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Greenhouse Effect, Sea Level Rise, and Salinity in the *Delaware* Estuary

GREENHOUSE EFFECT, SEA LEVEL RISE, AND SALINITY IN THE DELAWARE ESTUARY

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This document has been reviewed in accordance with the U.S. Environmental Protection Agency and Delaware River Basin Commission peer and administrative review policies and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. Please send comments to James G. Titus (PM-220), Strategic Studies Staff, U.S. Environmental Protection Agency, Washington, D.C. 20460.

SUMMARY

Increasing atmospheric concentrations of carbon dioxide and other gases are expected to warm the earth a few degrees (C) in the next century by a mechanism commonly known as the "greenhouse effect." Such a warming could alter precipitation patterns and raise sea level. Although it is not yet possible to predict whether particular areas will receive more or less rainfall, there is a general agreement that sea level will rise. Unfortunately, estimates for the year 2025 range from 5 to 21 inches above current sea level, while estimates of the rise by 2100 range from 2 to 11 feet.

Several issues must be resolved for society to rationally address the possibility of significant changes in climate and sea level. Officials making decisions about near-term projects with long lifetimes must examine the potential consequences and determine whether these risks justify a shift to strategies that are less vulnerable to changes in sea level or the frequency or severity of droughts. Research officials must assess the opportunities for improving predictions and decide whether the need for these improvements justifies accelerating the necessary research. Decision makers must decide whether to base policies on today's inadequate knowledge or ignore the implications until they are more certain.

One potential impact of a global warming and rise in sea level would be an increase in the salinity of estuaries, which might threaten drinking water and aquatic ecosystems. The Delaware River Basin Commission (DRBC) has long considered the implications of droughts on management of water resources in the Delaware estuary; since 1979, it has also considered the implications of recent sea level trends. However, the DRBC has not previously focused on the possibility that the "greenhouse warming" could exacerbate salinity problems. The Environmental Protection Agency has initiated studies on the impacts of sea level rise and climate change on erosion, flooding, and wetland protection, but has not previously examined the impacts on salinity.

This joint report by the Environmental Protection Agency and the Delaware River Basin Commission examines the implications of the greenhouse warming for salinity control in the Delaware estuary. The study focuses on the implications of (1) a 21-inch rise in global sea level expected by 2050, which would imply a rise of 2.4 feet in the Delaware estuary; and (2) a 7-foot global rise by 2100, which would imply an 8.2-foot rise in the Delaware estuary. The authors estimate the increase in estuary salinity, estimate the possible increase in salinity of the Potomac-Raritan-Magothy aquifer system, discuss the implications, and examine possible responses. Potential changes in precipitation are not evaluated.

CONCLUSIONS

1. Sea level rise could substantially increase the salinity of the Delaware estuary in the next century. If no countermeasures are taken, a repeat of the 1960s' drought with a 2.4-foot rise would send the salt front upstream to river-mile 100, compared with mile 93 for current sea level. Moreover, the chloride concentration at mile 98, the DRBC salinity control point, would increase from 136 parts per million (ppm) to 305 ppm. An 8.2-foot rise would send the salt front upstream to mile 117 and would increase salinity to 1560 ppm at the salinity control point.

2. Accelerated sea level rise could cause excessive salinity concentrations at Philadelphia's Torresdale intake if no countermeasures are taken. For a 2.4-foot rise, sodium concentrations would exceed 50 ppm (the New Jersey drinking water standard) during 15 percent of the tidal cycles during a recurrence of the 1960s drought. For an 8.2-foot rise, sodium concentrations would exceed 50 ppm during 50 percent of the tidal cycles.

3. Accelerated sea level rise could threaten the New Jersey aquifers recharged by the Delaware River. During the 1960s drought, river water with chloride concentrations as high as 150 ppm recharged the Potomac-Raritan-Magothy aquifer in the vicinity of Camden, raising chloride concentrations of some wells from 20 ppm to 80 ppm. A repeat of the 1960s' drought with a 2.4-foot rise in sea level would result in river water with concentrations as high as 350 ppm recharging the aquifer in this area. During the worst month of the drought, over one-half of the river water recharging the aquifer would have chloride concentrations in excess of 250 ppm. With an 8.2-foot rise, 98 percent of the recharge during the worst month of the drought would have chloride concentrations greater than 250 ppm, and 75 percent of the recharge would be greater than 1000 ppm. (The EPA drinking water standard is 250 ppm, and water with chloride concentrations greater than 78 ppm generally exceeds the 50-ppm sodium standard.)

4. Planned but unscheduled reservoirs could offset salinity increases expected in the next forty years. Salinity increases resulting from a one foot rise in sea level expected in the next forty years would require increased reservoir capacity of at least 110 thousand acre-feet. However, reservoirs planned by the DRBC but not yet scheduled would have a combined capacity of 592 thousand acre feet.

5. Possible shifts in precipitation resulting from the greenhouse warming could overwhelm salinity increases caused by sea level rise. Excessive salinity has been a problem only during droughts. Unfortunately, it is not possible to determine whether the Delaware River Basin will receive more or less rainfall in the future. A recent study by NASA suggested that a tenfold increase in drought frequency cannot be ruled out. On the other hand, some researchers have suggested that most coastal areas will experience a 10 percent increase in precipitation.

6. Uncertainties regarding future climate change do not necessarily imply that waiting for better predictions is the most prudent strategy. There is no guarantee that accurate climate projections will be possible when they are needed. Moreover, some measures may have potential benefits so far in excess of their costs as to be warranted in spite of current uncertainties. For example, identifying potential reservoir sites long before they are necessary and not developing them for other uses can ensure that they are available if and when they are needed, without imposing substantial costs. Waiting until they are needed could result in no satisfactory sites being available.

7. A regional study should be initiated that examines the potential impacts of precipitation changes as well as sea level rise for the Delaware estuary and adjacent river basins. A thorough understanding of the water resource challenges faced by the Delaware River Basin is not possible without considering the needs of New York City and other areas outside the Basin that depend on the Delaware for water supply.

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I. INTRODUCTION

Increasing atmospheric concentrations of carbon dioxide, methane, chlorofluorocarbons, and other gases are expected to raise the earth's average surface temperature several degrees in the next century by a mechanism commonly known as the "greenhouse effect." Such a global warming would probably raise sea level and substantially change precipitation patterns worldwide, altering water quality and availability and upsetting wetland and aquatic ecosystems. Scientific understanding is not yet sufficient to estimate the impacts accurately, but it is sufficient to expect that the changes will be substantial.

Although it is not yet possible to project future climate change for specific regions, there is a consensus on the probable increase in average temperatures. Because sea level depends mostly on the global average temperature, it is possible to estimate the likely range of its rise. Recent reports by the National Academy of Sciences and the Environmental Protection Agency project a worldwide rise in sea level of sixty to one hundred fifty centimeters (two to five feet) in the next century. Such a rise would be a substantial acceleration over the rise of thirty centimeters (one foot) that has taken place along the Atlantic coast in the last century.

One of the impacts of a rise in sea level is an increase in the salinity of estuaries and aquifers. In 1979, the Delaware River Basin Commission (DRBC) investigated the impact of recent sea level trends on salinity in the estuary and determined the measures that would be necessary by the year 2000 to counteract the increased salinity caused by droughts and sea level rise. Because no projections on the impact of the greenhouse effect were available at the time, that study did not consider the implications of an acceleration of the current rate of sea level rise.

This report examines the potential impacts of accelerated sea level rise on salinity in the Delaware estuary and adjacent aquifers in New Jersey. Although the impacts we examine are uncertain and contingent upon particular rates of sea level rise occurring in the future, this type of analysis is useful because it may be possible to identify cost-effective opportunities to prevent or mitigate possible consequences that warrant consideration even today. We hope that this report stimulates interest in the long-term planning necessary for management of the Delaware estuary to meet successfully the challenge of a rise in sea level.

This report first describes the basis for expecting a rise in sea level. It then explains how droughts and rising sea level increase the salinity of an estuary, describes the impact of droughts on salinity that would result from a 73- and 250-centimeter (2.4- and 8.2-foot) rise in sea level, and discusses some of the consequences. Section 4 discusses the impact of increased river salinity on the adjacent Potomac-Raritan-Magothy aquifer system in New Jersey. Section 5 provides a qualitative discussion of possible responses, including ways of preventing salinity increases in the estuary and the aquifer, and ways of adjusting to the increases.

The report concludes by outlining the next steps that should be taken to determine the best responses to the greenhouse effect. Problems with increased salinity generally occur during droughts, the frequency of which may be different in the future. Although this effort is limited to sea level rise, a more in-depth assessment must also consider possible changes in precipitation.

II. THE BASIS FOR EXPECTING A RISE IN SEA LEVEL

Past Changes in Climate and Sea Level

Throughout geologic history, sea level has risen and fallen by over three hundred meters (one thousand feet). Although changes in the size and shape of the oceans' basins have played a role over very long periods of time (Hays and Pitman 1973), the most important changes in sea level have been caused by changes in climate. During the last ice age (18,000 years ago), for example, the earth was about five degrees celsius colder than today, glaciers covered most of the northern hemisphere, and sea level was one hundred meters (three hundred feet) lower than today (Donn, Farrand, and Ewing 1962).

Although most of the glaciers have melted since the last ice age, polar glaciers in Greenland and Antarctica still contain enough water to raise sea level more than seventy meters (over two hundred feet) (Untersteiner 1975). A complete melting of these glaciers has not occurred in the last two million years, and would take tens of thousands of years even if the earth warmed substantially. However, unlike the other glaciers, which rest on land, the west antarctic ice sheet is marine-based and more vulnerable to temperature increases. Warmer ocean water would be more effective than warmer air at melting glaciers, causing West Antarctica to melt. Mercer (1970) suggests that the West Antarctic Ice Sheet completely disappeared during the last interglacial period (which was one or two degrees warmer than today and occurred 100,000 years ago), at which time sea level was five to seven meters (about twenty feet) above its present level.

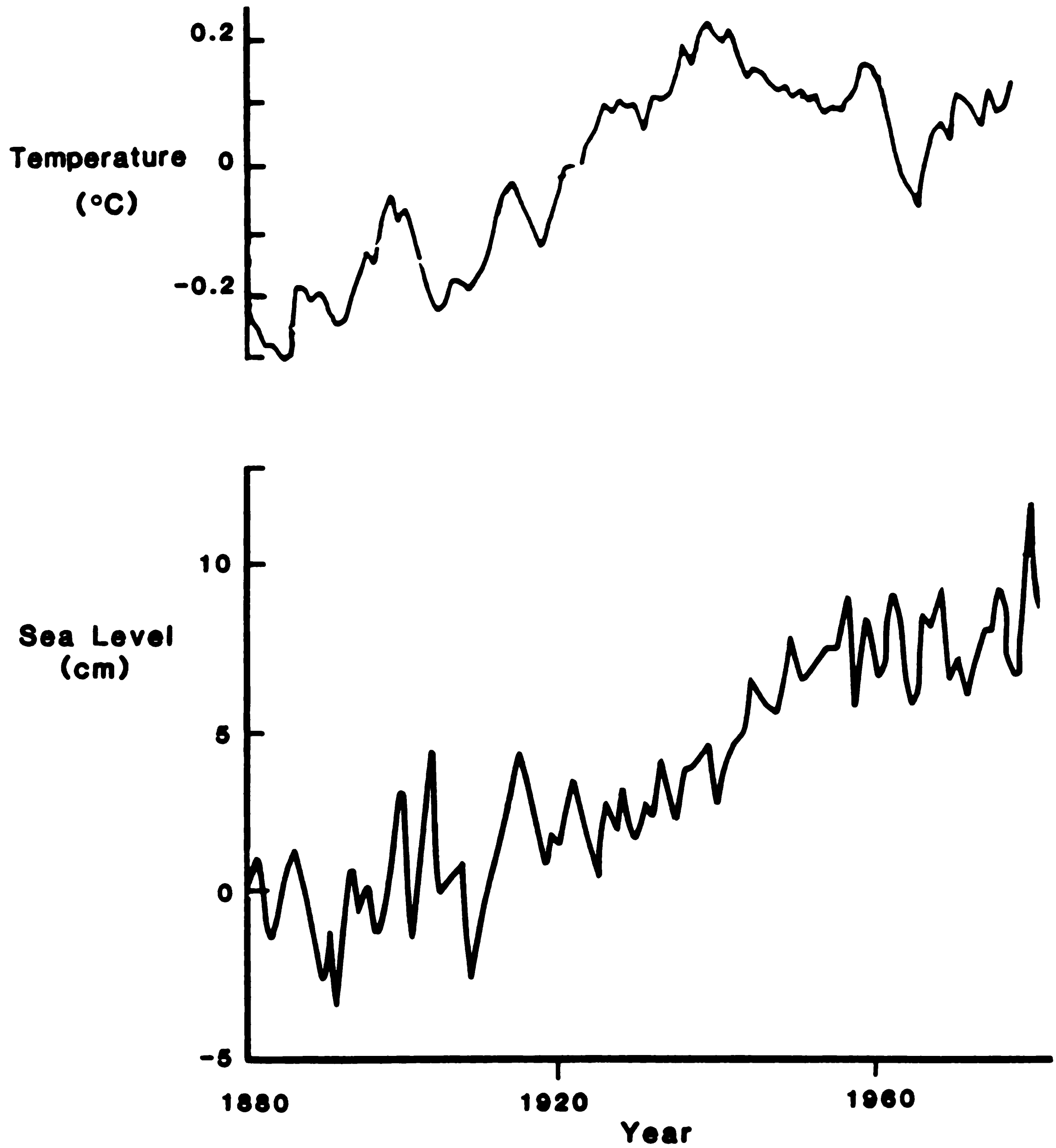
Over relatively short periods of time, climate can influence sea level by heating and thereby expanding (or cooling and contracting) sea water. In the last century, tidal gauges have been available to measure relative sea level in particular locations. Along the Atlantic Coast, sea level has risen about 30 centimeters (one foot) in the last century (Hicks, Debaugh, and Hickman 1983). (Figure 7 shows the rise that has taken place at Philadelphia.) Studies combining all the measurements have concluded that average worldwide sea level has risen ten to fifteen centimeters (four to six inches) in the last one hundred years (Barnett 1983; Gornitz, Lebedeff, and Hansen 1982). At least part of this rise can be explained by the thermal expansion of the upper layers of the oceans resulting from the observed warming of 0.4°C in the last century (Gornitz, Lebedeff, and Hansen 1982). Meltwater from mountain glaciers has also contributed to sea level rise (Meier 1984). Figure 1 shows that global temperature and sea level have been rising in the last century. Nevertheless, questions remain over the magnitude and causes of sea level rise in the last century.

