted of combinations of gradual increases in mean annual temperature of 2°C and 4°C, gradual changes in mean annual precipitation ranging from -20 to +20 percent, and a gradual increase of 20 percent in stomatal resistance of plants to transpiration. Changes were linear and were applied uniformly throughout the year. Other factors that affect soil moisture, such as vegetation type, were not considered in this approach. The approach also did not account for additional possible and largely unknown effects of climate change, such as the effects of increasing CO<sub>2</sub> on the variability of temperature and precipitation and on other transpiration and growth changes of plants.

The daily Thornthwaite water-balance model was used to calculate soil moisture for two soil layers and to determine when irrigation was required (Thornthwaite and Mather, 1955; Mather, 1978). The stochastic model generated daily potential evapotranspiration (from temperature) and daily precipitation. The total storage capacity of soil moisture (field capacity) of both layers, 150 mm, was based on the capacity of sandy-loam soil and an average crop rooting depth of 610 mm. The capacity of the top layer was 25 mm; water was withdrawn from the top layer at a rate equal to potential evapotranspiration. The capacity of the bottom layer was 125

**Table 3.** Simulated average annual volume of irrigation needed in southern New Jersey for simulated changes in temperature, precipitation, and stomatal resistance

[Changes from current (1948–88) conditions. —, not available; °C, degrees Celsius]

Change in temperature	Change in stomatal resistance	Irrigation volume in millimeters, for indicated change in precipitation		
		+20 percent	No change	–20 percent
None	None	—	182	—
+2°C	None	204	242	279
+4°C	None	269	311	362
+2°C	+20%	99	134	176
+4°C	+20%	156	194	231

mm; water was withdrawn at a decreasing rate proportional to the ratio of soil moisture to capacity of the bottom layer.

On the basis of irrigation guidelines for New Jersey, irrigation was applied when daily soil moisture storage dropped to 50 percent of field capacity or below. The amount of water applied during each simulated irrigation event was 75 mm, the amount needed to bring the soil moisture storage to field capacity.

Hypothetical changes in mean annual temperature and precipitation without any change in stomatal resistance of plants to transpiration resulted in increases in mean annual irrigation demand, even with a 20-percent increase in mean annual precipitation (table 3). The increases ranged from 22 mm/year (a 12-percent increase) to 180 mm/year (a 99-percent increase). The effect on mean annual irrigation demand was greater from changes in mean annual temperature than from changes in mean annual precipitation. The greater influence of temperature changes in this case is important because climate models are more in agreement in regard to regional changes in mean annual temperature than to regional changes in precipitation.

A simulated increase in stomatal resistance of plants to transpiration, however, counteracted the effects of increased temperature and decreased precipitation on irrigation demand (table 3). When a 20-percent increase in stomatal resistance was assumed, changes in mean annual irrigation demand ranged from –83 mm per year (a 46-percent decrease) to +49 mm per year (a 27-percent increase). A regression analysis of the simulated results indicates that changes in stomatal resistance had more effect on changes in annual irrigation demand than did the specified changes in mean annual temperature and precipitation.

Regression models of the results of the irrigation-demand simulations were developed. A comparison of regression coefficients derived from the regression analyses indicates that a 5.1-percent increase in stomatal resistance can counteract the effects of a 1°C increase in mean annual temperature on irrigation demand and that a 2.8-percent increase in stomatal resistance can counteract a 100-mm (9.3-percent) decrease in mean annual precipitation. The regression also indicates that, when no change occurs in stomatal resistance, a 16.9-percent (182-mm) increase in mean annual precipitation can counteract the effects of a 1°C increase in mean annual temperature on irrigation demand.

### Potential Changes in Streamflow

We have demonstrated that the differences in most of the hydrologic characteristics for small basins in the Delaware River basin are due to differences in climate from one part of the basin to another and that changes in regional precipitation patterns could have a larger effect on streamflow than changes in temperature. The following discussion will focus on the sensitivities of streamflow in the basin to changes in climate.

### Relation of Changes in Temperature, Precipitation, and Stomatal Resistance to Streamflow Variability

A set of 200 simulations (each 60 years long) was performed with the daily stochastic climate model of the basin as input to the physically based daily streamflow model of the basin (TOPMODEL; Wolock and others, 1989) to evaluate how uncertainty in changes in temperature, precipitation, and plant stomatal resistance to transpiration will affect daily streamflow (in this example, maximum daily streamflow). Each simulation represented a ran-

**Table 4.** Percentage of variance in Kendall's tau for maximum daily flow in the basin due to components of uncertainty

Source of variability	Percentage of the variance explained
Climate-change components	
Average daily precipitation	40
Storm-period duration	4
Interstorm-period duration	11
Mean annual temperature	6
Stomatal resistance	1
Natural variability	28
Nonlinearities	10

domly selected combination of climate-change variables in the following hypothetical ranges of model parameters: average daily precipitation, storm-period duration, and interstorm-period duration,  $-20$  to  $+20$  percent of current basin values; mean annual temperature,  $0^{\circ}\text{C}$  to  $+6^{\circ}\text{C}$  of current basin values; and plant stomatal resistance to transpiration,  $0$  to  $+20$  percent of current basin values. These ranges reflect current estimates of the potential for climate change.

For each simulation, Kendall's tau (a measure of trend in the data) was calculated for the predicted annual time series of maximum daily streamflow. The variability in Kendall's tau for the 200 simulations was partitioned into three categories: variability in climate-change variables, natural variability, and variability inherent in the methodology (table 4).

The largest explained variance (40 percent) is associated with average daily precipitation, indicating that the largest uncertainty in forecasting the effects of climate change is due to the current lack of confidence in projecting how average daily precipitation will change. The combined effects of average daily precipitation, storm-period duration, and interstorm-period duration account for 55 percent of the explained variance or uncertainty. The second-largest explained variance (28 percent) is due to natural variability in streamflow response to climate. Temperature changes accounted for only 6 percent of the uncertainty, and stomatal resistance only 1 percent. Simulation results for mean daily streamflow and for 7-day low flow (not shown here) were similar to the results for maximum daily streamflow.

Uncertainty in the predictions of climate change will decrease as our understanding of climate-change processes and feedbacks increases.

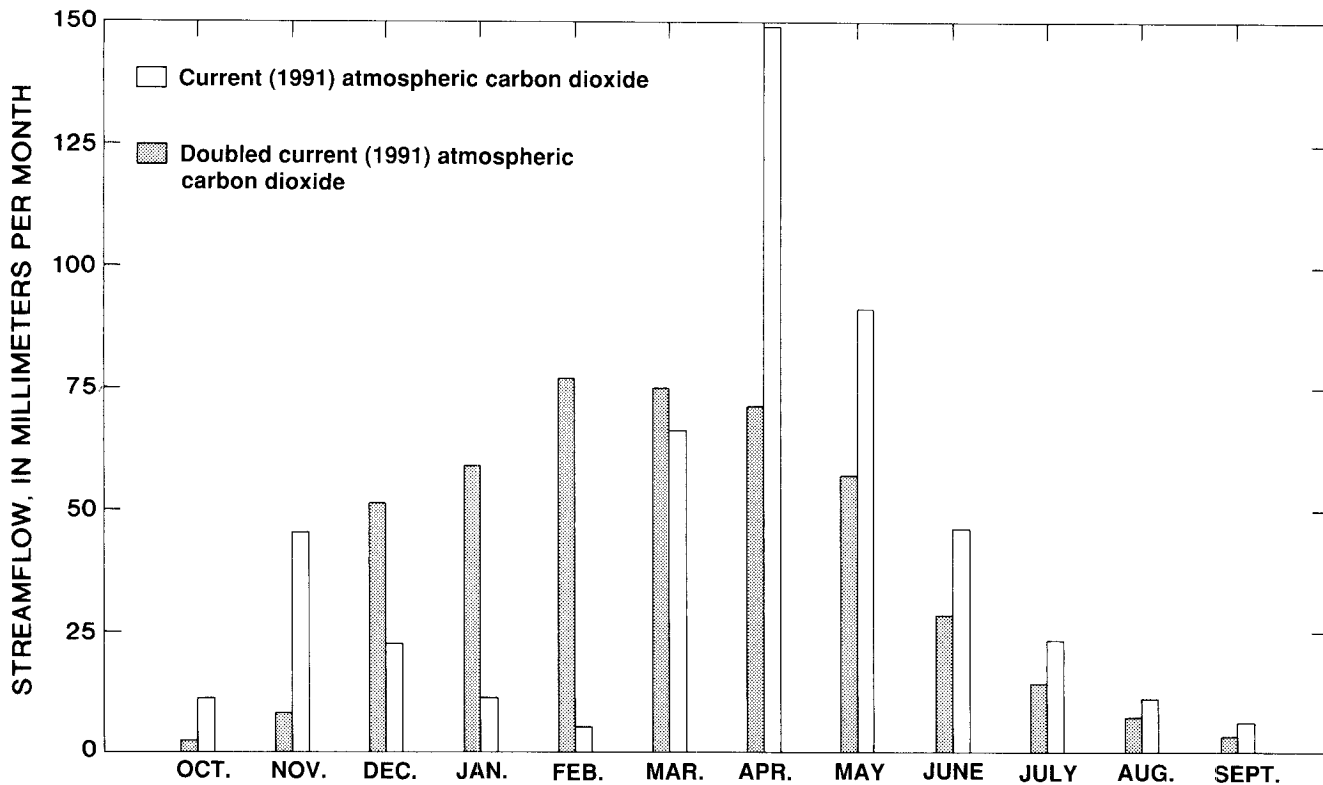
Predictions of the effects of climatic change on streamflow will become more certain, but uncertainty due to natural variability will never be eliminated.

### Sensitivity of Streamflow to Changes in Climate and Stomatal Resistance

The Thornthwaite monthly water-balance model and combinations of hypothetical temperature and precipitation changes were used to estimate potential changes in streamflow in the Delaware River basin (McCabe and Ayers, 1989). The simulated effects of  $\text{CO}_2$ -induced warming on annual streamflow indicated that a 3-percent increase in precipitation would be necessary to counteract the effects of each  $1.0^{\circ}\text{C}$  warming. A warming of  $4^{\circ}\text{C}$  could increase evapotranspiration and reduce annual basin streamflow by as much as 25 percent if current precipitation patterns remain unchanged. The magnitude of change in streamflow in each simulated climate-change scenario was highly dependent on the direction and magnitude of the precipitation changes in combination with the temperature increases.

Results from the daily (Wolock and others, 1989) and monthly (McCabe and Ayers, 1989) streamflow simulation of the basin indicate that atmospheric warming would increase the proportion of winter precipitation that falls as rain, which would increase winter streamflow, reduce snow accumulation, and reduce spring streamflow in the northern part of the basin. These findings agree with findings from other studies (Schaake and Kaczmarek, 1979; Gleick, 1987, 1989; Lettenmaier and others, 1988; Schaake, 1990), in which only changes in temperature and precipitation were considered. The effect of  $\text{CO}_2$ -induced warming on increased winter streamflows in the northern part of the basin for the GFDL model projection of climate change at Montrose, Pa., is shown in figure 18. Although the GFDL-projected annual streamflow decreases only 7 percent from the current average, there is a substantial shift in the timing of the projected streamflow.

In the southern two-thirds of the basin, snow accumulation generally is negligible, as illustrated for Trenton (fig. 19). The GFDL model projection of  $\text{CO}_2$ -induced warming resulted in streamflow changes that reflect increased summer evapotranspiration, reduced fall precipitation and soil moisture, and increased winter precipitation.