The Greenhouse Effect

Concern about a possible acceleration in the rate of sea level rise stems from measurements showing that concentrations of carbon dioxide (CO_2), methane, chlorofluorocarbons, and other gases released by human activities are increasing. Because these gases absorb infrared radiation (heat), scientists generally expect the earth to warm substantially. Although some people have suggested that unknown or unpredictable factors could offset this warming, the National Academy of Sciences (NAS) has twice reviewed all the evidence and found that the warming will take place. In 1979, the Academy concluded: "We have tried but have been unable to find any overlooked physical effect that could reduce the currently estimated global warming to negligible proportions"

FIGURE 1

GLOBAL TEMPERATURES AND SEA LEVEL
RISE IN THE LAST CENTURY



Sources: Temperature curve from: HANSEN, J.E., D. JOHNSON, A. LACIS, S. LEBEDEFF, D. RIND, AND G. RUSSELL, 1981. Climate Impact of Increasing Atmospheric Carbon Dioxide, Science 213:957-966. Sea level curve adapted from: GORNITZ, V., S. LEBEDEFF, and J. HANSEN, 1982. Global Sea Level Trend in the Past Century. Science 215:1611-1614.

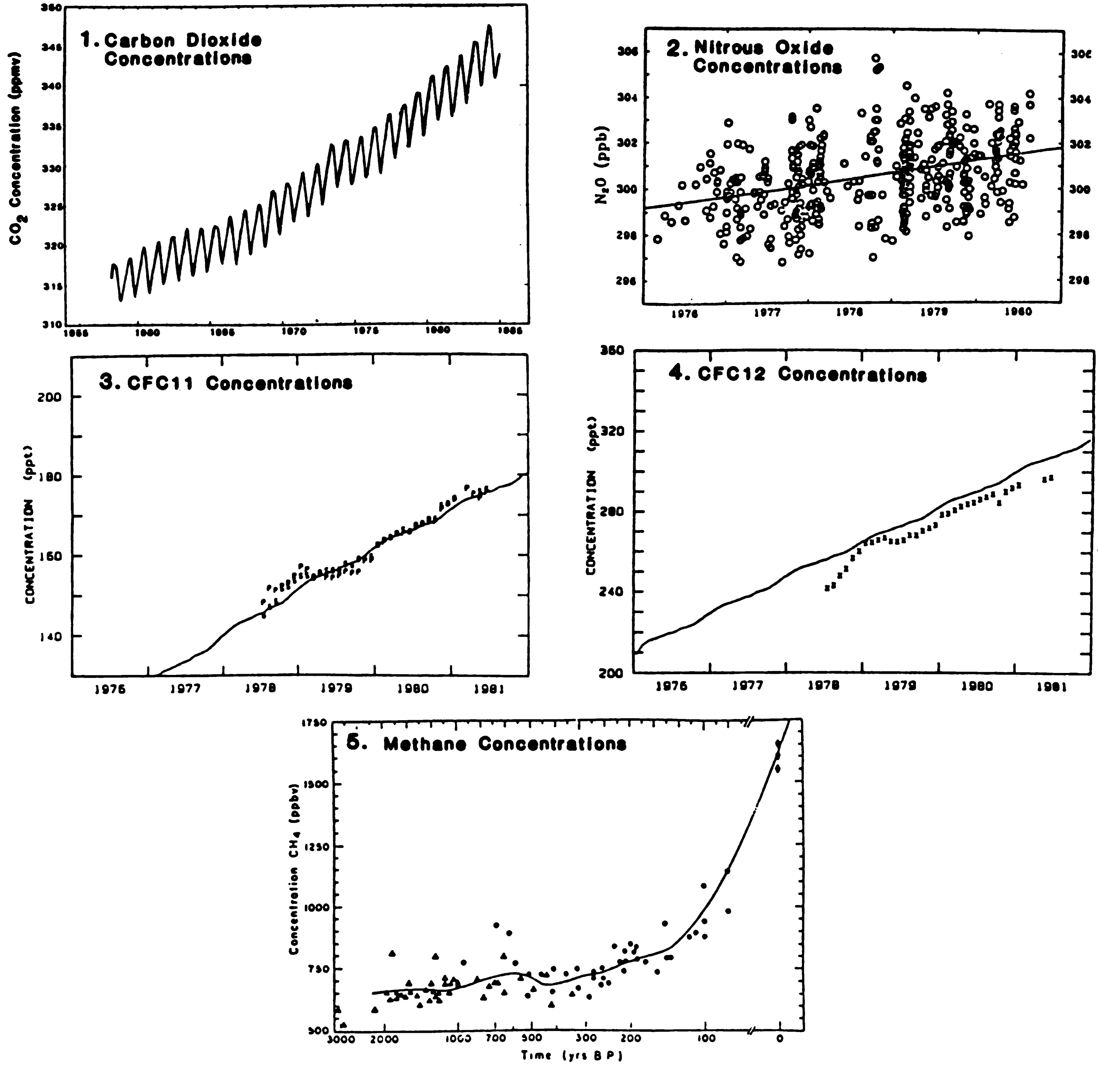
(Charney 1979). In 1982, the NAS confirmed the 1979 assessment (Smagorinsky 1982).

A planet's temperature is determined primarily by the amount of sunlight it receives, the amount of sunlight it reflects, and the extent to which its atmosphere retains heat. When sunlight strikes the earth, it warms the surface, which then reradiates the heat as infrared radiation. However, water vapor, CO_2, and other gases in the atmosphere absorb some of the energy rather than allowing it to pass undeterred through the atmosphere to space. Because the atmosphere traps heat and warms the earth in a manner somewhat analogous to the glass panels of a greenhouse, this phenomenon is generally known as the "greenhouse effect." Without the greenhouse effect of the gases that occur in the atmosphere naturally, the earth would be approximately 33°C (60°F) colder than it is currently (Hansen et al. 1984). Thus, the greenhouse effect per se is not just something that will happen in the future; it is an existing natural characteristic of the atmosphere.

In recent decades, the concentrations of these "greenhouse gases" have been increasing. Since the industrial revolution, the combustion of fossil fuels, deforestation, and cement manufacture have released enough CO_2 into the atmosphere to raise the atmospheric concentration of carbon dioxide by 20 percent. As Figure 2 shows, the concentration has increased 8 percent since 1958 (Keeling, Bacastow, and Whorf 1982). Recently, the concentrations of methane, nitrous oxide, chlorofluorocarbons, and some other trace gases that also absorb infrared radiation have also been increasing (Lacis et al. 1981). Ramanthan et al. (1985) estimate that these gases will warm the earth as much as CO_2 alone.

FIGURE 2

CONCENTRATION OF SELECTED GREENHOUSE GASES OVER TIME



1. C.D. Keeling, R.B. Bacastow, and T.P. Whorf, 1982. "Measurements of the Concentration of Carbon Dioxide at Mauna Loa, Hawaii." In Carbon Dioxide Review 1982, edited by W. Clark, New York: Oxford University Press, 377-382. Unpublished data from NOAA after 1981.

2. R.F. Weiss, 1981. "The Temporal and Spatial Distribution of Tropospheric Nitrous Oxide." Journal of Geophysical Research, 86(C8):7185-7195.

3. D.M. Cunnold et al., 1983. "The Atmospheric Lifetime Experiment. 3. Lifetime Methodology and Application to Three years of CFCL3 Data." Journal of Geophysical Research, 88(C13):8379-8400.

4. D.M. Cunnold et al., 1983. "The Atmospheric Lifetime Experiment. 4. Results for CF2CL2 Based on Three Years' Data." Journal of Geophysical Research, 88(C13):8401-8414.

5. R.A. Rasmussen and M.A.K. Khalil, 1984. "Atmospheric Methane in the Recent and Ancient Atmospheres: Concentrations, Trends, and Interhemispheric Gradient." Journal of Geophysical Research, 89(D7):11599-11605.

Although there is no doubt that the concentration of greenhouse gases is increasing, the future rate of that increase is uncertain. A recent report by the National Academy of Sciences (NAS) examined numerous uncertainties regarding future energy use patterns, economic growth, and the extent to which CO_2 emissions remain in the atmosphere (Nordhaus and Yohe 1983). The Academy estimated a 98 percent probability that CO_2 concentrations will be at least 450 parts per million (1.5 times the year-1900 level) by 2050 and a 55 percent chance that the concentration will be 550 parts per million. The Academy estimated that the probability of a doubling of CO_2 concentrations by 2100 is 75 percent. Other investigators have estimated that a doubling is likely by 2050 (Wuebbles, MacCracken, and Luther 1984).

If the impact of the trace gases continues to be equal to the impact of CO_2, the NAS analysis implies that the "effective doubling" of all greenhouse gases has a 98 percent chance of occurring by 2050.[1] An international conference of scientists recently estimated that an effective doubling by 2030 is likely (UNEP 1985). However, uncertainties regarding the emissions of trace gases are greater than those for CO_2. Although the sources of chlorofluorocarbon emissions are well documented, regulatory uncertainties related to their possible impact on stratospheric ozone depletion make their growth rate--currently about 5 percent--difficult to forecast. The current sources of methane, nitrous oxide, and other trace gases have not yet been fully catalogued.

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[1] Studies on the greenhouse effect generally discuss the impacts of a carbon dioxide doubling. By "effective doubling of all greenhouse gases" we refer to any combination of increases in the concentration of the various gases that causes a warming equal to the warming of a doubling of carbon dioxide alone. If the other gases contribute as much warming as carbon dioxide, the effective doubling would occur when carbon dioxide concentrations have reached 450 ppm, 1.5 times the year-1900 level.

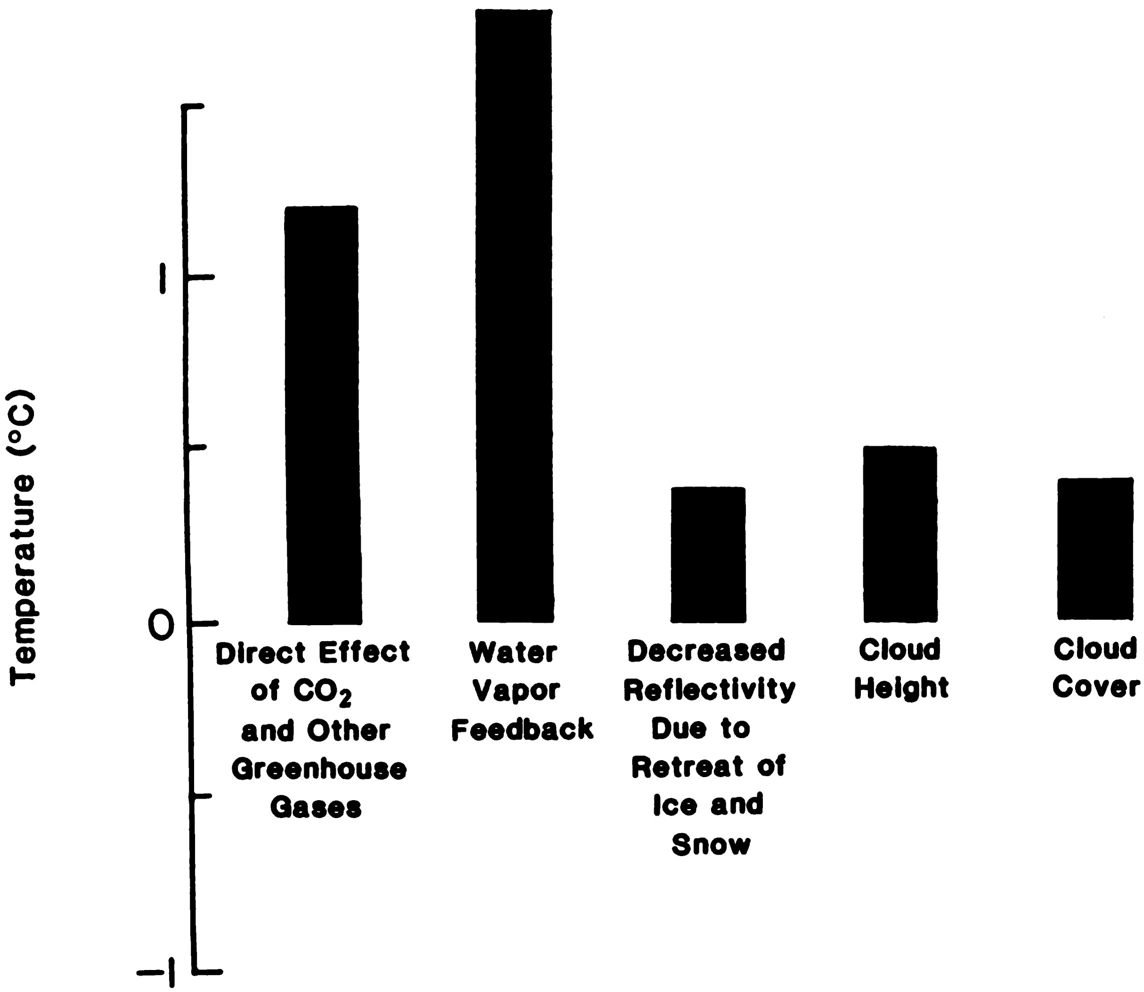
Considerable uncertainty also exists regarding the impact of a doubling of greenhouse gases. Physicists and climatologists generally agree that a doubling would directly raise the earth's average temperature by about 1°C if nothing else changed. However, if the earth warmed, many other aspects of climate would be likely to change, probably amplifying the direct effect of the greenhouse gases. These indirect impacts are known as "climatic feedbacks."