**Figure 18.** Simulated monthly average streamflow at Montrose, Pa., for present climate conditions and a scenario for a Geophysical Fluid Dynamics Laboratory general circulation model of doubled atmospheric carbon dioxide.

Although the two areas illustrated above appear to respond differently to the GFDL model projection of climate change, a reduction in annual streamflow of about 7 percent was simulated for both areas. Projections from two other GCM's produced simulated changes in annual streamflow for the basin ranging from -39 percent for the GISS model to +9 percent for the OSU model. The wide disparity in the three GCM projections is largely due to the difference in projected changes in precipitation.

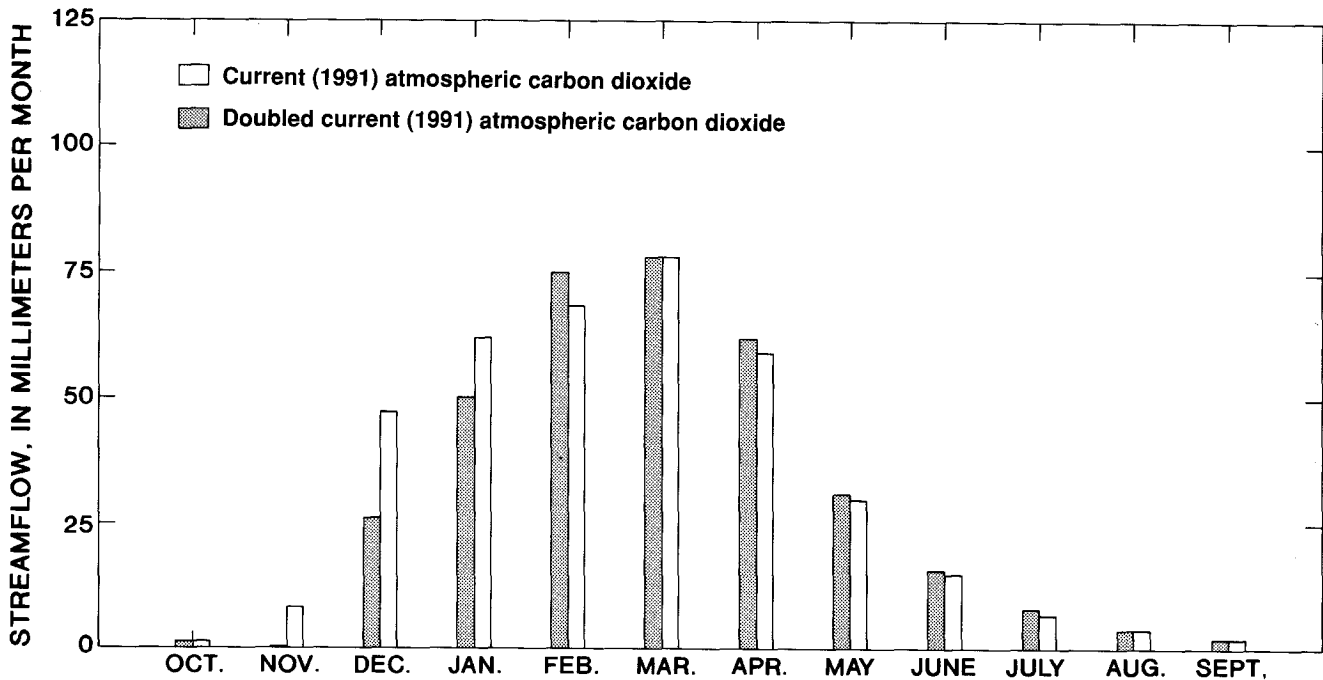
Changes in the 7-day low flow that would result from hypothetical changes in climate and plant stomatal resistance to transpiration were simulated with the stochastic daily climate model as input again to the daily streamflow model of the basin (TOPMODEL; Wolock and others, 1989). Fifty 60-year simulations were performed for several hypothetical scenarios (table 5). The percentage change in 7-day low flow was calculated for each run of each hypothetical climate-change scenario.

The 20th, 50th (median), and 80th percentile values of the percentage change in the 7-day low flow for current conditions (no change) are -11,

+3, and +12, respectively (table 5). These results can be interpreted as a forecast of the potential-change after 60 years in the 7-day low flow due to natural variability alone. The results indicate that the 60-percent confidence interval for the forecast is between -11 and +12 percent, a range of 23 percentage points.

The effect of a 3°C warming on 7-day low flow is indicated by the changes in the 20th, 50th, and 80th percentile values to -27, -13, and -2 percent, respectively (table 5). The negative shift in this distribution of forecasted change in 7-day low flow indicates that the low flow is more likely to decrease with the 3°C warming.

The range in percentage change in 7-day low flow is strongly affected by changes in precipitation and stomatal resistance to transpiration that may accompany a global or regional warming (table 5). If precipitation were to increase 20 percent with the warming, then the range defined by the 20th and 80th percentile values for percentage change in the 7-day low flow would be 0 to 24. If precipitation were to decrease 20 percent with the warming, then the range would be -61 to -34 percent. Finally, if warming were accompanied by a 20-percent increase



**Figure 19.** Simulated monthly average streamflow at Trenton, N.J., for present climate conditions and a scenario for a Geophysical Fluid Dynamics Laboratory general circulation model of doubled atmospheric carbon dioxide.

**Table 5.** Range in percentage change in the 7-day low flow among the fifty 60-year simulations for each hypothetical scenario

[Median 7-day low flow for the first year of the 50 simulations was 1.62 mm. °C, degrees Celsius]

Climate-change scenario			Percentage change in indicated percentiles		
Temperature	Precipitation	Stomatal resistance	20th	50th	80th
No change	No change	No change	-11	3	12
+3°C	No change	No change	-27	-13	-2
+3°C	+20 percent	No change	0	12	24
+3°C	-20 percent	No change	-61	-43	-34
+3°C	No change	+20 percent	-5	9	21

in stomatal resistance, the range would be -5 to +21 percent.

Three categories of uncertainty—the direct CO<sub>2</sub> effects on change in vegetation transpiration, the indirect CO<sub>2</sub> effects on change in precipitation, and the natural variability in climate—have a demonstrated effect on streamflow predictions. Incorporation of a 20-percent increase in stomatal resistance raised the median 7-day low flow change by 22 percentage points. Including a 20-percent increase in precipitation raised the median 7-day low flow change by 25 percentage points. For each climate-change scenario, the range between the 20th and 80th percentile values (natural variability) was about

25 percentage points. Thus, uncertainty in the predictions of streamflow due to the three categories is of the same magnitude, given the ranges used in the simulations.

These results are consistent with other findings (Gleick, 1989). The directions and magnitudes of streamflow changes were highly dependent on the changes in precipitation and stomatal resistance that were assumed to accompany the hypothetical warming. A component of uncertainty that previous studies have ignored, however, is the effect of natural variability. In forecasts of the effects of climate change on streamflow, for the Delaware River basin, the amount of uncertainty due to natural vari-

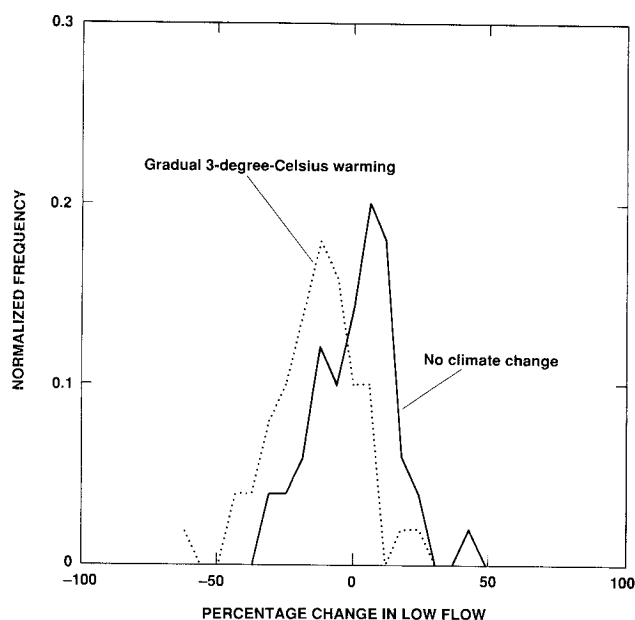
ability is of the same order of magnitude as that due to uncertainty in how the precipitation characteristics or the effects of CO<sub>2</sub> on vegetative transpiration will change. As workers improve their projections of precipitation that accompanies increasing concentrations of atmospheric CO<sub>2</sub>, the uncertainty in forecasts of effects on streamflow will be reduced accordingly. In addition, as research progresses on how increasing atmospheric CO<sub>2</sub> affects vegetation and transpiration, the uncertainty associated with stomatal resistance will decrease. The uncertainty in forecasts due to natural variability, however, is probably irreducible.

### Potential Difficulty in Detecting Changes in Streamflow

Changes in annual streamflow that would result from changes in climate were simulated with the stochastic daily model of climate as input to the daily streamflow model of the basin (TOPMODEL; Wolock and others, 1989). The stochastic climate model was forced to generate daily precipitation statistics equivalent to the statistics of the 1954–88 period of record, and in the simulations, a warming of 0.5°C per decade was assumed to apply to the temperature statistics for that same period. Differences in streamflow between the first and last years of each of the fifty 60-year simulations indicated that most model runs resulted in streamflow decreases (fig. 20). Natural variability in precipitation, however, was large enough to cause some of the model runs to yield streamflow increases and thus partially mask the detection of streamflow decreases resulting from the 3.0°C warming.

Three GCM projections (GISS, GFDL, and OSU models) of climate change were used in another series of TOPMODEL simulations to determine the extent to which a significant decreasing trend in streamflow would be masked by the variability in precipitation. All three GCM's projected a warming greater than 3.0°C. GISS and GFDL projected decreased and unchanged precipitation, respectively, along with the warming, whereas OSU projected slightly increased precipitation. The resulting changes in streamflow (fig. 21) would be detectable much sooner with the first two GCM projections than with the third.

In another TOPMODEL analysis, fifty 60-year simulations were performed for an assumed warming of 3°C and no change in precipitation character-

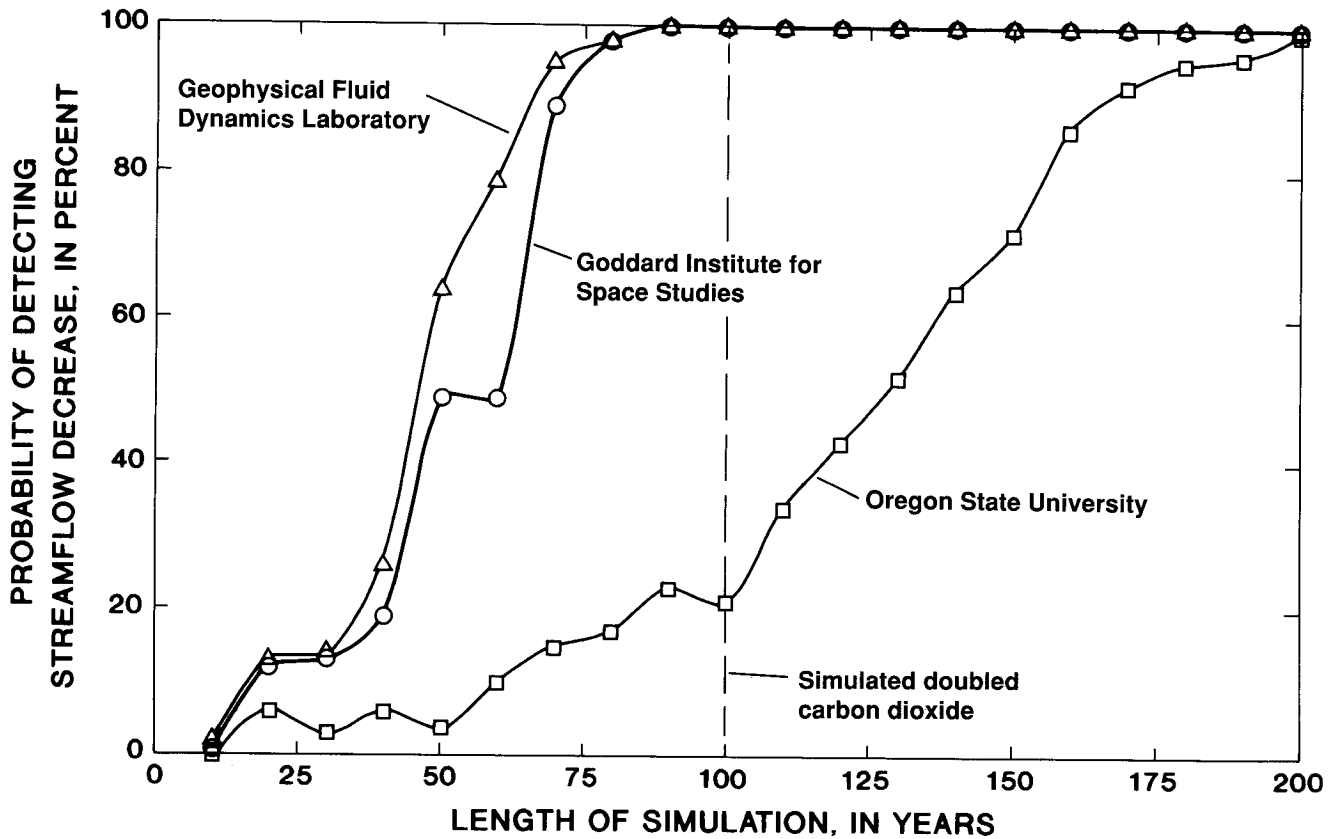


**Figure 20.** Normalized frequency distribution of the percentage change in 7-day low flow in the Delaware River basin for simulations with no climate change and with gradual 3-degree-Celsius warming, both with present precipitation amounts and variability.

istics. Each of the 50 simulations represents a different future realization of the same climate-change projection (warming of 3°C). Annual and monthly maximum daily streamflow and Kendall's tau trend statistics were calculated for each of the 60-year streamflow time series to detect trends in streamflow.

These simulations (table 6) illustrated two important characteristics of the sensitivity of basin streamflow to climate change. First, there are seasonal differences in the expected effects of the hypothetical warming on streamflow. Maximum daily streamflow increases with time (has more positive than negative trends in Kendall's tau) in mid-winter, decreases in spring and summer, and changes little in autumn and early winter. These seasonal differences in trend primarily reflect changes in snowfall accumulation and snowmelt. With a warming, more winter precipitation falls as rain than as snow, and snowmelt occurs earlier. The warming effect is strongest in the northern part of the basin (above lat 40.8°N.), where snow accumulation currently is significant. Second, the natural variability in precipitation masks the effects of increasing temperature. The percentage of simulations that showed no significant increase or decrease





**Figure 21.** Probability of detecting streamflow change in the Delaware River basin over the next 200 years according to three scenarios of general circulation models.

**Table 6.** Numbers and types of trends in maximum daily streamflow for 50 simulations and six streamflow records in Delaware River basin

[Positive (+) or negative (-) trend at significance level equals 0.05; 0, no trend; °N., degrees north, columns 1-6 refer to different gages]

Month	Number of simulated trends			Trends in observed streamflow records					
				Latitude greater than 40.8°N.				Latitude less than 40.8°N.	
	+	-	0	1	2	3	4	5	6
January	12	2	86	0	0	0	0	0	0
February	34	8	58	+	+	+	+	0	0
March	4	22	74	0	0	0	0	0	0
April	0	42	58	0	+	0	0	0	0
May	0	20	80	0	+	0	+	0	0
June	0	14	86	0	0	0	+	0	+
July	0	14	86	-	0	0	0	0	0
August	0	14	86	-	0	0	0	0	0
September	0	8	92	-	0	0	0	0	0
October	0	8	92	0	0	0	0	0	0
November	0	8	92	0	0	0	0	0	0
December	4	8	88	0	0	0	0	+	+
Annual	0	16	84						

in Kendall's tau was greater than 58 in any month and averaged 84.

Six U.S. Geological Survey streamflow gaging stations in the basin were identified as having at least 75 years of streamflow record and few effects from diversions, reservoirs, or urbanization. Data from these stations reveal a positive trend for February maximum daily streamflow during the past 75 years for the more northern watersheds. This trend is similar to the simulated trend in table 6. These six stations represent only a few streams in the basin, and no other general statement can be made about historical trends in streamflow.

The effects of global or regional warming on basin streamflow cannot be determined precisely as yet, principally because of the unreliability of precipitation projections. Furthermore, streamflow changes due to climate change will be extremely difficult to separate from the large natural variability in precipitation.

### Potential Changes in Drought

A monthly water-balance model of the Delaware River basin was developed to analyze the effects of climate change on drought in the basin (Tasker, 1990). In these analyses, drought was defined in terms of either the contents of the New York City water-supply reservoirs or of specified (target) streamflows of the Delaware River at Trenton. The model was developed for five major subbasins of the basin, and algorithms were used to simulate the reservoir operations (reservoir contents and releases) of each subbasin, diversions out of the basin, consumptive water use in each subbasin, and ground-water pumpage from the confined aquifers in the basin (Ayers, Tasker, and others, 1990). A stochastic model of monthly temperature and precipitation also was developed for the five major subbasins as input to each subbasin component of the monthly flow model of the basin (Tasker, 1990). The stochastic climate model was based on monthly statistics of temperature and precipitation for 1895 to 1988 from the U.S. Climate Division data base of the National Weather Service.

### Sensitivity of Drought to Changes in Climate

Simulations with the monthly flow model of the basin indicate that the risk of drought is highly dependent on the changes in precipitation associated with a warming trend (Ayers, Tasker, and others,

**Table 7.** Simulated percentage of time Delaware River basin is in drought, based on New York City reservoir contents, for various changes in climate and consumptive water use

[Drought is defined as a period during which New York City reservoir contents are below levels specified by a seasonal rule curve (Delaware River Basin Commission, 1985). °C, degrees Celsius; —, no data]

Temperature change/ from current conditions	Percentage of time in drought for given precipitation change		
	No change	-10 percent	+10 percent
<u>1986 water use</u>			
None	9.5	—	—
+2°C	17.7	45.8	5.6
+4°C	27.2	61.1	10.3
<u>2040 water use</u>			
None	9.6	—	—
+2°C	17.8	46.0	5.7
+4°C	29.3	61.3	10.4

1990; Tasker, 1990). In this analysis, drought was defined as the percentage of time (for example, 9.5 percent is 1,140 out of the 12,000 simulated months) that the New York City reservoir contents are below volumes specified by a seasonal rule curve (Delaware River Basin Commission, 1985). Current (1986) water-use and climate variability were assumed in fifty 20-year simulations. Results indicate that, under current climate conditions, the basin is in drought about 9.5 percent of the time (table 7).

An increase of 2°C or 4°C in mean temperature increases the time in drought by 1.9 or 2.9 times, respectively. When the warming is accompanied by a 10-percent decrease in precipitation, the time in drought increases 4.8 or 6.4 times, respectively, whereas a 10-percent increase in precipitation significantly decreases the effect of the temperature increases on drought.

To place these simulated climate changes in perspective with the natural variability of the basin, a precipitation change of ±10 percent is about half the standard deviation of annual precipitation at Philadelphia, whereas a temperature change of +4°C is about 6 times the standard deviation of mean annual temperature at Philadelphia. The data in table 7 indicate that a greater sensitivity of basin drought to changes in precipitation than to temperature. Given the large uncertainty associated with climate-change projections, the scenarios in table 7 represent a hypothetical but reasonable range. Consequently, the large range in change (from a 40-percent decrease to a 540-percent increase) in

time the basin is in drought exemplifies the large uncertainty that water-supply planners face regarding climate change.

### Sensitivity of Drought to Changes in Consumptive Water Use

Changes in drought simulated by the monthly flow model (Tasker, 1990) were far less sensitive to the estimated (year 2040) growth in consumptive water use in the basin than to changes in temperature and precipitation (table 7). In that analysis, drought was defined by the contents of the New York City reservoirs. The effects of projected growth in consumptive water use in the upper part of the basin were small (less than a 2-percent increase in time in drought) relative to the effects of climate changes. In other simulations, in which drought was defined by a failure to meet the target flows of the Delaware River at Trenton (not shown in table 7), the effects of projected growth in consumptive water use were somewhat greater but still small (less than a 15-percent increase in time in drought) relative to the effects of climate changes.

### Sensitivity of Drought to Changes in Reservoir Capacity and Use of Ground Water

Reservoirs for water supply, flood control, and low-flow augmentation have been built on several tributary streams of the Delaware River (fig. 16). About 390 billion gallons of total long-term active storage capacity is available in the basin—a volume equal to about 50 days of average flow of the Delaware River at Trenton. The three reservoirs

**Table 8.** Simulated percentage of time Delaware River basin is in drought for various scenarios of reservoir use, diversions, and ground-water use under current (1948–88) climate conditions

[Drought is defined by failure to meet the target discharges of the Delaware River at Trenton, N.J., based on 1986 water-use conditions]

Scenario	Percentage of time in drought
Without reservoirs or out-of-basin diversions	5.00
With upper basin reservoirs and out-of-basin diversions, but without lower basin reservoirs	3.38
With existing reservoirs and diversions, and with:	
No increases in storage or ground-water usage	.69
Increases in ground-water usage	.63
Increases in storage in F.E. Walter reservoir	.38
Increases in storage and ground-water usage	.29

of the New York City system (Cannonsville, Pepacton, and Neversink) in the northern part of the basin account for about 72 percent of this capacity.

Results of other simulations with the monthly flow model (Tasker, 1990), in which drought was also defined by a failure to meet the target flows of the Delaware River at Trenton, indicate that the current system of reservoirs has improved basin water supply substantially during low-flow periods (table 8). Without the current reservoirs and diversions out of the basin, the simulated time the basin would be in drought was 5.00 percent. The presence of reservoirs in the upper basin (above Montague, N.J.), principally the New York City system, reduced the simulated time in drought to 3.38 percent. The entire system of reservoirs and diversions, as existed in 1988, reduced the simulated time in drought to 0.69 percent, a 7-fold decrease in drought compared with unregulated conditions (table 8).

The plans of the Delaware River Basin Commission to increase storage in the Francis E. Walter Reservoir (fig. 16) were simulated with the monthly flow model, and results indicate an improvement in low-flow augmentation. The simulated reservoir decreased the time in drought to 0.38 percent, a 13-fold decrease compared with unregulated conditions (table 8).