Figure 3 shows estimates by Hansen et al. (1984) of the most important known feedbacks. A warmer atmosphere would retain more water vapor, which is also a greenhouse gas, warming the earth more. Snow and floating ice would melt, decreasing the amount of sunlight reflected to space, causing additional warming. Although the estimates of other researchers differ slightly from those of Hansen et al., climatologists agree that these two feedbacks would increase the expected global warming. However, the impact of clouds is far less certain. Although recent investigations have estimated that changes in cloud height and cloud cover would add to the warming, the possibility that changes in cloud cover would offset part of the warming cannot be ruled out. After evaluating the evidence, two panels of the National Academy of Sciences concluded that the eventual warming from a doubling of greenhouse gases would be between 1.5° and 4.5°C (3°-8°F).

A global warming of a few degrees could be expected to raise sea level in the future, as it has in the past. The best understood mechanism is the warming and resulting expansion of sea water, which could raise sea level one-half meter in the next century (Hoffman, Keyes, and Titus 1983). Mountain glaciers could melt and release enough water to raise sea level ten to thirty centimeters (four to twelve inches) (Meier 1984). Revelle (1983) estimates

FIGURE 3

ESTIMATED GLOBAL WARMING DUE TO A DOUBLING OF GREENHOUSE GASES: DIRECT EFFECTS AND CLIMATIC FEEDBACKS



NOTE: Although Hansen et al. estimate a positive feedback from the clouds, a negative feedback cannot be ruled out.

Sources: Adapted from: HANSEN, J.E., A. LACIS, D. RIND, and G. RUSSELL, 1984. Climate Sensitivity to Increasing Greenhouse Gases. In Greenhouse Effect and Sea Level Rise: A Challenge for This Generation, edited by M.C. Barth and J.G. Titus. New York: Van Nostrand Reinhold, p. 62.

that Greenland's glacier meltwater will raise the sea another twelve centimeters in the next century, while Bindschadler (1985) estimates the impact to be between ten and twenty-five centimeters. Antarctica could contribute to sea level rise either by meltwater running off or by glaciers sliding into the oceans. Although no one has estimated the impact of melting, Thomas (1985) estimates that Antarctic ice discharges are likely to add another twenty-four centimeters to worldwide sea level.

In 1983, two independent reports estimated future sea level rise. In the National Academy of Sciences report Changing Climate, Revelle (1983) estimated that the combined impacts of thermal expansion, the Greenland icesheet, and mountain glaciers could raise sea level seventy centimeters (two and one-third feet) in the next century. Although he also stated that Antarctica could contribute two meters per century to sea level starting around 2050, Revelle did not add this contribution to his estimate.

In a report by the Environmental Protection Agency entitled Projecting Future Sea Level Rise, Hoffman, Keyes, and Titus (1983) stated that the uncertainties regarding the factors that could influence sea level are so numerous that a single estimate of future sea level rise is not practical. Instead, they consulted the literature to specify high, medium, and low estimates for all the major uncertainties, including fossil fuel use; the absorption of carbon dioxide through natural processes; future emissions of trace gases; the global warming that would result from a doubling of greenhouse gases (the NAS estimate of 1.5°-4.5°C); the diffusion of heat into the oceans; and the impact of ice and snow. They estimated that if all of the low assumptions prove to be correct, the sea will rise 13 cm (5 in) by 2025 and 38 cm (15 in) by 2075 over the 1980 level. If all of the high assumptions are correct, the sea will rise 55 cm (2 ft) by 2025 and 211 cm (7 ft) by 2075. However, because it is very unlikely that either all the high or all the low assumptions will prove to be correct, the authors concluded that the rise in sea level is likely to be between two mid-range scenarios of 26 to 39 cm (11 to 15 in) by 2025 and 91 to 136 cm (3 to 4-1/2 ft) by 2075. Figure 4 and Table 1 illustrate the EPA and NAS estimates. Although neither of these studies examined options to limit the rise in sea level by curtailing emissions, Seidel and Keyes (1983) estimated that even a ban on coal, shale oil, and synfuels would only delay the rise in sea level expected through 2050 by twelve years.[2]

Recent analysis by the Polar Research Board of the National Academy of Sciences indicates that glaciers in Greenland and East Antarctica, as well as those in West Antarctica, could eventually release enough ice into the oceans to raise sea level two or three centimeters (about one inch) per year (Meier et al. 1985). However, current thinking holds that such a rapid rise is at least one hundred years away. Moreover, a complete disintegration of the West Antarctic Ice Sheet--and the resulting six-meter (twenty-foot) rise in sea level--would take several centuries (Bentley 1983; Hughes 1983). It is possible that snowfall accumulation could partially offset the effect of melting ice.

The East Coast of the United States is slowly sinking (Hoffman, Keyes, and Titus 1983). Thus relative sea level rise along the Delaware estuary will be twenty-five to thirty centimeters (ten to twelve inches) per century greater than global sea level rise, as shown in Table 1.

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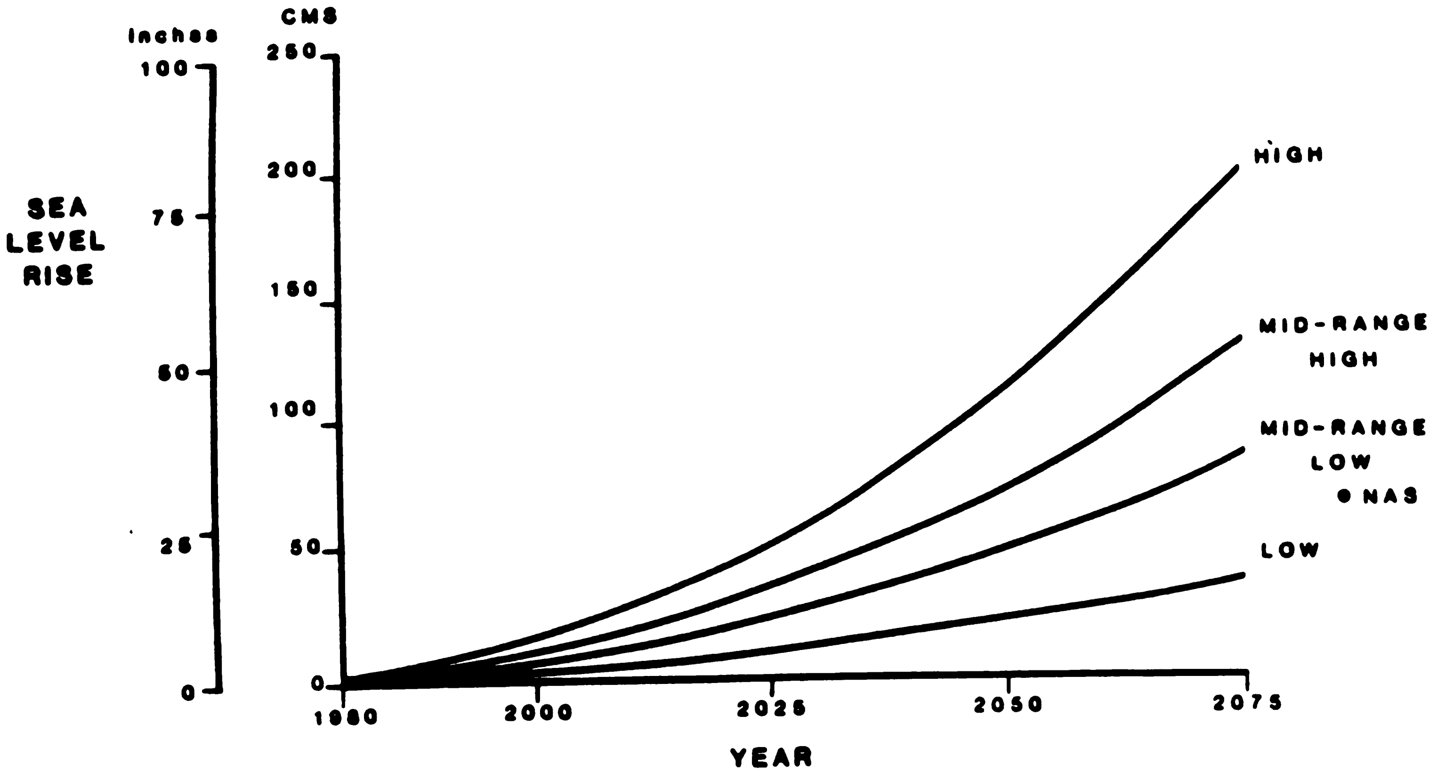
[2] Computer printout underlying calculations from Seidel and Keyes 1983.

FIGURE 4

GLOBAL SEA LEVEL RISE SCENARIOS:
LOW, MID-RANGE LOW, MID-RANGE HIGH, AND HIGH



Sources: HOFFMAN, J.S., D. KEYES, and J.G. TITUS, 1983. Projecting Future Sea Level Rise. U.S. GPO #055-000-0236-3. Washington, D.C.: Government Printing Office; REVELLE, R., 1983. Probable Future Changes in Sea Level Resulting From Increased Atmospheric Carbon Dioxide. In Changing Climate. Washington, D.C.: National Academy Press (Revelle estimate does not include Antarctica).

TABLE 1

SCENARIOS OF GLOBAL SEA LEVEL RISE: 1980-2100
(centimeters)

	2000	2025	2050	2075	2080	2100
Current Trends	2.0-3.0	4.5-6.8	7.0-10.5	9.5-14.3	10-15	12.0-18.0
EPA Scenarios						
High	17.1	54.9	116.7	211.5	-	345.0
Mid-range high	13.2	39.3	78.9	136.8	-	216.6
Mid-range low	8.8	26.2	52.6	91.2	-	144.4
Low	4.8	13.0	23.0	38.0	-	56.2
NAS Estimate*	-	-	-	-	70.0	-

SCENARIOS OF SEA LEVEL RISE AT LEWES, DELAWARE: 1965-2100
(centimeters)

	2000	2025	2050	2075	2080	2100
Current Trends	13	22	31	41	43	50
EPA Scenarios						
High	27.7	71.7	140.0	290.8	-	380.6
Mid-range high	23.7	56.1	102.0	166.1	-	251.5
Mid-range low	19.3	43.0	76.7	120.5	-	180.0
Low	15.3	29.8	46.0	67.3	-	91.8
NAS Estimate*	-	-	-	-	100.6	-

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* Excluding Antarctic contribution.

Sources: HOFFMAN, J.S., D. KEYES, and J.G. TITUS, 1983. Projecting Future Sea Level Rise. U.S. GPO #055-000-0236-3. Washington, D.C.: Government Printing Office; REVELLE, R., 1983. Probable Future Changes in Sea Level Resulting From Increased Atmospheric Carbon Dioxide. In Changing Climate. Washington, D.C.: National Academy Press (does not include Antarctica); HICKS, S.D., H.A. DeBAUGH, and L.E. HICKMAN, 1983. Sea Level Variation for the United States 1855-1980. Rockville, MD: National Ocean Service.

III. SALINITY IN THE DELAWARE ESTUARY

A rise in sea level of even thirty centimeters (one foot) would have major impacts on coastal erosion, flooding, and saltwater intrusion. Until this effort, no one had estimated the saltwater intrusion expected to result from an accelerating rise in sea level due to the greenhouse effect. However, previous EPA studies have examined the impacts of erosion and flooding, as well as possible responses (Barth and Titus 1984). Ongoing EPA studies are investigating the potential impacts on coastal sewerage systems, wetlands, and seawalls.

The Delaware River Basin Commission (DRBC) has considered the implications of recent sea level trends in its policy making since the late 1970s. Accordingly, the DRBC already had the necessary model and data for assessing accelerated sea level rise. This section provides background information on the Delaware estuary, and presents estimates of saltwater intrusion likely to result from sea level rise in the next century due to the expected global warming.

Saltwater Intrusion

Salinity in an estuary ranges from that of sea water (at the mouth) to that of fresh water (near the head of tide). The salinity at a particular point varies over the course of a year, depending primarily on the amount of fresh water flowing into the estuary. Mixing and advection caused by tidal currents and wind can also change the salinity at a particular point.