Other simulations indicate that increased ground-water pumpage from the confined Coastal Plain aquifers during drought could be an additional source to offset drought-induced water shortages, but not as effective an alternative as the increased storage in the Francis E. Walter Reservoir (Ayers, Tasker, and others, 1990). Together, however, the increased ground-water pumpage and reservoir storage decreased the time in drought to 0.29 percent, a 17-fold decrease in drought compared with unregulated conditions (table 8). The simulations were based on an increase in ground-water pumpage from the confined Coastal Plain aquifers instead of a restriction (as is currently mandated for periods of drought). The model allowed for a constant pumpage of 55 Mgal/d (30 percent less than current ground-water withdrawals) and a 4-fold increase in pumpage when the Delaware River at Trenton was below the target flow. Because ground-water recharge induced from the river lags considerably behind the onset of pumping, the simulation delayed most of the induced recharge to periods of higher runoff and hence simulated a gain in streamflow during drought conditions.

**Table 9.** Simulated percentage of time salt front is above river kilometer 160 or New York City reservoir storage is zero for various percentage reductions in target flows of Delaware River at Montague, N.J., for 4-degree-Celsius warming and 10-percent decrease in precipitation

	Percentage reduction in specified flows <sup>1</sup>						
	0	10	20	30	40	50	60
Percentage of time salt front above river kilometer 160	0.0	0.0	0.0	0.0	0.5	2.0	5.0
Percentage of time reservoir storage zero	4.0	3.0	2.0	1.5	1.0	.05	.0

<sup>1</sup>From current (1988) conditions.

### Sensitivity of Drought to Changes in Specified Flows

Releases from major reservoirs in the basin are managed, according to a rule curve, to meet specified flows in the Delaware River at Montague and Trenton and thus prevent upstream movement of the salt front (the point in the estuary where chloride concentrations are 250 mg/L) into freshwater reaches where surface- and ground-water supplies now derive their water (Delaware River Basin Commission, 1985). New York City reservoirs are the most highly managed of the basin's reservoirs.

Sensitivity analyses were performed for changes in contents of the New York City reservoirs and position of the salt front caused by reductions in specified flows of the Delaware River at Montague. The monthly flow model (Tasker, 1990) was used to simulate the system changes that would result from a 4°C warming and a 10-percent reduction in precipitation. Simulation results indicate that the percentage of time that New York City reservoir storage would reach zero declined from 4.0 percent of the time for zero reduction in specified flows (current requirements) to 1.5 percent of the time for a 30-percent reduction in specified flows (table 9). A reduction in specified flows reduces the amount of reservoir releases needed to satisfy the specified flow and hence conserves reservoir storage. At the same time, the simulated percentage of the time the salt front intruded to river kilometer 160 or above was zero for a 30-percent reduction in specified flows and increased only with a 40-percent or greater reduction in specified flows. The position of the salt front as simulated in this monthly model is not as sensitive to reductions in specified flows as the reservoir contents are. These results indicate that the time the basin would be in drought might be substantially reduced by lowering current or future requirements in meeting target flows of the Delaware River.

### Potential Effects of Sea-Level Rise

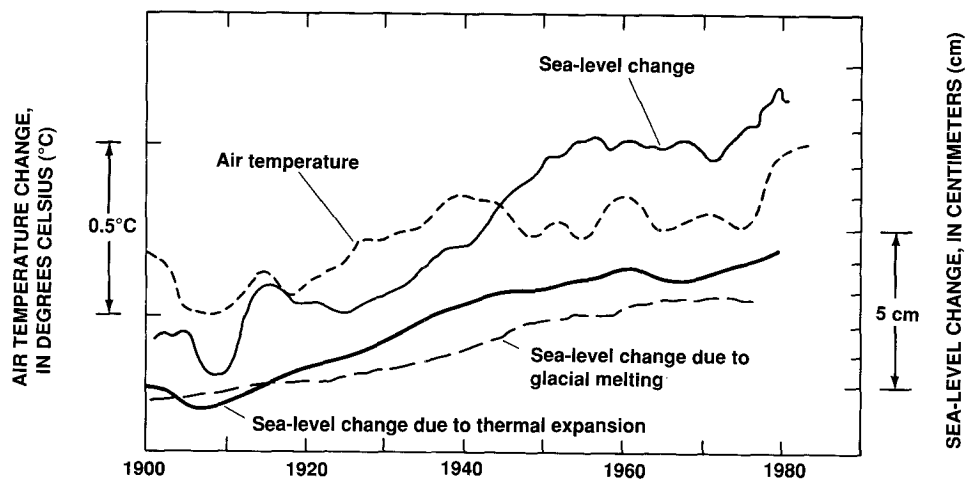
Sea-level rise is likely to accompany a global warming (National Research Council, 1984; Robin, 1986; Titus, 1986). Concerns associated with potential sea-level rise are increases in estuary salinity, increases in saltwater intrusion into coastal aquifer systems, inundation of coastal wetlands and marshes, increases in tidal and storm flooding in coastal areas, and increases in coastal erosion.

### Historical and Potential Changes in Sea Level

Changes in global mean sea level computed since 1900 correlate closely with global mean surface-air temperatures (fig. 22); the correlation coefficient between temperature and sea level is 0.8 when the sea-level record is lagged 18 years behind the temperature record (Robin, 1986). The major factors contributing to sea-level rise are estimated to be thermal expansion of the ocean and melting of small glaciers and ice caps (Gornitz and others, 1982; Meier, 1984; Robin, 1986), both due to global warming. The rise in sea level of 10 to 15 centimeters (cm) over the last 100 years may indicate that global warming is occurring, but does not prove that increased atmospheric CO<sub>2</sub> is the cause of the warming.

Estimates of future sea-level rise, derived from the relation between temperature and sea level in figure 22, range from 15 to 30 cm of rise per 1.0°C of warming (Robin, 1986). A warming of 1.5°C to 4.5°C for doubled CO<sub>2</sub> concentrations could result in an estimated sea-level rise of 23 to 137 cm. Thermal expansion of the ocean and melting of small glaciers and ice caps would be the expected major contributors to the rise.

Titus (1986) qualitatively summarized recent estimates of sea-level rise with four scenarios (fig. 23). These estimates do not include local land uplift or subsidence. For example, the rate of subsidence in the mid-Atlantic coast is 10 to 15 cm per century,



**Figure 22.** Changes in air temperature (Jones and others, 1982) and sea level (Gornitz and others, 1982) since 1900 and contribution to sea-level rise from thermal expansion of oceans (Gornitz and others, 1982) and melting of glaciers (Meier, 1984).

and along the gulf coast the rate is higher. The latest “consensus” estimate of rise in sea level, however, is  $34 \pm 40$  cm in response to a warming due to doubled atmospheric  $\text{CO}_2$  (Meier, 1990). The consensus mean corresponds to the low to middle estimates in figure 23, but the estimates range from a rise of 74 cm to a fall of 6 cm. The large uncertainty is an expression of scientists’ lack of understanding of all the processes involved. Nevertheless, the sensitivities of several hydrologic systems to the potential effects of sea-level rise are discussed below.

### Effects on Estuary Salinity

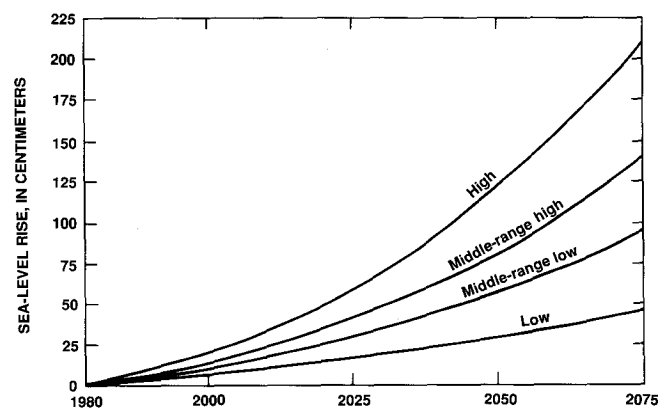
By R.A. Walters and M.A. Ayers

Sea-level rise would affect conditions at the mouth of the Delaware Bay (fig. 24) and would effectively push saltwater farther upstream for a given amount of freshwater flow (fig. 25). For example, a rise of 74 cm would cause the salt front (the point in the estuary where chloride concentration is 250 mg/L) to move about 13 km farther upstream than it normally extends (Hull and others, 1986). Although this scenario is based on the highest current estimates of sea-level rise, such a shift in the salt front would have serious implications for the freshwater withdrawals by the city of Philadelphia and by many industrial users in these reaches.

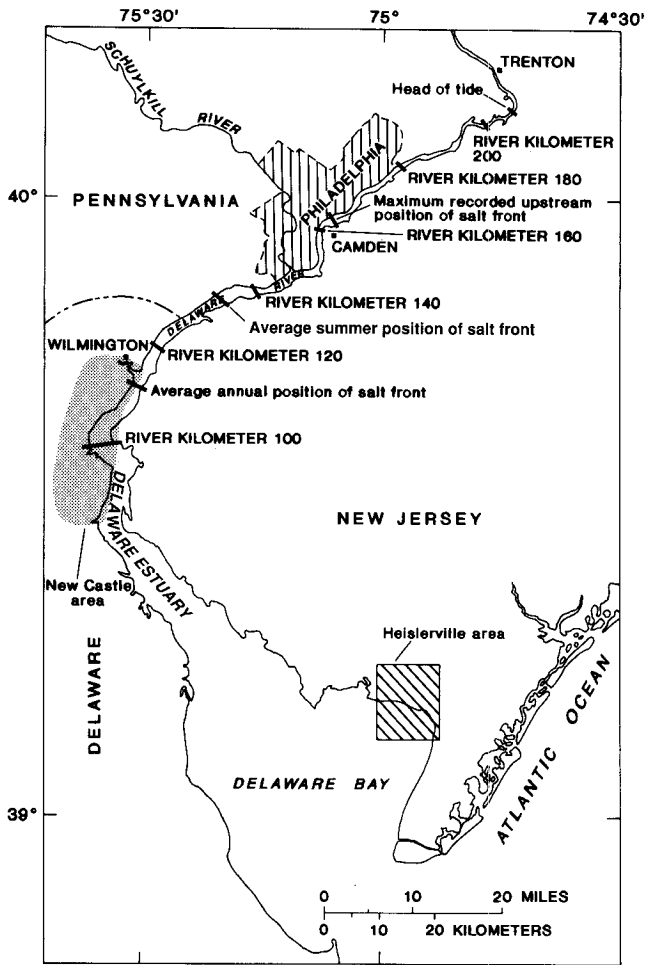
The estimates of Hull and others (1986) are based on a one-dimensional model analysis of the Delaware Bay and Estuary. Walters (1992a, b) developed a three-dimensional model that indicates

that a 100-cm rise in sea level would substantially amplify the tidal oscillation in the upper half of the estuary (above river kilometer 97). The model indicates that the current tidal cycle of about  $\pm 100$  cm would increase to  $\pm 130$  cm. This amplification causes an increase in longitudinal dispersion of saltwater in the model and a simulated increase in saltwater intrusion in the Delaware system beyond what the one-dimensional analysis indicates. At a minimum, the three-dimensional analysis indicates a significant sensitivity of the Delaware system to what would be small changes in channel geometry brought on by a 100-cm rise in sea level.

These scenarios do not consider any change in freshwater flows to the estuary. A decrease in flow would increase upstream salinity movement, whereas an increase in flow would help counteract



**Figure 23.** Projections of sea-level rise, 1980–2075 (modified from Titus, 1986).



Base from U.S. Geological Survey State base map, 1:500,000

**Figure 24.** Location of study areas and average annual, average summer, and maximum recorded upstream positions of salt front in the Delaware Estuary (modified from Ayers and Leavesley, 1988).

upstream salinity movement due to sea-level rise. In essence, additional runoff may be needed to counteract the upstream movement of the salt front during drought conditions, and this need could amplify the shortage of water supplies in the basin during periods of drought.

### Effects on Coastal Aquifers

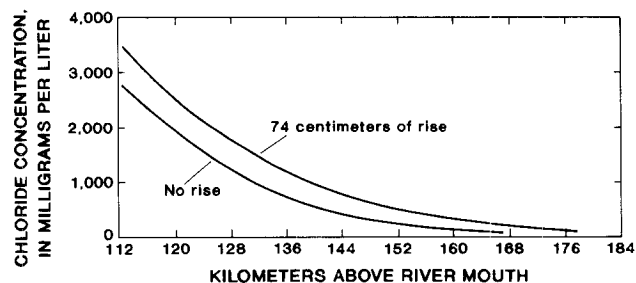
By W.H. Werkheiser and M.A. Ayers

Any upstream movement of the salt front in the Delaware Estuary caused by sea-level rise could increase saltwater intrusion into adjacent aquifers. For example, about 70 percent of the recharge to a New Jersey aquifer system in the Camden, N.J., area currently is induced from the freshwater part of the Delaware Estuary by ground-water pumpage

(figs. 16 and 24; Ayers and Leavesley, 1988). Upstream movement of the salt front would result in saltwater intrusion into previously fresh parts of the aquifer system and would seriously affect major water supplies. Aquifers already affected by saltwater intrusion could undergo accelerated rates of intrusion with a rise in sea level.

One area of concern is near New Castle, Del. (figs. 16 and 24), where a semiconfined aquifer system currently receives about 11 percent of its recharge (Phillips, 1987) from the estuary (usually saline in this reach). Saltwater intrusion moves inland along tributary streams in this area because saline estuary water flows up the tributaries during high tide. Chloride concentrations in the aquifer extend farther inland in some tributaries than in others because the silty confining unit that underlies the estuary does not extend upstream; thus, these areas receive more saline recharge than those where the underlying silty confining unit is present. Local geology is a major factor affecting saltwater intrusion now and would also determine the effect of sea-level rise on future intrusion into coastal aquifers.

A quasi-three-dimensional ground-water flow model of this aquifer system (Phillips, 1987) was used to test the sensitivity of the flow system to two scenarios of sea-level rise (W. Werkheiser, U.S. Geological Survey, written commun., May 1989). In the first scenario, a 150-cm rise in estuary (sea) level was assumed to be accompanied by no change in estuary shoreline boundary. The flow model of the aquifer system estimated that 12.5 percent of the ground-water recharge would be from the estuary—only 1.5 percent more than at present. In the second scenario, however, a 150-cm rise in estuary level was assumed to be accompanied by a new



**Figure 25.** Effect of hypothetical 74-centimeter rise of sea level on 30-day chlorinity in the Delaware Estuary for 1960's drought-equivalent flow in the Delaware River (modified from Hull and others, 1986).

shoreline boundary resulting from the subsequent estimated inundation. The flow model of the aquifer system estimated that more than 30 percent of the aquifer recharge would be from the estuary—almost triple the recharge amount under present conditions or for the first scenario.

The modeling results indicate that this aquifer system is more sensitive to inundation than to sea-level rise alone because the absence of a silty confining unit in areas inundated by a rise in estuary levels allows greater recharge of saline water. Werkheiser (oral commun., 1990), however, tried to verify the extent of current inundation with field reconnaissance and existing maps of the study area. He concluded that the lack of detailed topographic maps (with a 30- to 50-cm contour-interval range) and detailed description of the silty confining unit limited confidence in estimates of current inundation or of potential inundation due to the 150-cm rise. Hence, accurate estimates of either the current amount of recharge or the change in recharge that might result from sea-level rise are practically impossible because of a lack of detailed topographic and geologic data in the study area. No doubt such data are lacking in many other coastal areas.

### **Effects on Coastal Wetlands**

An area along the Delaware Bay near Heislerville, N.J. (fig. 24), illustrates the effects that sea-level rise could have on coastal wetlands. For illustration purposes, a sea-level rise of 150 cm and a new shoreline near the 150-cm contour interval are assumed. The mapped difference between the present and new shorelines (fig. 26) indicates that large areas of tidal wetlands and marshes could be inundated and presumably lost unless they can migrate inland with the rise. The State of New Jersey estimates that 30 to 80 percent of these important ecosystems in the estuary could be lost should a rise of 150 cm occur. Because these systems serve as important filters of sediment and provide habitat and food for a wide range of organisms, a decrease in the extent of coastal wetlands would harm estuarine and coastal water quality, fisheries, and ecology.

### **Effects on Coastal Flooding and Erosion**

Sea-level rise also could increase coastal flooding. Tidal or storm-induced flood surges at an increased sea level would cause water to reach higher elevations and inundate larger areas than at

present. Near Heislerville, for example, an assumed sea-level rise of 150 cm shows that the estimated new 100-year flood elevations would result in more extensive inundation of developed areas (fig. 27). In this and other more developed coastal areas, sea-level rise will result in more frequent inundation of areas that were developed without considering the potential for sea-level rise.

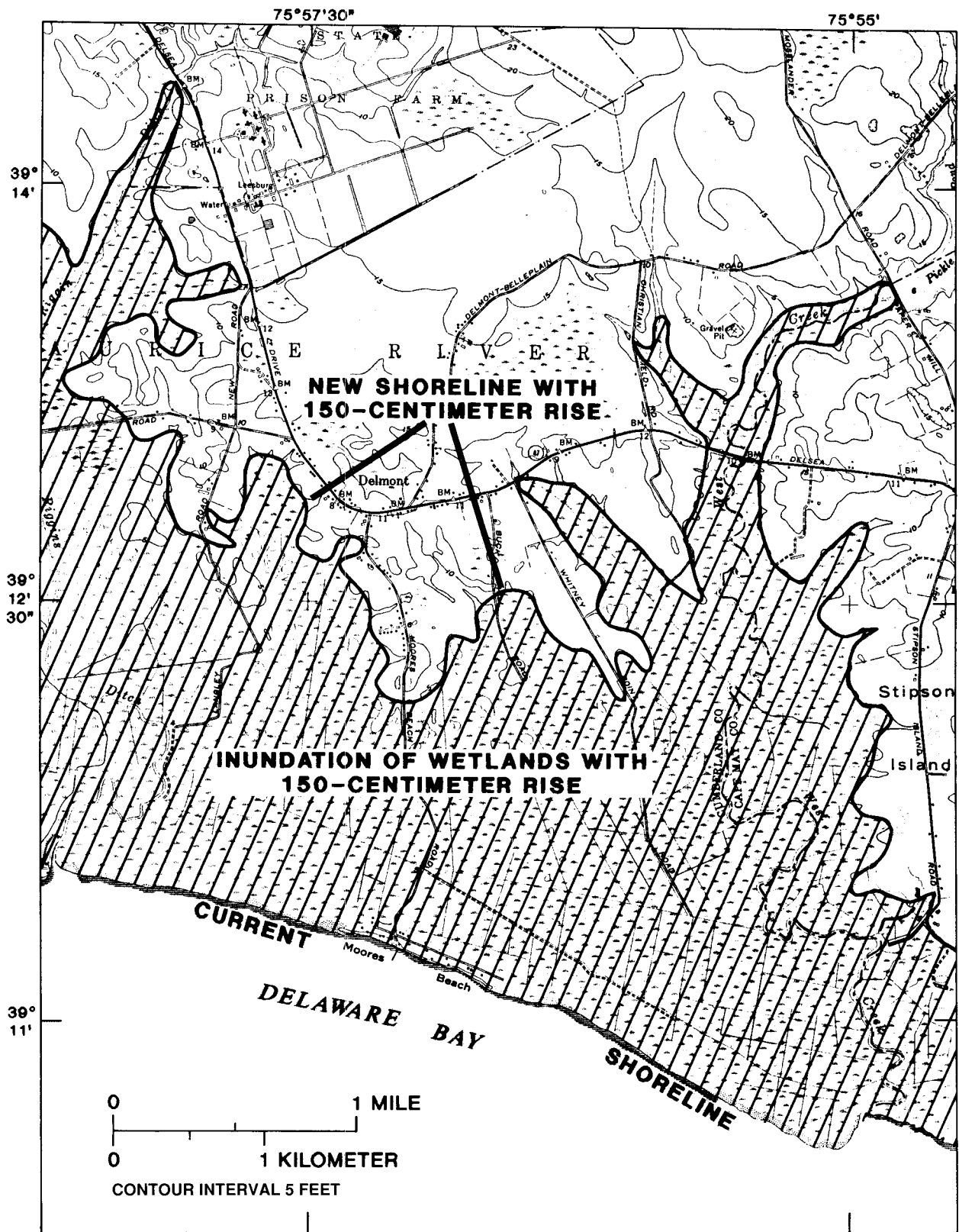
The geomorphic instabilities brought about by a rising sea level, and the resulting changes to shorelines and increased frequency of flooding, likely will result in increased coastal erosion. Coastal erosion already is a problem along much of the Atlantic and gulf coasts.

## **SUMMARY AND CONCLUSIONS**

The greenhouse effect is vital to the support of conditions favorable to Earth's life systems. Atmospheric concentrations of CO<sub>2</sub>, a greenhouse gas, are expected to double in the next century and thereby reach levels that probably have not existed on Earth in more than 1 million years. An increase in atmospheric concentrations of CO<sub>2</sub> is expected to cause global warming, increases in sea level, shifts in regional precipitation patterns, and changes in the transpiration efficiencies of plants.

Detecting CO<sub>2</sub>-induced warming in climate records has been difficult because the records are suspected to contain errors resulting from changes in observers, site measurements, measurement techniques, and local land use. For example, as much as 74 percent of the 0.5°C warming estimated from the records for the last 100 years might be due to the heat-island effect.