In the Delaware estuary, tidal effects extend as far upstream as Trenton, where the tidal range is more than twice that of the ocean boundary. Although the net flow of the estuary tends to carry salt water toward the ocean, tidal currents carry salt water upstream, where it mixes with fresh water. Differences in the densities of salt water and fresh water also contribute to saltwater intrusion; heavy salt water on the bottom tends to move upstream when adjacent to lighter fresh water, forming a wedge.

A rise in sea level generally results in increased salinity, assuming other factors remain constant. In this respect the impact of sea level rise is similar to the impact of reduced flows during a drought. The former increases the saltwater force, whereas the latter decreases the freshwater force. Salinity levels generally respond to changes in tide and river flow within a matter of minutes or hours.

In the past eighteen thousand years, sea level has risen one hundred meters (three hundred feet), converting freshwater rivers into brackish estuaries (Donn, Farrand, and Ewing 1962). Chesapeake Bay and the Delaware estuary are examples of such drowned river valleys. The Delaware estuary is probably the first estuary for which the salinity effects of future sea level rise have been studied (Hull and Tortoriello 1979).[3] The salinity of this estuary, as affected by the impacts of river diversion and flow regulation projects, has been the subject of study--and litigation--since the early 1930s.

The Delaware Estuary

The Delaware River Basin covers an area of thirteen thousand square miles in New York, Pennsylvania, New Jersey, and Delaware. It is located in the heart of the megalopolis that stretches from Boston to Washington, D.C., on

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[3] Louisiana is also experiencing salinity increases from sea level rise (Haydl 1984).

the eastern seaboard of the United States. The Delaware River reaches from the Catskill Mountains of southern New York to the head of Delaware Bay. The river is tidal from Trenton, New Jersey, to the bay; the tidal river and bay form the Delaware estuary, which is 215 kilometers (133 miles) long. The boundary between the estuary and the ocean is a line between Cape May, New Jersey, and Cape Henlopen, Delaware. Major cities on the estuary include Trenton and Camden, New Jersey, Philadelphia, Pennsylvania, and Wilmington, Delaware. The lower reach of the tidal river is physically connected with the northern part of Chesapeake Bay by the Chesapeake and Delaware Canal, which runs from Delaware City, Delaware, westward about twenty-seven kilometers (seventeen miles) to the Elk River in Maryland. Figure 5 shows the general location of the Delaware Basin; Figure 6 is a map of the estuary.

The Delaware estuary is one of the most extensively used tidal waterways in the world. From the ocean, past Philadelphia and almost to Trenton, the estuary has a navigable depth of at least twelve meters (forty feet) and is a major port for ships of all nations. Sport and commercial fishing are important uses of Delaware Bay, where oysters are the major shellfish harvested. Many industries along the banks of the estuary use fresh or brackish water for cooling and other processes. The estuary also serves the region by assimilating or transporting to the sea the residual wastes discharged from its tributaries as well as from about one hundred municipal and industrial wastewater treatment plants located along the estuary.

Based on data published by the U.S. Geological Survey (Bauersfeld et al. 1985), we estimate that the average flow of fresh water into the Delaware estuary from its tributaries is 609 cubic meters per second (21,500 cubic feet per second). The nontidal Delaware River, which drains about half the

FIGURE 5

GENERAL LOCATION OF THE DELAWARE BASIN

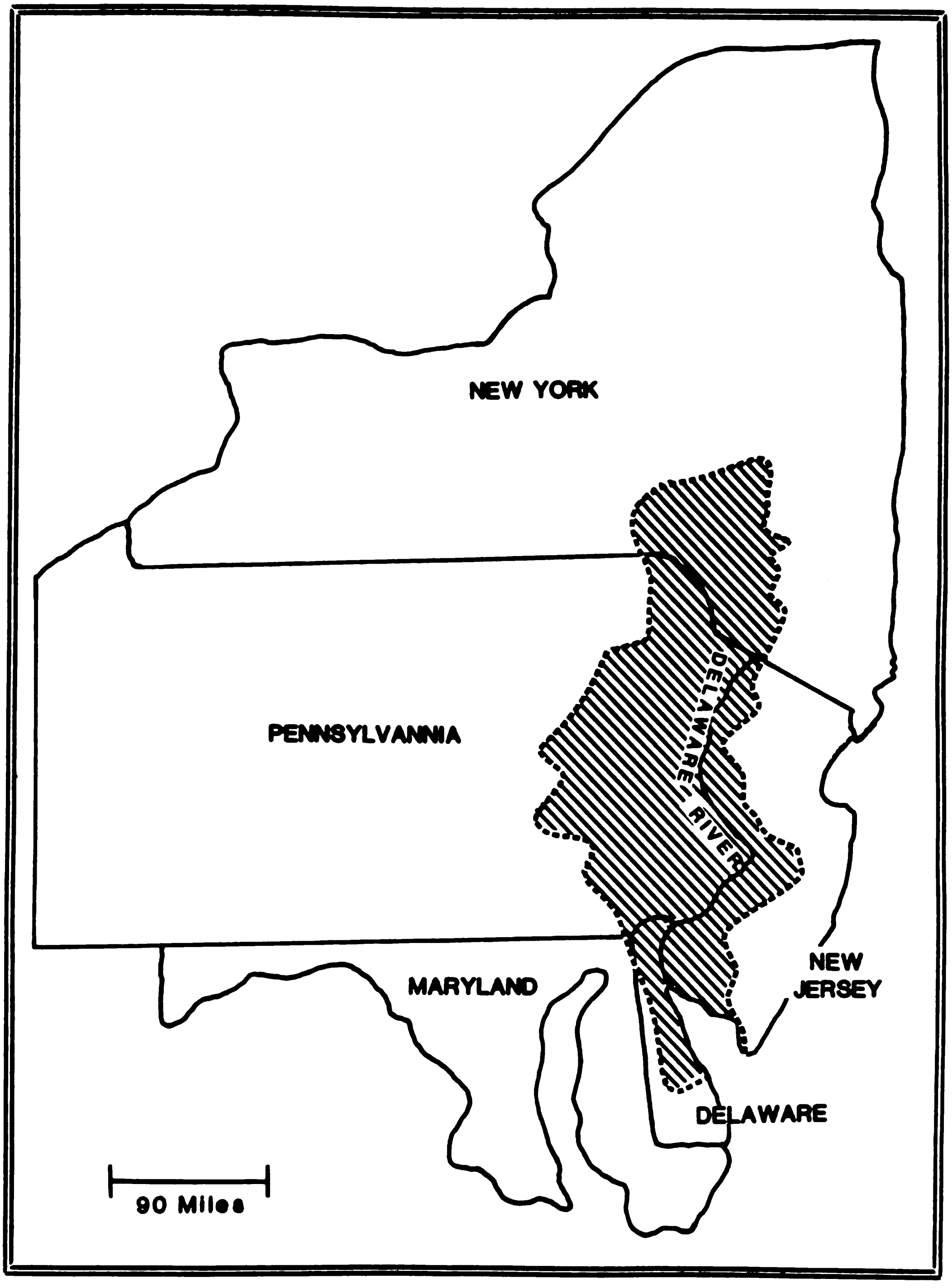
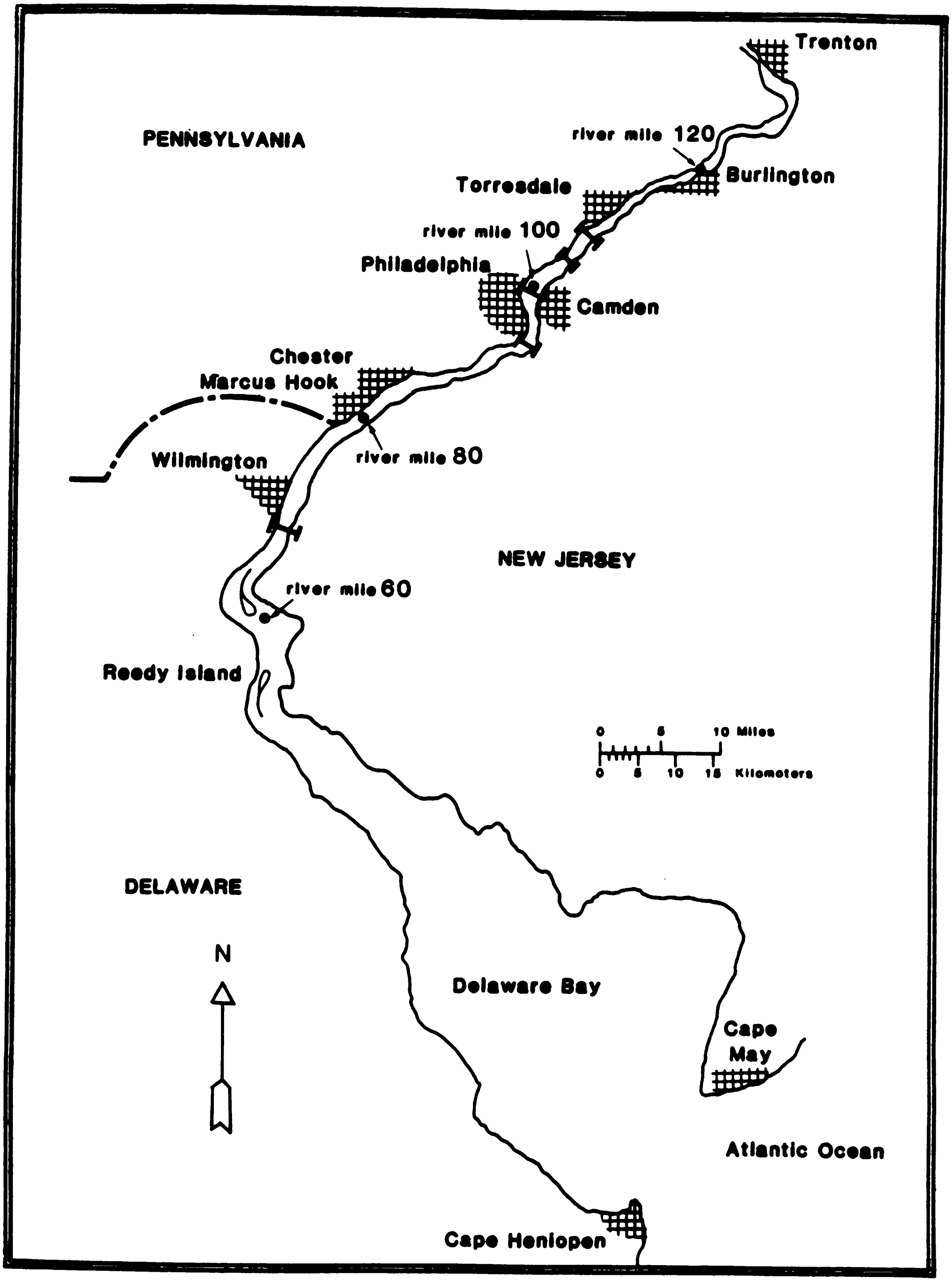


FIGURE 6

THE DELAWARE ESTUARY



basin, has an average flow rate of 332 cubic meters per second. The Schuylkill River drains about 15 percent of the Basin and conveys an average flow of 84 cubic meters per second. The Christina, which drains 5 percent of the Basin, has an average flow of 24 cubic meters per second. Smaller tributaries provide most of the remaining freshwater input, with smaller contributions from aquifers and direct rainfall onto the estuary.

The waters of the tidal river at Philadelphia and northward are normally fresh, and several municipalities, including Philadelphia, obtain portions of their public water supplies directly from this part of the river. Other cities take ground water from aquifers that are recharged in part by the tidal portion of the river.

The many consumptive uses of water throughout the Delaware Basin reduce the flow of fresh water into the estuary. Basin-wide withdrawal of fresh water is estimated at 351 cubic meters per second (8 billion gallons per day), of which 24.9 cubic meters per second (568 mgd) is used consumptively (i.e. evaporated or otherwise removed from the Basin instead of draining back into the estuary). Community water systems withdraw approximately 51.7 cubic meters per second (1,180 mgd), of which approximately 10 percent is consumed. The average daily per capita water use in the Basin is 0.617 cubic meters per day (163 gpd), compared with the mean rate of 0.606 cubic meters per day (160 gpd) for the United States (Seidel 1985). In addition, diversion of Delaware River water to New York and northeastern New Jersey are authorized up to 35 and 4.4 cubic meters per second (800 and 100 mgd), respectively (Supreme Court 1954). Basin-wide consumption is projected to rise to 52.2 cubic meters per second (1,191 mgd) by the year 2000 (DRBC 1981).

Saltwater Intrusion and the DRBC

The water resources of the Delaware River Basin are under the regulatory control of the Delaware River Basin Commission (DRBC), a regional federal-interstate compact agency established in 1961 to represent the federal government and the states that share the Basin. The five commission members are the U.S. Secretary of the Interior and the Governors of Delaware, New Jersey, New York, and Pennsylvania. The DRBC cooperates with state and federal agencies to ensure that the water resources of the Basin are protected and developed to meet the growing demands for all reasonable uses.

One of the most important responsibilities of the DRBC is to monitor and control salinity in the estuary. Excessive concentrations of ocean salts at water intakes would create public health risks, increase the cost of water treatment, and damage plumbing and machinery. High salinity could also upset the ecology of the estuary.