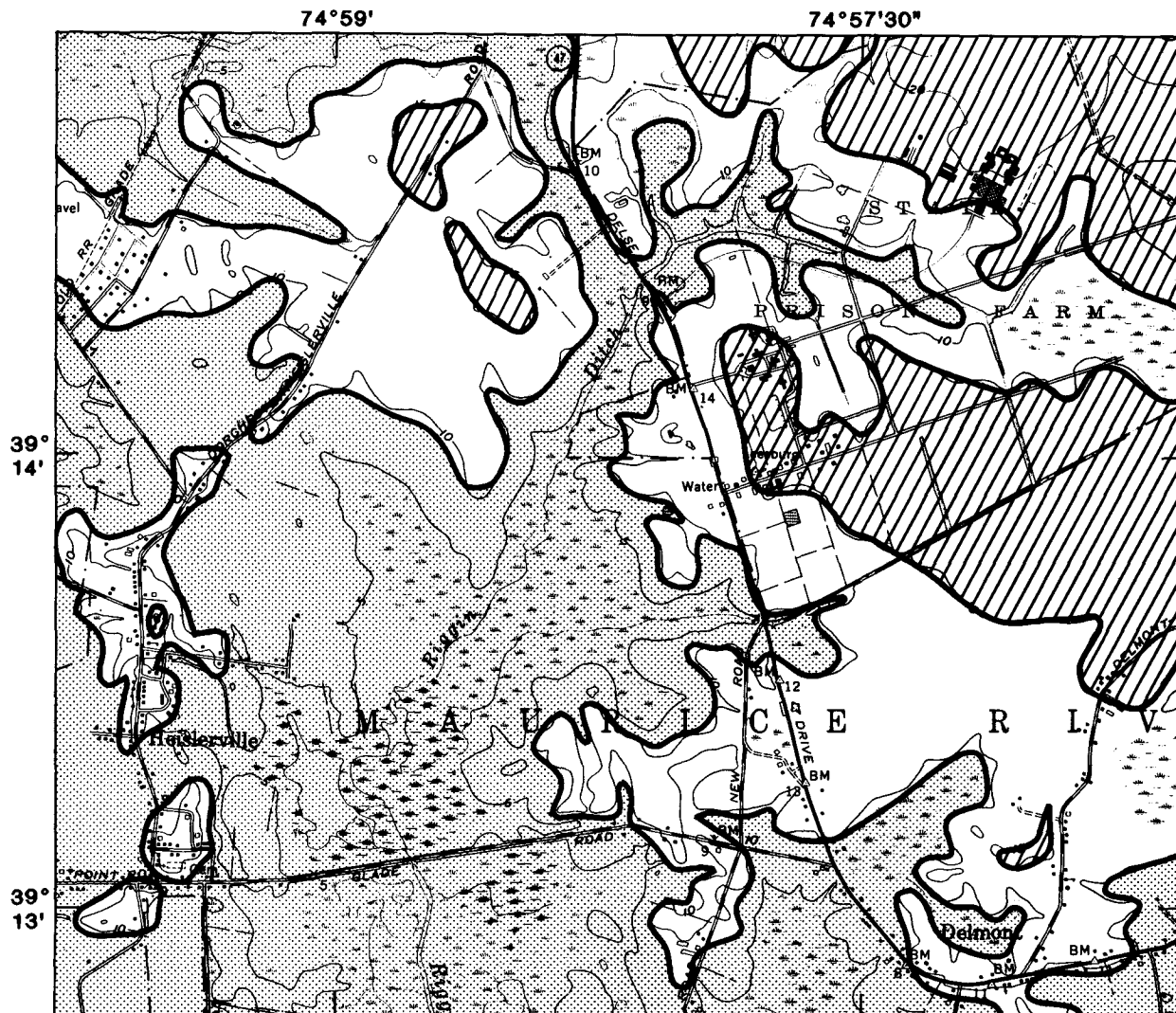
Numerical simulation models of the global climate system, referred to as general circulation models (GCM's), are the most advanced approach used to evaluate the effects of increasing atmospheric CO<sub>2</sub> and other greenhouse gases on climate. Representations of climate feedbacks of energy and moisture are critical to the overall performance of GCM's. Knowledge of these complex interactions and, hence, model representations are inadequate as yet to determine with much confidence what effects the various feedbacks will produce. GCM's indicate that a doubling of atmospheric CO<sub>2</sub> concentrations will induce a global atmospheric warming of 1.5°C to 4.5°C. Large differences among GCM estimates of regional temperature and precipitation, however,



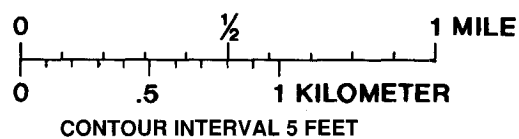
Base from U.S. Geological Survey  
Heislerville, 1:24,000, photo revised 1972

**Figure 26.** Estimated extent of wetland inundation near Heislerville, N.J., that would result from sea-level rise of 150 centimeters.








Base from U.S. Geological Survey  
Heislerville, 1:24,000, photo revised 1972



**EXPLANATION**

-  Current area prone to 100-year flood
-  Area of extended flooding
-  Area not flooded

**Figure 27.** Estimated increase in extent of 100-year flood near Heislerville, N.J., for sea-level rise of 150 centimeters.

exemplify the great uncertainty associated with GCM projections of climate change. The GCM outputs, however, are valuable in setting ranges of potential changes to test hydrologic sensitivities.

GCM results indicate that temperature and precipitation under doubled-CO<sub>2</sub> conditions cause a reduction in Thornthwaite moisture indices, implying drier climate in the Delaware River basin. The amount of decrease depends on the GCM used. Simulation using GCM projections and a hypothetical 4°C increase in temperature both resulted in simulated increases in potential evapotranspiration and decreases in the Thornthwaite moisture indices across the United States. Decreases in the moisture index were greatest in cool, wet regions (Pacific Northwest, Great Lakes, and New England States) and least in hot, dry regions (Southwestern States). Results also show that natural variability strongly influences the detectability of the effects of the temperature increase on the Thornthwaite moisture index.

Simulated changes in mean annual temperature had a greater effect on mean annual irrigation demand for the southern part of the Delaware River basin than did changes in mean annual precipitation. Increased stomatal resistance to transpiration, however, counteracted the effects of increases in temperature and decreases in precipitation.

Daily simulations of basin streamflow indicate that climate has the strongest effect on maximum daily flow, mean daily flow, evapotranspiration, and 7-day low flow. These results indicate that the differences in most of the hydrologic characteristics for small basins in the Delaware River basin are due to differences in climate from one part of the basin to another.

Three categories of uncertainty—direct CO<sub>2</sub> effects on change in stomatal resistance of vegetation to transpiration, indirect CO<sub>2</sub> effects on change in precipitation, and natural variability in climate—were shown to have about the same magnitude of effect on streamflow predictions. As workers improve their projections of precipitation that accompanies increasing atmospheric CO<sub>2</sub> concentrations, the uncertainty in forecasts of effects on streamflow will be reduced accordingly. Furthermore, as research progresses on how increasing atmospheric CO<sub>2</sub> affects vegetation and transpiration, the uncertainty associated with stomatal resistance will decrease. The uncertainty in forecasts due to natural variability, however, probably is irreduc-

ible and will continue to make changes in streamflow due to global warming difficult to distinguish from natural variability.

Simulations of daily and monthly streamflow indicate that a transient warming trend would increase the proportion of winter precipitation that falls as rain, increase winter runoff, reduce snow accumulation, and reduce spring runoff in the northern part of the basin. A warming of 4°C could increase basinwide evapotranspiration and reduce annual basin runoff by as much as 25 percent if current precipitation patterns continue. An increase in precipitation of about 3 percent would be needed to counteract decreases in streamflow that would result from each 1°C of warming.

Simulation results indicate that the Delaware River basin is in drought under current climate conditions about 9.5 percent of the time. An increase of 2°C or 4°C in mean temperature multiplies the time in drought by 1.9 or 2.9, respectively. When the warming is accompanied by a 10-percent decrease in precipitation, the time in drought increases 4.8 and 6.4 times, respectively, whereas a 10-percent increase in precipitation significantly offsets the effect of the temperature increases on time in drought. Basin drought was most sensitive to changes in precipitation and less sensitive to increases in temperature, reservoir capacity, groundwater pumpage during drought, and consumptive water use, in that order. Sensitivity analysis results further indicate that the time the basin would be in drought might be substantially reduced by lowering current or future requirements in meeting target flows of the Delaware River (based on the position of the salt front as simulated in a monthly model).

Global warming will likely cause a rise in sea level through ocean thermal expansion and melting of small glaciers and ice caps. Sea level has risen 10 to 15 cm over the last 100 years. According to current consensus, an estimated future sea-level rise of 34±40 cm would occur in response to a warming caused by a doubling of atmospheric CO<sub>2</sub>, excluding effects of land-surface subsidence.

A sea-level rise would cause the salt front in the Delaware Estuary to move upstream. For example, a sea-level rise of 74 cm would cause the normal position of the salt front to move upstream about 13 km, which would affect surface-water supplies and could increase saltwater intrusion into adjacent aquifer systems. Analysis of the effects of sea-level rise with a three-dimensional estuary

model indicates that the position of the salt front is very sensitive to small changes in channel geometry.

Analysis of the effects of sea-level rise with a quasi-three-dimensional ground-water flow model of an aquifer system in New Castle, Del., indicates that changes in recharge of saltwater to the aquifer were sensitive not so much to the rise itself as to the area inundated by the rise. Clearly limiting the analysis was a lack of detailed (30- to 50-cm contour-interval) maps of coastal areas, which would be needed to define the areas of inundation accurately.

A sea-level rise could result in loss of large areas of tidal wetlands and marshes, unless these features migrate landward with the rise. In many coastal areas, a sea-level rise would increase the frequency of flooding in areas developed without considering rising sea level and would increase coastal erosion, which already is a problem in many areas.

Distinguishing CO<sub>2</sub>-induced changes in climate from natural variability and measurement error is difficult. Furthermore, GCM projections of regional changes are inconsistent and, therefore, considerably lacking in certainty. Results of sensitivity analyses of climate-change effects on water resources described herein, however, have serious implications for future availability of water resources for some climate-change scenarios. Unless more reliable estimates of future precipitation amounts and variability are obtainable along with global warming estimates, the future direction of changes in basin water resources cannot be determined precisely.

Current resource planning and protection policies could either preserve or endanger the future availability of water-related resources. Mitigative measures for one resource may not be beneficial for other resources. For example, in response to sea-level rise, building a dike around a well field or other cultural feature might inadvertently prevent the migration of a wetland system.

Resource planners and managers face many uncertainties in choosing appropriate estimates of climate change to use in resource planning. The best that planners and managers can do is to develop a better understanding of the interactions of the resources involved and, through use of either conceptual or deterministic system models, to define the systems' sensitivity to a range of potential changes in climate. Contingency plans for each scenario of climate change could define how to account for,

evaluate, and respond to each scenario. Then, as confidence is gained about potential changes in temperature, precipitation, and sea-level rise, new change estimates could be applied to system models, and contingency plans could be refined.

## SELECTED REFERENCES

- Anderson, P.W.; Faust, S.D.; and McCall, J.E., 1972, Impact of drought on New Jersey's water resources: American Society of Civil Engineers Proceedings, Journal of the Irrigation and Drainage Division, September 1972, p. 375-385.
- Aston, A.R., 1984, The effect of doubling atmospheric CO<sub>2</sub> on streamflow: Journal of Hydrology, v. 67, p. 273-280.
- Avissar, R., and Verstraete, M.M., 1990, Representation of continental surface processes in atmospheric models: Reviews of Geophysics, v. 28, no. 1, p. 35-52.
- Ayers, M.A., and Leavesley, G.H., 1988, Assessment of the potential effects of climate change on water resources of the Delaware River basin—work plan for 1988-90: U.S. Geological Survey Open-File Report 88-478, 66 p.
- Ayers, M.A.; Tasker, G.D.; Wolock, D.M.; McCabe, G.J.; and Hay, L.E., 1990, Simulated effects of climatic change on runoff and drought in the Delaware River basin, in American Society of Civil Engineers National Conference, San Francisco, Calif., November 1990, Proceedings: American Society of Civil Engineers, p. 31-38.
- Ayers, M.A.; Wolock, D.M.; McCabe, G.J., Jr.; and Hay, L.E., 1989, Hydrologic effects of climatic change in the Delaware River basin: U.S. Geological Survey Yearbook Fiscal Year 1989, p. 31-33.
- 1990, Simulated hydrologic effects of climatic change in the Delaware River basin, in Symposium on International and Transboundary Water Resources Issues, Toronto, Canada, April 1990, Proceedings: Toronto, Canada, American Water Resources Association, p. 587-594.
- Balling, R.C., Jr., and Idso, S.B., 1989, Historical temperature trends in the United States and the effect of urban population growth: Journal of Geophysical Research, v. 94, no. D3, p. 3359-3363.
- Beven, K.J., and Kirkby, M.J., 1979, A physically based, variable contributing area model of basin hydrology: Hydrologic Sciences Bulletin, v. 24, p. 43-69.
- Bolin, B.; Doos, B.R.; Jager, J.; and Warrick, R.A., eds., 1986, The greenhouse effect, climatic change, and ecosystems: New York, Wiley, 541 p.
- Cess, R.D.; Potter, G.L.; Blanchet, J.P.; Boer, G.J.; Ghan, S.J.; Keihl, J.T.; Le Treut, H.; Li, Z.X.;

- Liang, X.Z.; Mitchell, J.F.B.; Morcrette, J.J.; Randall, D.A.; Riches, M.R.; Roeckner, E.; Schlese, U.; Slingo, A.; Taylor, K.E.; Washington, W.M.; Wetherald, R.T.; and Yagai, I., 1989, Interpretation of cloud-climate feedback as produced by 14 atmospheric general circulation models: *Science*, v. 245, p. 513–516.
- Cooperative Holocene Mapping Project Members, 1988, Climatic changes of the last 18,000 years—observations and model simulations: *Science*, v. 241, p. 1043–1052.
- Delaware River Basin Commission, 1985, Water code of the Delaware River basin: West Trenton, N.J., Delaware River Basin Commission, 79 p.
- Dickinson, R.E., 1986, How will climate change?—the climate system and modeling of future climate, *in* Bolin, B.; Doos, B.R.; Jager, J.; and Warrick, R.A., eds., *The greenhouse effect, climatic change, and ecosystems*: New York, Wiley, p. 206–270.
- Eamus, D., and Jarvis, P.G., 1989, The direct effects of increases in global atmospheric CO<sub>2</sub> concentration on natural and commercial trees and forests: *Advances in Ecological Research*, v. 19, p. 1–55.
- Emanuel, W.R.; Shugart, H.H.; and Stevenson, M.P., 1985, Climatic change and the broad scale distribution of terrestrial ecosystem complexes: *Climatic Change*, v. 7, p. 29–43.
- Enfield, D.B., 1989, El Niño, past and present: *Reviews of Geophysics*, v. 27, no. 1, p. 159–187.
- Fouquart, Y.; Buriez, J.C.; Herman, M.; and Kandel, R.S., 1990, The influence of clouds on radiation—a climate modeling perspective: *Reviews of Geophysics*, v. 28, no. 2, p. 145–166.
- Gammon, R.H.; Sundquist, E.T.; and Fraser, P.J., 1985, History of carbon dioxide in the atmosphere, *in* Trabalka, J.R., ed., *Atmospheric carbon dioxide and the global carbon cycle*: U.S. Department of Energy Report DOE/ER-0239, p. 28–62.
- Gates, W.L., 1985, The use of general circulation models in the analysis of the ecosystem impacts of climate change: *Climatic Change*, v. 7, p. 267–284.
- Gleick, P.H., 1986, Methods for evaluating the regional hydrologic impacts of global climate changes: *Journal of Hydrology*, v. 88, p. 97–116.
- 1987, Regional hydrologic consequences of increases in atmospheric CO<sub>2</sub> and other trace gases: *Climatic Change*, v. 10, p. 137–161.
- 1989, Climate change, hydrology, and water resources: *Reviews of Geophysics*, v. 27, no. 3, p. 329–344.
- Goodridge, J.D., 1985, Urban and rural differences in long range temperature trends in California: Los Angeles, Calif., American Meteorological Society, p. 1950–2100. [Preprint from Third Conference on Climatic Variations and Symposium on Contemporary Climate.]
- Gornitz, V.; Lebedeff, L.; and Hansen, J., 1982, Global sea level trend in the past century: *Science*, v. 215, p. 1611–1614.
- Hansen, J.E.; Johnson, D.; Lacis, A.; Lebedeff, S.; Lee, P.; Rind, D.; and Russell, G., 1981, Climate impact of increasing atmospheric carbon dioxide: *Science*, v. 213, p. 957–966.
- Hansen, J.E.; Lacis, A.; Rind, D.; and Russell, G., 1984, Climate sensitivity to increasing greenhouse gases, *in* Barth, M.C., and Titus, J.G., eds., *Greenhouse effect and sea-level rise, a challenge for this generation*: New York, Van Nostrand Reinhold, 62 p.
- Hansen, J.E., and Lebedeff, S., 1988, Global trends of measured surface air temperature: *Journal of Geophysical Research*, v. 92, p. 13345–13372.
- Hansen, J.E.; Russell, G.; Rind, D.; Stone, P.; Lacis, A.; Lebedeff, S.; Ruedy, R.; and Travis, L., 1983, Efficient three-dimensional global models for climate studies—models I and II: *Monthly Weather Review*, v. 111, p. 609–662.
- Hay, L.E.; McCabe, G.J., Jr.; Wolock, D.M.; and Ayers, M.A., 1991, Simulation of precipitation by weather-type analysis: *Water Resources Research*, v. 27, no. 4, p. 493–501.
- 1992, Use of weather types to disaggregate general circulation model predictions: *Journal of Geophysical Research*, v. 97, no. D3, p. 2781–2790.
- Hull, C.H.J.; Thatcher, M.L.; and Tortoriello, R.C., 1986, Salinity in the Delaware Estuary, *in* Hull, C.H.J., and Titus, J.G., eds., *Greenhouse effect, sea-level rise, and salinity in the Delaware Estuary*: Washington, D.C., U.S. Environmental Protection Agency, EPA 230/5–86–010, p. 15–39.
- Hull, C.H.J., and Titus, J.G., eds., 1986, *Greenhouse effect, sea-level rise, and salinity in the Delaware Estuary*: Washington, D.C., U.S. Environmental Protection Agency, EPA 230/5–86–010, 88 p.
- Idso, S.B., and Brazel, A.J., 1984, Rising atmospheric carbon dioxide concentrations may increase streamflow: *Nature*, v. 312, p. 51–53.
- Idso, S.B.; Clawson, K.L.; and Anderson, M.G., 1985, Foliage temperature—effects of environmental factors with implications for plant water stress assessment and the CO<sub>2</sub> climate connection: *Water Resources Research*, v. 22, p. 1702–1716.
- Jenner, C.B., and Lins, H.F., 1991, Climatic atlas of the Delaware River basin: U.S. Geological Survey Professional Paper 1392, 127 p.
- Jones, P.D., and Wigley, T.M.L., 1990, Global warming trends: *Scientific American*, v. 263, no. 2, p. 84–91.
- Jones, P.D.; Wigley, T.M.L.; and Kelley, P.M., 1982, Variations in surface air temperature—part 1, North-

- ern hemisphere 1881–1980: *Monthly Weather Review*, v. 110, p. 59–70.
- Karl, T.R., 1988, Multi-year fluctuations of temperature and precipitation—the gray area of climate change: *Climatic Change*, v. 12, p. 179–197.
- 1989, The recent climate record—what it can and cannot tell us: *Geophysics*, v. 27, no. 3, p. 405–430.
- Keeling, C.D.; Barcastow, R.B.; and Whorf, T.P., 1982, Measurements of the concentration of carbon dioxide at Mauna Loa Observatory, Hawaii, *in* Clark, W.C., ed., *Carbon dioxide review*: New York, Oxford University Press, p. 377–385.
- Kimball, B.A., and Idso, S.B., 1983, Increasing atmospheric CO<sub>2</sub> effects on crop yield, water use, and climate: *Agricultural Water Management*, v. 7, p. 55–72.
- Klemes, V., 1985, Sensitivity of water resource systems to climate variations: Geneva, World Meteorological Organization, World Climate Program, 98 p.
- Lacis, A.; Hansen, J.E.; Lee, P.; Mitchell, T.; and Lebedeff, S., 1981, Greenhouse effect of trace gases, 1970–80: *Geophysical Research Letters*, v. 8, no. 10, p. 1035–1038.
- LaMarche, V.C., Jr.; Graybill, D.A.; Fritts, H.C.; and Rose, M.R., 1984, Increasing atmospheric carbon dioxide—tree ring evidence for growth enhancement in natural vegetation: *Science*, v. 225, p. 1019–1021.
- Lamb, P.J., 1987, On the development of regional climate scenarios for policy-oriented climate-impact analysis: *American Meteorological Society Bulletin*, v. 60, no. 9, p. 1116–1123.
- Lettenmaier, D.P.; Gan, T.Y.; and Dawdy, D.R., 1988, Interpretation of hydrologic effects of climate change in the Sacramento–San Joaquin River basin, California: Seattle, Department of Civil Engineering, Environmental Engineering, and Science, University of Washington, Water Resources Technical Report 110, 111 p.
- Lins, H.F.; Shiklomanov, I.A.; and Stakhiv, E.Z., 1990, Hydrology and water resources, *in* Tegart, W.J.M., Sheldon, G.W., and Griffiths, D.C., eds., *Climate change—the IPCC impacts assessment*: Canberra, Australian Government Publishing Service Press, p. 4.1–4.42.
- Lins, H.F.; Sundquist, E.T.; and Ager, T.A., 1988, Information on selected climate and climate-change issues: U.S. Geological Survey Open-File Report 88–718, 26 p.
- MacCracken, M.C., 1985, Carbon dioxide and climate change—background and overview, *in* MacCracken, M.C., and Luther, F.M., eds., *Projecting the climatic effects of increasing carbon dioxide*: U.S. Department of Energy Report DOE/ER–0237, p. 1–24.
- MacCracken, M.C., and Luther, F.M., 1985, Detecting climatic effects of carbon dioxide: U.S. Department of Energy Report DOE/ER–0235, 198 p.
- Manabe, S., and Stouffer, R.J., 1980, Sensitivity of a global climate model to an increase of CO<sub>2</sub> concentration in the atmosphere: *Journal of Geophysical Research*, v. 85, p. 5529–5554.
- Manabe, S.; Wetherald, R.T.; and Stouffer, R.J., 1981, Summer dryness due to an increase of atmospheric CO<sub>2</sub> concentration: *Climatic Change*, v. 3, p. 347–386.
- Martin, P.; Rosenberg, N.J.; and McKinney, M.S., 1989, Sensitivity of evapotranspiration in a wheat field, a forest, and a grassland to changes in climate and direct effects of carbon dioxide: *Climatic Change*, v. 14, p. 117–151.
- Mather, J.R., 1978, *The climatic water budget in environmental analysis*: Lexington, Mass., Lexington Books, 239 p.
- Mather, J.R., and Feddema, J., 1986, Hydrologic consequences of increases in trace gases and CO<sub>2</sub> in the atmosphere, *in* *Effects of changes in stratospheric ozone and global climate*, volume 3—Climate change: Washington, D.C., U.S. Environmental Protection Agency, p. 251–271.
- McCabe, G.J., 1989, A conceptual weather-type classification for the Philadelphia, Pennsylvania, area: U.S. Geological Survey Water-Resources Investigations Report 89–4183, 23 p.
- McCabe, G.J., and Ayers, M.A., 1989, Hydrologic effects of climate change in the Delaware River basin: *Water Resources Bulletin*, v. 25, no. 6, p. 1231–1242.
- McCabe, G.J.; Hay, L.E.; Kalkstein, L.S.; Wolock, D.M.; and Ayers, M.A., 1989, Simulation of precipitation by weather-type analysis, *in* *Hydraulic Engineering 1989 Proceedings*, National Conference on Hydraulic Engineering, Hydraulics Division, New Orleans, La., August 14–18, 1989: American Society of Civil Engineers, p. 679–684.
- McCabe, G.J., and Wolock, D.M., 1991a, Detectability of the effects of a hypothetical temperature increase on the Thornthwaite moisture index: *Journal of Hydrology*, v. 125, p. 25–35.
- 1991b, Effects of climatic change in the Delaware River basin on the Thornthwaite moisture index: *Climatic Change*, v. 20, p. 143–153.
- 1992, Sensitivity of irrigation demand in a humid-temperate region to hypothetical climatic change: *Water Resources Bulletin of the American Water Resources Association*, v. 28, no. 3, p. 535–543.
- McCabe, G.J., Jr.; Wolock, D.M.; Ayers, M.A.; and Hay, L.E., 1990, Effects of climatic change on the