The DRBC tracks the levels of both sodium and chloride ions in the estuary. To protect public health, the Commission attempts to control salinity so that sodium levels of potable supplies do not exceed 50 milligrams per liter, based in part on New Jersey's 50-mg/l drinking water standard. For a variety of purposes, the DRBC also tracks the 250-mg/l isochlor (the line across the estuary where chloride concentrations equal 250 mg/l). Although this isochlor represents more than detectable levels of sea salts, it is commonly known as the "salt front." This level also represents the EPA drinking water standard for chlorides and the concentration at which water tastes salty to many people.

DRBC seeks to attain its salinity goals by keeping the chloride and sodium concentrations at river mile 98 below 180 mg/l and 100 mg/l, respectively.

These limits were designed primarily to protect the public groundwater supplies pumped from aquifers upstream of mile 98, which have a good hydraulic connection with the estuary. Over one-half of the water entering these aquifers is supplied by the estuary. DRBC has estimated that as long as the river mile 98 objective is met, sodium levels in most wells tapping the aquifers will remain below 50 mg/l. Moreover, the Philadelphia water intake at Torresdale (river mile 110.4) will be supplied with water with sodium concentrations less than 30 mg/l.

Because the flow of fresh water opposes salt water migrating upstream, the highest salinities in the estuary occur during droughts. Thus, the DRBC keeps salinity from reaching unacceptable levels both by limiting consumptive uses of water and by releasing water from various reservoirs during periods of low streamflow.

When reservoir releases are needed for salinity control in the estuary, the DRBC directs the U.S. Army Corps of Engineers to release water from DRBC-financed impoundments operated by the Corps. Table 2 lists reservoirs on which the DRBC currently relies, and scheduled increases in reservoir capacity. The Corps has constructed two multipurpose impoundments in the Basin: Beltsville Reservoir on a tributary of the Lehigh River, and Blue Marsh Reservoir on a tributary of the Schuylkill River. Two reservoirs originally designed for flood control (Francis E. Walter Reservoir on the Lehigh River and Prompton Reservoir on the Lackawaxen River) have also been operated for salinity control during drought emergencies. The U.S. Congress has authorized modifications of these facilities for water storage purposes; the DRBC plans to fund these modifications. Augmentation of low flows is also provided by many small reservoirs that are not listed in Table 2. Although these other reservoirs were designed for local community water supplies, they sometimes augment freshwater flows into the estuary, incidentally, during critical low-flow periods.

Efforts to decrease consumptive uses of water require the Commission to address both the diversion of water to other basins and consumptive uses of water in the Delaware River Basin. The City of New York diverts fresh water from the upper part of the Basin, as authorized by the U.S. Supreme Court in 1954. The court decreed that the City release water from its reservoirs during low-flow periods to compensate downstream interests for the water that is diverted or stored at other times. The current (1986) Basin Comprehensive Plan incorporates an agreement among the parties to the 1954 decree--New York City and the Four Basin States--calling for special drought operation of the City's Delaware River Basin reservoirs to meet downstream needs for salinity control while conserving and storing water against the possibility of an extended drought. Water is also diverted through the Delaware and Raritan Canal to northeastern New Jersey, with similar provisions to curtail diversion during droughts.

Some of the most important consumptive users of water in the Basin are steam-electric power plants. Because scheduled publicly owned reservoir capacity in the Basin will not be sufficient to meet increased consumption of water projected to the year 2000 (the DRBC's current planning horizon), the DRBC has required these utilities to develop storage capacity to provide freshwater flows into the estuary to offset their consumption.

The most severe drought of record in the Delaware River Basin was that of the 1960s. For a four-month period the average flow at Trenton was only one quarter the long-term average flow, and during the worst month the flow was

TABLE 2

EXISTING AND SCHEDULED RESERVOIRS THAT CAN CONTROL SALINITY IN THE DELAWARE ESTUARY a/

Name of Facility or Project	Location of dam, stream (River-mile g/)	Long-Term Active Storage Capacity a/		
		Cubic Meters	Billions of Gallons	Acre-Feet
(1)	(2)	(3)	(4)	(5)
Existing				
Cannonsville Reservoir	W. Br. Delaware River (330.71 - 18.0)	373×10^6	98	302,000
Pepacton Reservoir	E. Br. Delaware River (330.7 - 33.3)	560×10^6	148	454,000
Lake Wallenpaupack e/	Wallenpaupack Creek b/ (277.7 - 16.4 - 1.4)	-------- e/	--- e/	------- e/
Mongaup River System e/	Mongaup River (261.1 - 12.0)	-------- e/	--- e/	------- e/
Neversink Reservoir	Neversink River (253.64 - 41.9)	135×10^6	36	109,200
Francis E. Walter Reservoir f/	Lehigh River (183.66 - 77.8)	0 f/	0 f/	0 f/
Beltzville Reservoir	Pohopoco Creek c/ (183.66 - 41.5 - 5.2)	49×10^6	13	39,830
Nockamixon Reservoir	Tohickon Creek (157.0 - 11.0)	49×10^6	13	39,815
Blue Marsh Reservoir	Tulpehocken Creek d/ (92.47 - 76.8 - 6.5)	18×10^6	4.8	14,620
Scheduled				
Cannonsville Reservoir Modification h/	West Branch, Delaware River (330.7 - 18.0)	49×10^6	13	39,800
Prompton Reservoir Modification i/	West Branch Lackawaxen River (277.7 - 27.1 - 4.9)	38×10^6	10	30,900
Merrill Creek Reservoir j/	Merrill Creek (177.4 - 7.8 - 3.8)	57×10^6	15	46,000
Francis E. Walter h/ Reservoir Modification 87	Lehigh River (183.7 - 77.8)	86×10^6	23	70,000
Trexler Reservoir j/	Jordan Creek (183.7 - 36.3 - 4.6)	49×10^6	13	40,000

TABLE 2 (continued)

FOOTNOTES

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a/ These reservoirs are operated or designed to serve multiple purposes, including salinity control, or will tend to provide salinity control as an incidental benefit when operated for other purposes. Only part of the storage capacity in these impoundments will be available for salinity control. The operating plan for these reservoirs is based in part on offsetting the projected rise in sea level to the year 2000 based on the recent trend, but does not take into account any future acceleration of that trend related to the greenhouse effect.

b/ Tributary of the Lackawaxen River.

c/ Tributary of the Lehigh River.

d/ Tributary of the Schuylkill River.

e/ Privately owned hydroelectric power system. Storage available for salinity control only after DRBC declares a drought emergency.

f/ Federal flood-control reservoir. Storage capacity available for salinity control only after DRBC declares a drought emergency.

g/ Statute miles, measured along the axis of Delaware Bay and River from the mouth of the bay. Second and third mileages indicate distances above the mouths of tributaries.

h/ Scheduled for completion in 1990; designed primarily to maintain conservation releases in upper Delaware River, with secondary use to support downstream flow objectives and diversions to New York City within limits of U.S. Supreme Court decree of 1954.

i/ Scheduled for completion in 1995.

j/ Construction began in 1985. Planned completion date is 1988.

only 13 percent of the average. In late 1964, the salt front advanced up the estuary as far as river mile 102, just above the Benjamin Franklin Bridge in Philadelphia. (The salt front's average location is near river mile 69.) The drought continued through 1966. Because of the threat to water systems depending on the estuary, the DRBC declared an emergency, as authorized by the Delaware River Basin Compact (DRBC 1981). Under its emergency powers, the DRBC regulated the river flows to control salinity and conserve water. The emergency was in effect for many months. Several impoundments in the Basin in 1965 made it possible for the DRBC to call for water releases at strategic times to control salinity in the estuary, thereby preventing major harm to water users that draw upon the estuary for their supplies. However, significant economic damages associated with the higher salinities were reported by some water users. Some industries in the reach below Philadelphia were forced to switch temporarily to a municipal system that imports water from the Susquehanna River Basin. Shellfish production was subject to abnormal stresses related to the high salinities.

The DRBC uses a mathematical model to study salinity changes. The Delaware estuary salinity model, developed for the DRBC by Thatcher and Harleman (1978),[4] relates freshwater inflows, tides, and ocean salinities to chloride distribution in the estuary. (Technical details of the model are

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[4] The model is a deterministic, one-dimensional time-varying model that simulates saltwater intrusion in the tidal system extending from the head of tide at Trenton to the Atlantic Ocean. A one-dimensional model was developed because the Delaware estuary is well mixed vertically, especially in the tidal river above Delaware Bay, and even the bay is vertically homogeneous during low-flow periods when salinity intrusion is likely to be a problem. The well-mixed character of this estuary is related to strong tidal currents and shallow average depth. The normal range of tides at the mouth of the bay varies from 3.95 feet in December to 4.3 feet in August. At the head of the tidal river at Trenton, the tidal range varies from 7.6 feet in January to 8.55 feet in June.

explained in Appendix A.) The dynamic nature of the estuary is reflected in the model outputs, which can show the average chloride concentration every few minutes at one hundred equally spaced cross sections along the 214-kilometer (133-mile) estuary. Typical simulations have produced maximum and minimum chlorinity readings at key locations for each tidal cycle over a period of a year or more (Thatcher and Harleman 1981). These simulations have been used to analyze the effects of various methods of reservoir operation on year-round salinity distribution in the estuary. The model has also been used to predict the effects of rising sea level on estuarine salinity, as discussed next.

The salinity distribution of an estuary affects sedimentation and shoaling. Thus, changes in salinity could change the geometry of the estuary. Although maintenance dredging for navigation would tend to maintain the present dimensions of the main channel in the tidal Delaware River and Bay, changes in salinity-related sedimentation and shoaling outside the channel accompanying a very large rise in sea level might alter the geometry and thus the dispersion characteristics of the estuary. In modeling the changes in sea level and salinity intrusion, we have not attempted to take into account possible changes in shoaling characteristics. This is not a serious modeling flaw for a rise less than one meter. Additional research in this aspect of the problem would be useful for more accurate projections of the impact of a large rise in sea level.

The DRBC (1983a) uses the 1961-1966 drought as the basis for planning a dependable water supply. Thus, for assessing most salinity problems, the model is calibrated for the drought conditions of 1965, the driest year of record in the Delaware Basin. The model is adjusted to reflect post-1965 changes in reservoir capacity, depletive uses of water, and sea level.

Estimating Impacts of Sea Level Rise on Salinity

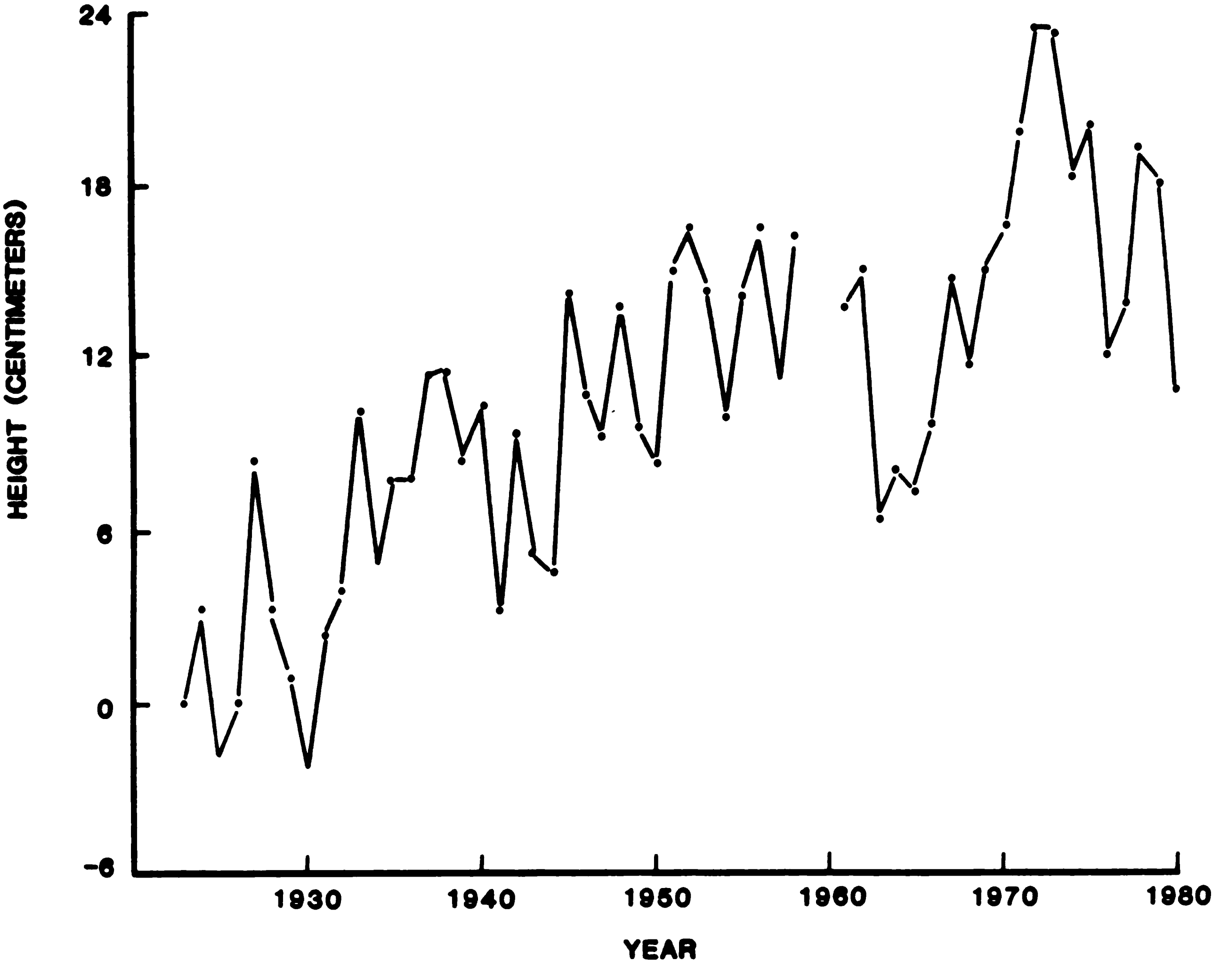
Current Sea Level Trends. Although worldwide sea level has been rising 1 to 1.5 millimeters per year (4 to 6 inches per century), the measured rise along the east coast has been greater, because of local subsidence. Hicks (1978) reported an average rise of 3.7 millimeters per year at Lewes, Delaware, for the period 1921 through 1975. Hicks, DeBaugh, and Hickman (1983) report a rise of 2.6 millimeters per year at Philadelphia, as shown in Figure 7.