- Thornthwaite moisture index: *Water Resources Bulletin of the American Water Resources Association*, v. 26, p. 633–643.
- Meier, M.F., 1984, Contribution of small glaciers to global sea level: *Science*, v. 226, p. 1418–1421.
- 1990, Reduced rise in sea level: *Nature*, v. 343, p. 115–116.
- Mitchell, J.F.B., 1989, The “greenhouse” effect and climate change: *Reviews of Geophysics*, v. 27, no. 1, p. 115–140.
- Monastersky, R., 1989, Cloudy concerns—will clouds prevent or promote a drastic global warming?: *Science News*, v. 136, no. 7, p. 106–110.
- Moss, M.E., and Lins, H.F., 1988, Water resources in the twenty-first century—a study of the implications of climate uncertainty: U.S. Geological Survey Circular 1030, 25 p.
- National Academy of Sciences, 1977, Climate, climate change, and water supply overview and recommendations: Washington, D.C., National Academy of Sciences, p. 1–23.
- National Research Council, 1975, Understanding climatic change—a program for action: Washington, D.C., Panel on Climatic Variation, U.S. Committee for GARP, National Academy of Sciences, 239 p.
- 1984, Glaciers, ice sheets, and sea level—effects of carbon dioxide-induced climatic change: Washington, D.C., National Academy of Sciences and U.S. Department of Energy, Report DOE/ER/60235-1, 330 p. [Report of a Workshop, September 13–15, 1984.]
- Neftel, A.; Moor, E.; Eschar, H.; and Stauffer, B., 1985, Evidence from polar ice cores for the increase in atmospheric CO<sub>2</sub> in the last two centuries: *Nature*, v. 315, p. 45–47.
- Nemec, J., and Shaake, J.S., Jr., 1982, Sensitivity of water resource systems to climate variation: *Journal of Hydrological Sciences*, v. 27, no. 3, p. 327–343.
- Omernik, J.M., 1986, Ecoregions of the conterminous United States: Corvallis, Oreg., U.S. Environmental Protection Agency, Corvallis Environmental Research Laboratory, 2 p.
- Palutikof, J.P.; Wigley, T.M.L.; and Lough, J.M., 1984, Seasonal scenarios for Europe and North America in a high-CO<sub>2</sub>, warmer world: U.S. Department of Energy, Carbon Dioxide Research Division, Technical Report TR012, 70 p.
- Parker, G.G.; Hely, A.G.; Keighton, W.B.; Olmsted, F.H.; and others, 1964, Water resources of the Delaware River basin: U.S. Geological Survey Professional Paper 381, 200 p.
- Patterson, D.T., and Flint, E.P., 1980, Potential effects of global atmospheric enrichment on the growth and competitiveness of C<sub>3</sub> and C<sub>4</sub> weed and crop plants: *Weed Science*, v. 28, p. 71.
- Pearman, G.I., and Fraser, P.J., 1988, Sources of increased methane: *Nature*, v. 332, p. 489–490.
- Peng, L.; Chou, M.D.; and Arking, A., 1987, Climate warming due to increasing atmospheric CO<sub>2</sub>—simulation with a multilayer coupled atmospheric-ocean energy balance model: *Journal of Geophysical Research (Atmospheres)*, v. 92, no. D5, p. 5505–5521.
- Peng, T.H.; Broecker, W.S.; Freyer, H.D.; and Trumbore, S., 1983, A deconvolution of the tree ring based CO<sub>2</sub> record: *Journal of Geophysical Research*, v. 88, p. 3609–3620.
- Phillips, S.W., 1987, Hydrogeology, degradation of ground-water quality, and simulation of infiltration from the Delaware River into the Potomac aquifers, northern Delaware: U.S. Geological Survey Water-Resources Investigations Report 87–4185, 86 p.
- Ramanathan, V., 1981, The role of ocean-atmosphere interactions in the CO<sub>2</sub> climate problem: *Journal of Atmospheric Science*, v. 38, p. 918–930.
- Rind, D., 1988, The doubled carbon dioxide climate and the sensitivity of the modeled hydrologic cycle: *Journal of Geophysical Research*, v. 93, no. D5, p. 5385–5412.
- Rind, D.; Goldberg, R.; Hansen, J.; Rozenzweig, C.; and Ruedy, R., 1990, Potential evapotranspiration and the likelihood of future drought: *Journal of Geophysical Research*, v. 95, no. D7, p. 9983–10004.
- Robin, G.D., 1986, Changing the sea level—projecting the rise in sea level by warming of the atmosphere, *in* Bolin, B.; Doos, B.R.; Jager, J.; and Warrick, R.A., eds., *The greenhouse effect, climatic change, and ecosystems*: New York, Wiley, p. 323–362.
- Robock, A., 1985, An updated climatic feedback diagram: *American Meteorological Society Bulletin*, v. 66, p. 786–787.
- Rogers, H.H.; Thomas, J.F.; and Bingham, G.E., 1983, Response of agronomic and forest species to elevated atmospheric carbon dioxide: *Science*, v. 220, p. 428–429.
- Rosenberg, N.J.; McKinney, M.S.; and Martin, P., 1989, Evapotranspiration in a greenhouse-warmed world—a review and a simulation: *Agricultural and Forest Meteorology*, v. 47, p. 303–320.
- Schaake, J.S., 1990, From climate to flow, *in* Waggoner, P.E., ed., *Climate change and U.S. water resources*: New York, Wiley, p. 177–206.
- Schaake, J.S., and Kaczmarek, Z., 1979, Climate variability and the design and operation of water resource systems, *in* *Proceedings of World Climate Conference*: Geneva, World Meteorological Organization, p. 290–312.
- Schlesinger, M.E., and Gates, W.L., 1980, The January and July performance of the OSU two-level atmos-

- pheric general circulation model: *Journal of Atmospheric Science*, v. 37, p. 1914–1943.
- Schlesinger, M.E., and Mitchell, J.F.B., 1985, Model projections of equilibrium climate response to increased CO<sub>2</sub> concentrations, *in* MacCracken, M.C., and Luther, F.M., eds., *Projecting the climatic effects of increasing carbon dioxide*: U.S. Department of Energy Report DOE/ER-0237, p. 81–147.
- Shugart, H.H.; Antonovsky, M.Y.; Jarvis, P.G.; and Sandford, A.P., 1986, CO<sub>2</sub>, climatic change, and forest ecosystems, *in* Bolin, B.; Doos, B.R.; Jager, J.; and Warrick, R.A., eds., *The greenhouse effect, climatic change, and ecosystems*: New York, Wiley, p. 475–521.
- Smagorinsky, J., 1982, Carbon dioxide—a second assessment: Washington, D.C., National Academy of Sciences, Climate Research Board, 72 p.
- Strain, B.R., and Cure, J.D., 1985, Direct effects of increasing carbon dioxide on vegetation: U.S. Department of Energy Report DOE/ER-0239, 286 p.
- Tasker, G.D., 1990, Some hydrological impacts of climate change for the Delaware River basin, *in* Water Resources Planning and Management Division, National Conference, Ft. Worth, April 1990, Proceedings: Ft. Worth, Tex., American Society of Civil Engineers, p. 541–544.
- Thornthwaite, C.W., and Mather, J.R., 1955, *The water balance*: Newark, Del., University of Delaware, Publications in climatology, v. 8, no. 1, 104 p.
- Titus, J.G., 1986, The basis for expecting a rise in sea level, *in* Hull, C.H.J., and Titus, J.G., eds., *Greenhouse effect, sea-level rise, and salinity in the Delaware Estuary*: Washington, D.C., U.S. Environmental Protection Agency, EPA 230-05-86-010, p. 3–14.
- Vacarro, J.J., 1991, Sensitivity of ground-water-recharge estimates to climate variability and change, Ellensburg Basin, Columbia Plateau, Washington: U.S. Geological Survey Water-Resources Investigations Report 91-4001, 30 p.
- Verstraete, M.M., and Dickinson, R.E., 1986, Modeling surface processes in atmospheric general circulation models: *Annales Geophysicae*, v. 4, no. B4, p. 357–364.
- Vinnikov, K.Y., and others, 1980, [Current climate changes in the Northern Hemisphere]: *Meteorologiya i Gidrologiya* 1980, no. 6, p. 5–17. [in Russian.]
- Waggoner, P.E., ed., 1990, *Climate change and U.S. water resources*: New York, Wiley, 496 p.
- Walters, R.A., 1992a, A study of salt transport processes in Delaware Bay, *in* Spaulding, M.L., and others, eds., *Proceedings of the 2d International Conference on Estuarine and Coastal Modeling*, Tampa, Fla.: American Society of Civil Engineers, p. 240–251.
- 1992b, A 3D, finite element model for coastal and estuarine circulation: *Continental Shelf Research*, v. 12, no. 1, p. 83–102.
- Washington, W.M., and Meehl, G.A., 1984, Seasonal cycle experiment on the climate sensitivity due to a doubling of CO<sub>2</sub> with an atmospheric general circulation model coupled to a simple mixed-layer ocean model: *Journal of Geophysical Research*, v. 89, p. 9475–9503.
- Webb, T., and Wigley, T.M.L., 1985, What past climates can indicate about a warmer world, *in* MacCracken, M.C., and Luther, F.M., eds., *Projecting the climatic effects of increasing carbon dioxide*: U.S. Department of Energy Report DOE/ER-0237, p. 237–258.
- Wetherald, R.T., and Manabe, S., 1981, Influence of seasonal variation upon the sensitivity of a model climate: *Journal of Geophysical Research*, v. 86, p. 1194–1204.
- Wigley, T.M.L.; Angel, J.K.; and Jones, P.D., 1985, Analysis of the temperature record, *in* MacCracken, M.C., and Luther, F.M., eds., *Detecting climatic effects of carbon dioxide*: U.S. Department of Energy Report DOE/ER-0235, p. 55–90.
- Wigley, T.M.L., and Jones, P.D., 1985, Influences of precipitation changes and direct CO<sub>2</sub> effects on streamflow: *Nature*, v. 314, p. 149–152.
- Wolock, D.M.; Ayers, M.A.; Hay, L.E.; and McCabe, G.J., 1989, Effects of climate change on watershed runoff, *in* *Hydraulic Engineering 1989 Proceedings*, National Conference on Hydraulic Engineering, Hydraulics Division, New Orleans, La., August 14–18, 1989: American Society of Civil Engineers, p. 673–678.
- Wolock, D.M., and Hornberger, G.M., 1991, Hydrological effects of atmospheric changes in levels of carbon dioxide: *Journal of Forecasting*, v. 10, p. 105–116.
- World Meteorological Organization, 1987, *Water resources and climatic change—sensitivity of water-resources systems to climate change and variability*: World Climate Programme Applications, WCAP-4, WMO/TD 247, 51 p.