The DRBC was the first government agency to investigate the potential effects of recent sea level trends on salinity in a particular estuary (Hull and Tortoriello 1979). In 1979, the current DRBC planning horizon was the year 2000, and the DRBC wished to know what estuarine salinity changes would result from the projected change in sea level from 1965 to 2000. Considering only historical trends, not accelerated sea level rise from the greenhouse effect, Hull and Tortoriello (1979) estimated a 35-year rise of 13 centimeters (0.42 feet), and analyzed this rise with the Delaware estuary salinity model.

The model was first exercised for 1964-1965 drought conditions, including observed sea level, but with flow of the Delaware River at Trenton regulated by reservoirs to maintain an average flow of three thousand cubic feet per second for the low-flow season. A fifteen-month period (1 October 1964 through 31 December 1965) was simulated. The minimum, mean, and maximum chlorinities for each tidal cycle, as well as the running sixty-day averages, were simulated over the fifteen-month period. These data were produced for locations spaced along the axis of the estuary, with spacing close enough to allow easy interpolation between locations.

FIGURE 7

CHANGE IN YEARLY MEAN SEA LEVEL FROM 1923 TO 1980 AT PHILADELPHIA



Source: HICKS, S.D., H.A. DeBAUGH, and L.E. HICKMAN, 1983. Sea Level Variation for the United States 1855-1980. Rockville, MD: National Ocean Service.

Next, a model simulation was carried out for year-2000 conditions, assuming a recurrence of the 1964-1965 drought flows but with sea level adjusted upward by 13 centimeters (0.42 feet) to reflect the projected sea level rise. Other model inputs were held at the values used for 1965.

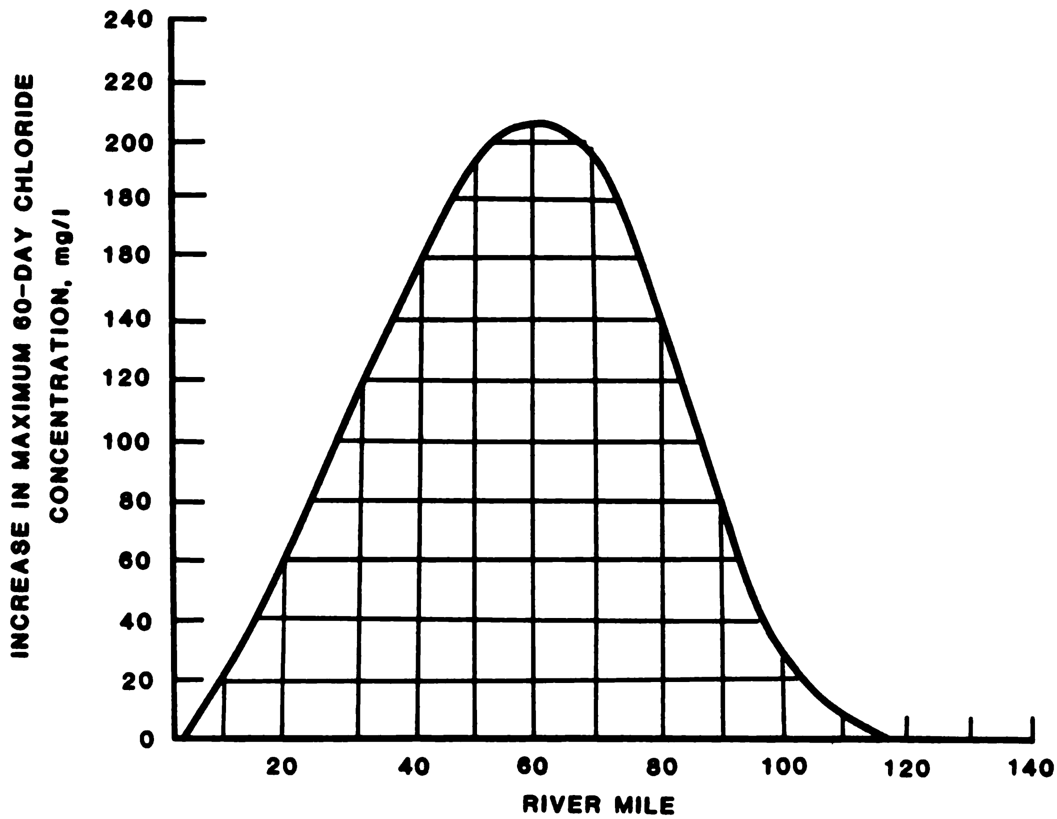
The maximum sixty-day average chlorinities for 1965 and 2000 were compared to show the effect of the thirty-five-year sea level rise. Figure 8 shows the increase in the maximum sixty-day average chlorinities as a function of river miles. The chlorinity increase due to the simulated sea level rise was most pronounced at river mile 60, where the sixty-day average increased by about 210 mg/l. The average position of the salt front moved two to four kilometers (one to two miles) upstream. The salinity impact of the projected sea level change decreased with distance seaward and landward of river mile 60, with no measureable effect above mile 120.

Using a series of year-2000 simulations with various degrees of streamflow regulation, Hull and Tortoriello (1979) found that the salinity increase caused by the projected thirty-five-year rise in sea level could be offset by a level of year-round river-flow regulation that augmented the summer flow by 150 cfs. This augmentation could be provided by a moderately sized reservoir (about fifty-seven million cubic meters, or forty-six thousand acre-feet) in the Delaware Basin. These findings have been used in the formulation of plans for water resources development for the Basin (DRBC 1981).

<u>Accelerated sea level rise</u>. Because of limited resources, we investigated only two scenarios of accelerated sea level rise. Because the magnitude of the future rise is uncertain, a conservative approach is to pick a wide range so that our results are most likely to encompass the actual situation. We finally settled on 73- and 250-centimeter (2.4- and 8.2-foot) rises over 1965

FIGURE 8

CHLORINITY RESPONSE OF DELAWARE ESTUARY TO PROJECTED 35-YEAR RISE IN SEA LEVEL, 1965 TO 2000



Source: HULL, C.H.J., and R.C. TORTORIELLO, 1979. Sea-Level Trend and Salinity in the Delaware Estuary. Staff Report. West Trenton, New Jersey: Delaware River Basin Commission.

levels at Lewes, Delaware. (For drought conditions the DRBC Salinity Model requires inputs relative to 1965 sea level, which was 6 centimeters lower than 1980 sea level.)

We hope that the reader will not attribute excessive significance to these scenarios. Nevertheless, it is useful to understand when a 73- or 250-centimeter rise is likely to take place. Because relative sea level at Lewes is rising about 2.5 millimeters per year more rapidly than the global average, these estimates do not correspond directly to published estimates of worldwide sea level rise. The 73-centimeter scenario is consistent with the National Academy of Sciences estimate for 2050, while the 250-centimeter case is consistent with the NAS projection for 2125.[5] The 73-centimeter scenario is also consistent with the EPA's mid-range low estimate for 2050, as well as EPA's high estimate for 2025. The 250-centimeter scenario is consistent with the EPA mid-range high estimate for 2100 and the EPA high estimate for 2075.

Although our understanding of future sea level rise is incomplete, the 73-centimeter scenario appears to be a more realistic near-term possibility than the 250-centimeter scenario. Nevertheless, when considering responses to sea level rise in the next fifty to seventy-five years, one should not completely ignore the rise that may occur in subsequent years.

The earlier DRBC simulations (Hull and Tortoriello 1979) involved only a relatively minor change in mean sea level, 13 centimeters (0.42 feet), which did not require any modification of the salinity model. However, in the study reported here, it was necessary to consider changes in the geometry of the estuary itself, as well as in the mathematical representation (model) of the

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[5] Revelle estimates 70 centimeters per century due to factors other than Antarctica and 2 meters per century after 2050 due to Antarctic deglaciation.

estuary. For sea level increases of 60 centimeters (2 feet) and more, not only would the depth of the estuary increase, but the width would also increase. The techniques used in these model-geometry modifications are described in Appendix B.

Table 3 and Figure 9 compare the maximum thirty-day average chloride levels at different river miles for a recurrence of the 1964-65 drought at the 1965 sea level and rises of 73 and 250 centimeters over that level. We estimated that a 73-centimeter rise would increase the maximum thirty-day chlorinity at river mile 98 from approximately 135 mg/l to 305 mg/l. The thirty-day average location of the salt front would advance to mile 100, compared with mile 93 for such a drought occurring in 1965. Although the salt front would be well below Philadelphia's Torresdale intake on average, the 78-mg/l isochlor would be at river mile 109, just below the intake at mile 110.4. A 250-centimeter rise would bring the salt front up to river mile 117, well above Torresdale.

Further analysis of the simulations of saltwater intrusion using the modified geometry yielded statistical information for comparing the numbers of tidal cycles during which chloride levels exceeded a particular value. Figure 10 presents these comparisons for river mile 110.4, Torresdale. This figure shows the effects of post-1965 sea level rises of 73 and 250 centimeters in terms of the percent of tidal cycles during which a given chloride concentration would be exceeded by the maximum and minimum concentrations calculated for every tidal cycle (total of 705 cycles in the simulation period). For example, a sea level rise of 250 centimeters would cause the 78-mg/l chloride value to be exceeded during more than 50 percent of the cycles, while a 73-centimeter rise would result in exceedance of that

TABLE 3

MAXIMUM 30-DAY CHLORIDE CONCENTRATION (MG/L) AT DIFFERENT RIVER MILES FOR A RECURRENCE OF THE 1960s' DROUGHT

River Mile	1965 Sea Level Base Case	73-Centimeter Rise	250-Centimeter Rise
61.9	4,660	5,357	7,726
64.6	4,010	4,718	7,127
67.3	3,358	4,084	6,571
70.0	2,760	3,474	5,943
72.7	2,243	2,928	5,373
75.4	1,778	2,427	4,873
78.1	1,390	1,998	4,398
80.8	1,065	1,619	3,914
83.5	800	1,295	3,426
86.2	588	1,021	3,021
88.9	431	804	2,652
91.6	301	605	2,289
94.3	210	450	1,967
96.9	151	335	1,655
98.0 a/	136 b/	305 b/	1,560 b/
99.6	114	262	1,421
102.3	82	193	1,211
105.0	57	135	1,001
107.7	38	89	789
110.4	26	56	608
113.1	19	35	437
115.8	15	23	301
118.5	14	17	196
121.2	13	14	110
123.9	13	13	55

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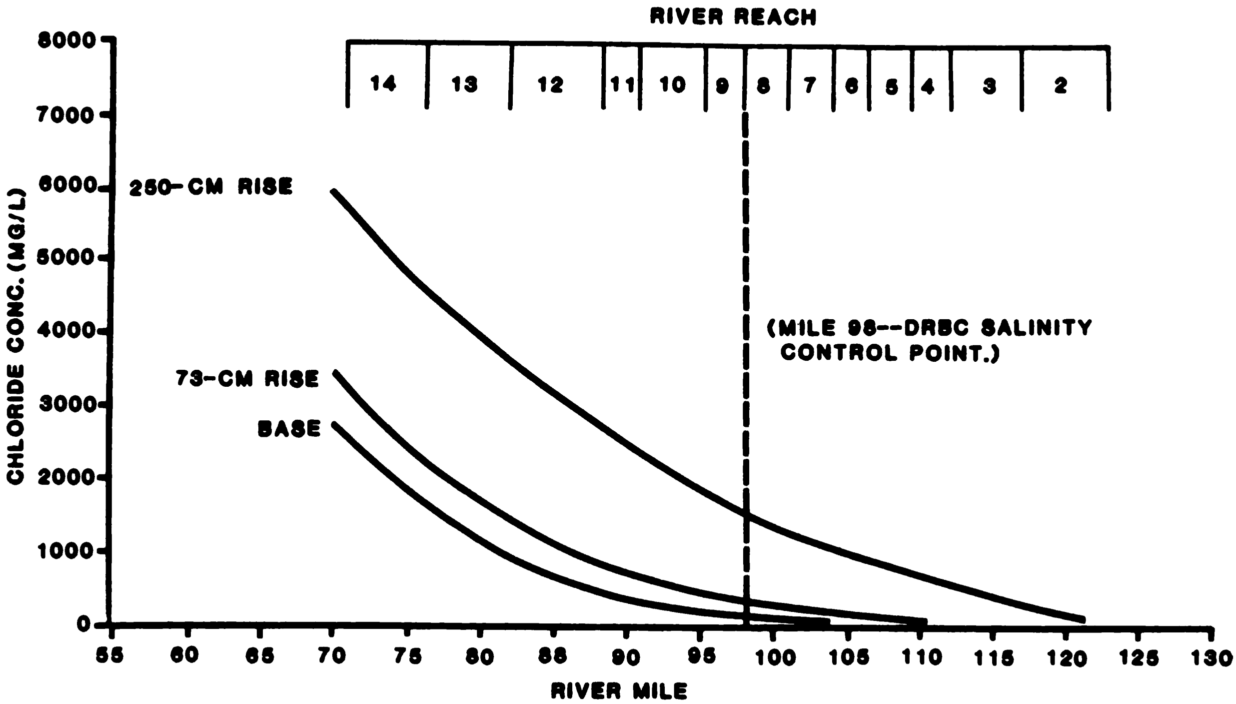
a/ DRBC salinity-control point, where objective is to prevent 30-day average chloride concentration from exceeding 180 mg/l.

b/ Interpolated value.

Note: Model inputs are based on observed tides during calendar year 1965.

FIGURE 9

MAXIMUM 30-DAY CHLORINITY VS. RIVER MILE FOR A RECURRENCE OF 1960s' DROUGHT:
(a) 1965 SEA LEVEL; (b) 73-CENTIMETER RISE;
(c) 250-CENTIMETER RISE



chlorinity about 15 percent of the cycles. The base case (1965 sea level) never showed chloride concentrations in excess of 78 mg/l; the maximum calculated chlorinity at Torresdale was 62 mg/l. Similarly, the calculated chloride concentration exceeded 250 mg/l about 42 percent of the tidal cycles for the 250-centimeter rise, but did not reach the 250-mg/l level for the 73-centimeter rise, which resulted in a maximum chlorinity of about 129 mg/l.

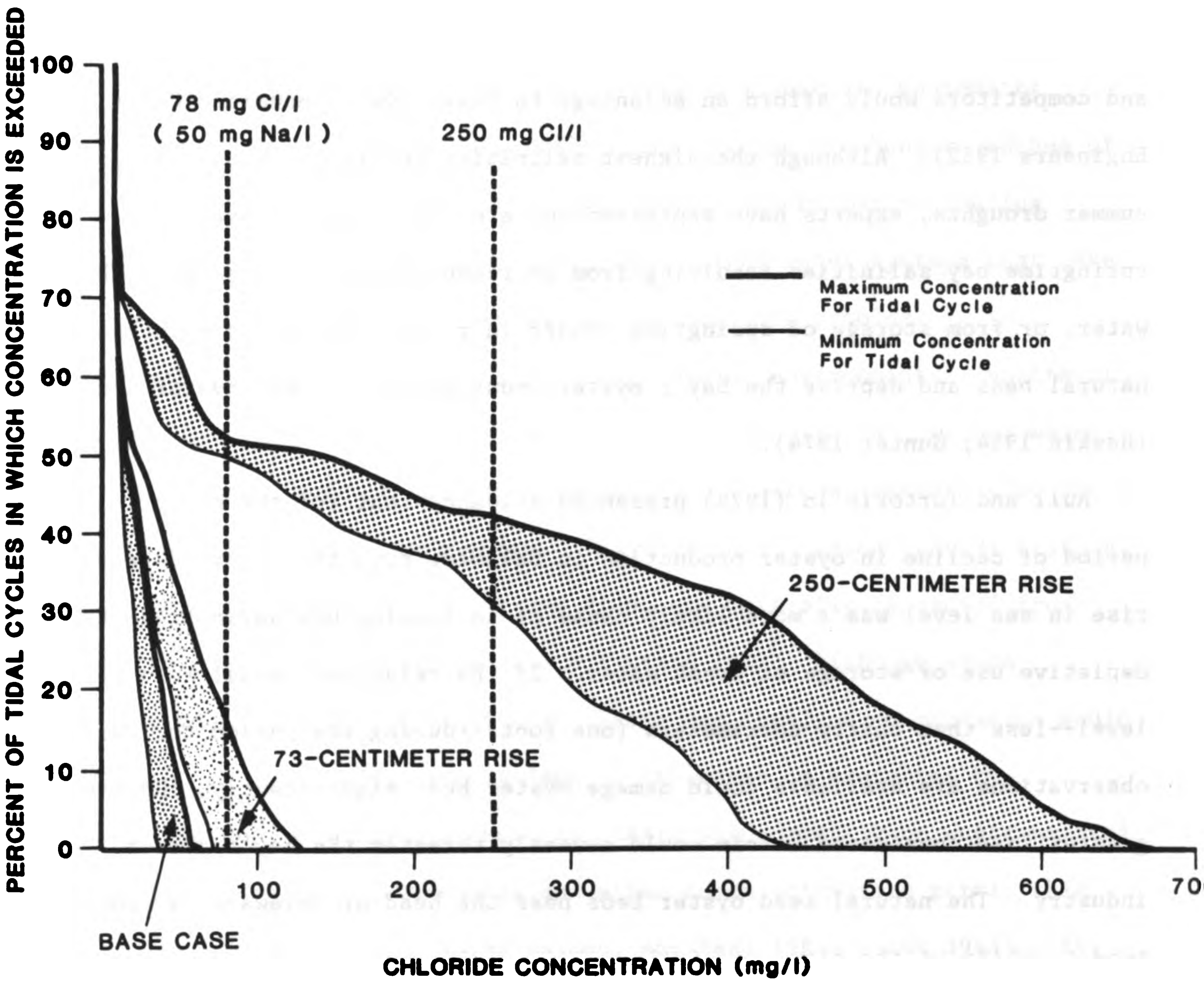
Implications

A rise in sea level of several feet would substantially exacerbate today's salinity problems in the Delaware estuary. The upper estuary above the Schuylkill River in Philadelphia, now a source of fresh water for both municipalities and industries, would become too salty for most uses, necessitating a switch to alternative supplies--at great expense. Philadelphia's water supply intake at Torresdale, now in the freshwater reach of the estuary, would be subject to occasional invasions of sea salts, which would sometimes leave the water unacceptable for the City's many water customers. Industries now using fresh water from the upper estuary would, after the sea level rise, find brackish water at their intakes during dry periods. Those industries now using brackish water from the middle and lower reaches of the estuary would experience much higher salinities than those for which their systems were designed, which would damage pipes, tanks, and machinery and increase water-treatment costs. In some cases these industries would have to shift permanently to alternative water supplies.

Oysters. In the upper, narrow reach of Delaware Bay are found natural oyster beds, which are managed by the oyster industry with supervision by the State of New Jersey to provide seed oysters for planting in leased growing

FIGURE 10

PERCENT OF TIDAL CYCLES IN WHICH SPECIFIED CONCENTRATION IS EXCEEDED AT TORRESDALE DURING A RECURRENCE OF THE 1960s' DROUGHT FOR THREE SEA LEVEL SCENARIOS



areas in seaward, more saline areas of the bay. Because of their location in less saline water, the natural seed-oyster beds provide havens for the young oysters from some of their natural enemies that require higher salinities for survival. Oyster biologists believe that increased salinities over the natural beds at critical periods in the annual life cycle of oyster predators and competitors would afford an advantage to these oyster enemies (Corps of Engineers 1982). Although the highest salinities generally occur during summer droughts, experts have expressed concern that the increases in springtime bay salinities resulting from increased depletive use of fresh water, or from storage of springtime runoff in reservoirs, would harm the natural beds and deprive the bay's oyster industry of its seed-oyster source (Haskin 1954; Gunter 1974).

Hull and Tortoriello (1979) presented evidence that for the historical period of decline in oyster production in Delaware Bay, the observed gradual rise in sea level was a more likely cause of increasing bay salinities than depletive use or storage of fresh water. If the relatively small rise in sea level--less than thirty centimeters (one foot)--during the period for which observations are available could damage oyster beds significantly, the much greater rise considered herein could severely threaten the bay's oyster industry. The natural seed oyster beds near the head of Delaware Bay would tend to shift up the estuary. Such a shift would reduce yields both because the estuary is much narrower above the bay and because shifting upstream would bring the oyster beds closer to upstream sources of pollution.

<u>General ecological impacts</u>. Potential impacts of increasing salinities on other estuarine plants and animals have been matters of concern expressed by ecologists (Corps of Engineers 1982). The magnitude of salinity increases

found in the DRBC model simulations of postulated accelerated rises in sea level would be expected to produce major changes in the ecology of the Delaware estuary. There would be an up-estuary advance of marine and estuarine species and a retreat of freshwater species. Some species now thriving in the relatively clean waters of the lower estuary would migrate into the more polluted areas of the upper estuary, closer to wastewater outfalls and other hazards. Water craft using the now freshwater reaches of the upper estuary would be subject to problems caused by marine fouling organisms. These marine organisms would also infest water systems that take water from the tidal river in reaches now free of this problem.

Although this report focuses on salinity, other environmental impacts of rising sea level may be important and should be investigated. Higher water levels could drown much of the approximately 830 square kilometers (320 square miles) of wetlands along the estuary. These wetlands, which provide critical habitats for many species of birds and fish, are partially protected from current human interference by federal and state laws. Although these ecosystems could migrate landward with rising sea level, such migration would be inhibited if development just inland of the marsh is protected by bulkheads, levees, and other structures; there are currently no environmental programs to ensure that development and other human activities permit this migration in the future (Titus, Henderson, and Teal 1984; Titus 1985). By removing one of nature's cleansing mechanisms, a loss of wetlands could increase pollution loadings in the estuary. Although long-term management of the estuary will have to consider these impacts, they are beyond the scope of this report.

IV. IMPACT OF INCREASED RIVER SALINITY ON NEW JERSEY AQUIFERS

Perhaps the most serious potential implication of increased river salinity would be saltwater contamination of adjacent aquifers. Many water users in the lower Delaware River Basin adjacent to the estuary depend on groundwater supplies, which are recharged in part by the river. Some New Jersey wells used for public water supply have already been shown to produce water with high concentrations of sodium, which, according to the State Health Department, represent a public health hazard (Braun and Florin 1963; Korch, Ramaprasad, and Ziskin 1984). The increasing salinities in the Delaware estuary that would accompany a large rise in sea level would severely aggravate the existing saltwater intrusion problems of aquifers in the Delaware Basin, primarily in New Jersey and Delaware. Some aquifers now heavily used would probably become too salty for drinking water and would have to be abandoned or limited to agricultural and industrial uses.

This section focuses on the impact of increased estuary salinity on the Potomac-Raritan-Magothy aquifer system, which supplies much of the water used in southern New Jersey. Although other aquifers are hydraulically connected to the estuary, this aquifer is the only major system with a connection to the part of the estuary likely to become salty as a result of future droughts or sea level rise.

The Relationship Between Sea Level and Aquifer Salinity

The only portion of an aquifer likely to be salty is the part below sea level. In coastal aquifers, a layer of fresh water floats on top of the heavier salt water. The salt water generally forms an intrusion wedge such that the farther inland (the higher the water table), the farther below sea level is the boundary between fresh and salt water, as shown in Figure 11. According to the simplistic Ghyben-Herzberg relation, for aquifers where the water table slopes toward the ocean, this boundary is forty meters below sea level for every meter above sea level the freshwater level in the aquifer lies. As sea level rises, the freshwater/saltwater boundary shifts inland and upward, with a time lag depending on how far that boundary is from the coast. Pumping wells cause water levels to fall below sea level, and if the withdrawal rate is too high, the equilibrium saltwater line will move far inland. The time lag is the major reason that many heavily pumped coastal aquifers are not yet salty.

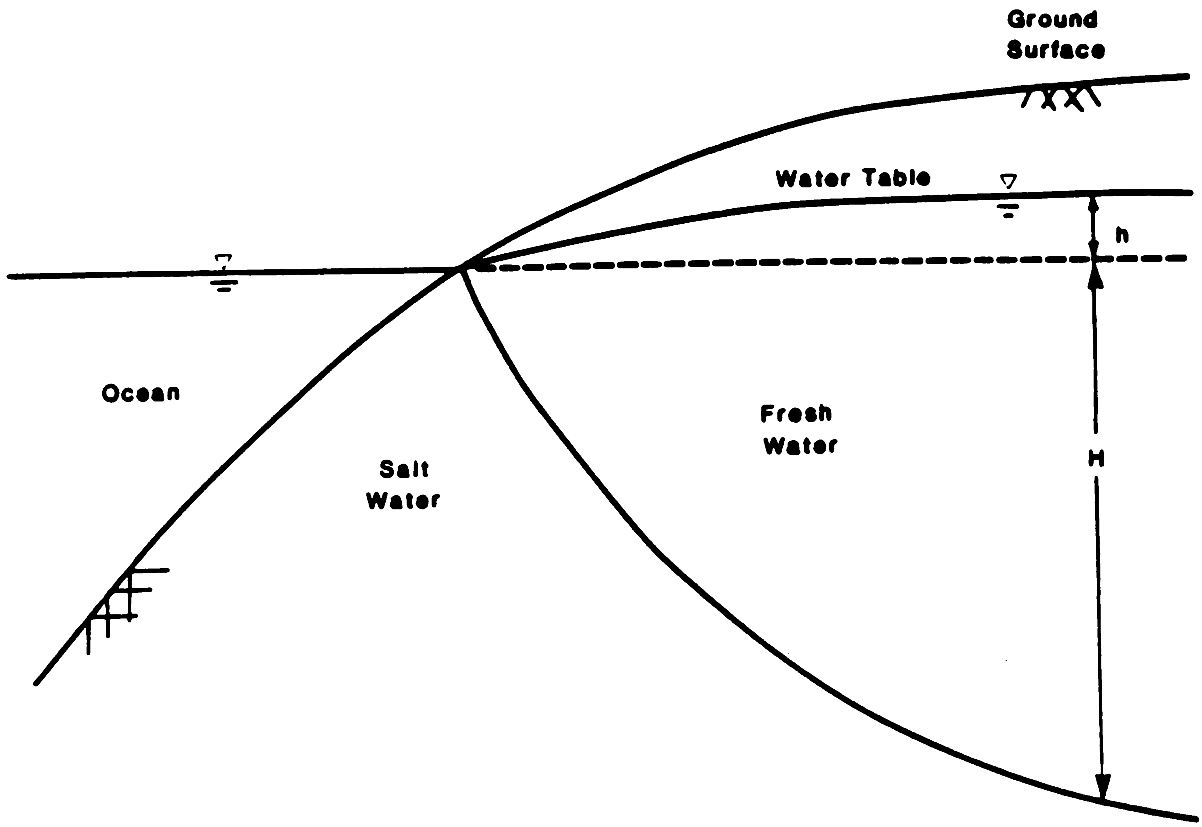
Many aquifers such as those in the Potomac-Raritan-Magothy aquifer system release water into rivers in their natural state. If such an aquifer is pumped so that groundwater levels fall below mean sea level, it will be recharged by nearby rivers. As discussed in Section 3, estuary salinity could respond to sea level rise or changes in precipitation quite rapidly. Thus, should the river become salty even temporarily, salt could infiltrate into such an aquifer and persist for a long time. The Potomac-Raritan-Magothy aquifer system is both a coastal aquifer and an aquifer recharged by a river.

The Potomac-Raritan-Magothy Aquifer System

The Potomac-Raritan-Magothy aquifer system is the principal source of water for the population and industrial centers in the coastal plain of southern New Jersey (Luzier 1980). The aquifer extends along the coast from North Carolina to Long Island. In New Jersey, the Potomac-Raritan-Magothy lies directly on top of bedrock, is confined above by a relatively tight clay

FIGURE 11

SALTWATER INTRUSION IN A COASTAL AQUIFER



Note: H = 40 x h

layer, and has a poor hydraulic connection to other aquifers far offshore. The Delaware River flows along the outcrop of the Potomac-Raritan-Magothy from Trenton, New Jersey, to Wilmington, Delaware (Figure 12), and there is a good hydraulic connection between the river and aquifer system, especially above river mile 98 (Camp Dresser and McKee 1982).

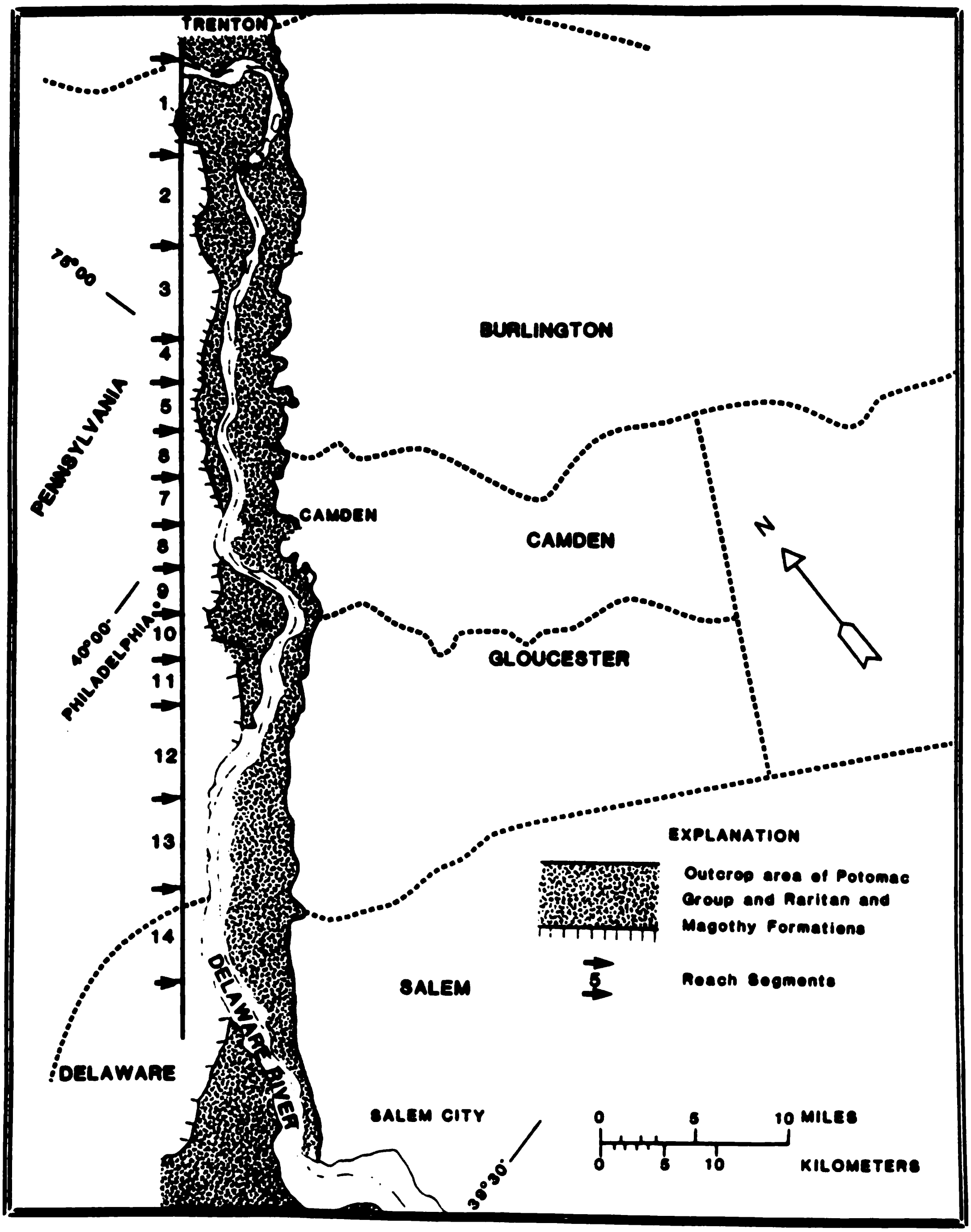
Vowinkle and Foster (1981) calculated the inflow into the aquifer for the river reaches shown in Figure 12 using a groundwater model developed by Luzier (1980) for 1973 and 1978 groundwater levels. The data showed that the greatest inflow occurs between river miles 101 and 106.5--adjacent to wells in the vicinity of Camden City--where water levels are significantly below mean sea level.

Even without a rise in sea level due to the greenhouse warming, saltwater intrusion into the aquifer will worsen in the future. The existing saltwater boundary to the south of Camden (Fig. 14) reflects a sea level that was fifteen to thirty meters (fifty to one hundred feet) lower than the present sea level, implying an ongoing adjustment to the one hundred meter rise that has taken place over the last eighteen thousand years (Meisler, Leahy, and Knobel 1984). As ground water is removed and the aquifer approaches equilibrium with current sea level, the salt front will move farther inland from the Atlantic Ocean.

Figure 13 illustrates the water levels in the Potomac-Raritan-Magothy aquifer system based on 1973 field data. Figure 14 illustrates a prediction that water levels will be more than 37 meters (120 feet) below mean sea level in Camden County by the year 2000, if the rate of groundwater withdrawal increases by 1.7 percent per year. As a result of deep saltwater movement from offshore, the saltwater line in the aquifer will advance to the location

FIGURE 12

MODELED AREA SHOWING OUTCROP AREA AND RIVER REACHES OF THE POTOMAC-RARITAN-MAGOTHY AQUIFER SYSTEM



Source: VOWINKLE, E.F., and W.K. FOSTER, 1981. Hydrogeologic Conditions in the Coastal Plain of New Jersey, Open-File Report 81-405. Trenton, New Jersey: U.S. Geological Survey, 39 pp.

shown in Figure 14, far enough inland to render the Potomac-Raritan-Magothy ground water in Atlantic, Cape May, and Cumberland Counties brackish or salty.

Impact of a Drought on the Aquifers--Current and Future Sea Level

Salinity levels in the ground water are monitored at selected locations by the United States Geological Survey and other agencies (see, for example, Schaefer 1983). Low salinity levels are normally found in the Potomac-Raritan-Magothy aquifer system adjacent to the Delaware River above river mile 98 because of freshwater inflows. However, when the salt front moves up the estuary during droughts, the high-salinity recharge water from the Delaware River increases salinity in the ground water, as shown in Figure 15.

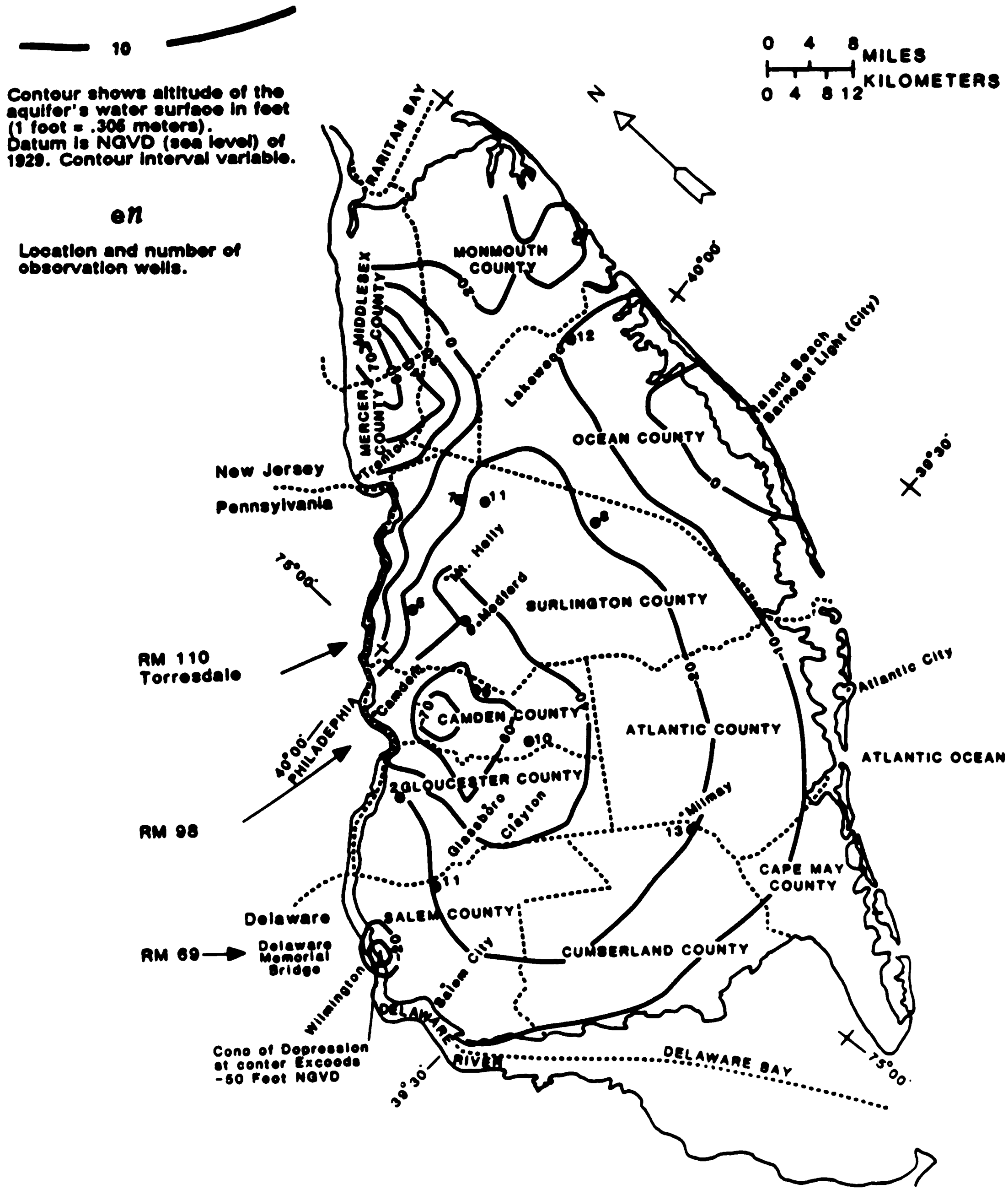
Table 4 shows the maximum thirty-day average chloride concentrations at the center of each reach for each of the three sea level scenarios for a recurrence of the 1964-65 drought. Because the DRBC is primarily concerned with protecting the Potomac-Raritan-Magothy aquifer system above river mile 98, we focus on reaches 1 through 8 (river mile 98 through 131).[6]

During the 1961-66 drought, the salt front moved up the Delaware estuary and allowed salt water to recharge the Potomac-Raritan-Magothy aquifer system. Increased salinity was observed in many wells adjacent to the Delaware River (Figure 15). In Camden County wells, for example, chloride concentrations increased 10 to 70 mg/l from background levels (5 to 10 mg/l) (Camp Dresser and McKee 1982). Elevated chloride levels persisted more than

[6] There are practical limits to the control of salinity in the Delaware estuary by reservoir regulation. Although it is recognized that some recharge of aquifers by the estuary takes place seaward of mile 98--some as far down as the Delaware Memorial Bridge--it is not practical to control salinity to provide drinking-water quality at all points along the estuary where recharge occurs. On the other hand, regulation at any point on the estuary, say at mile 98, does provide some control of salinity throughout the estuary.

FIGURE 13

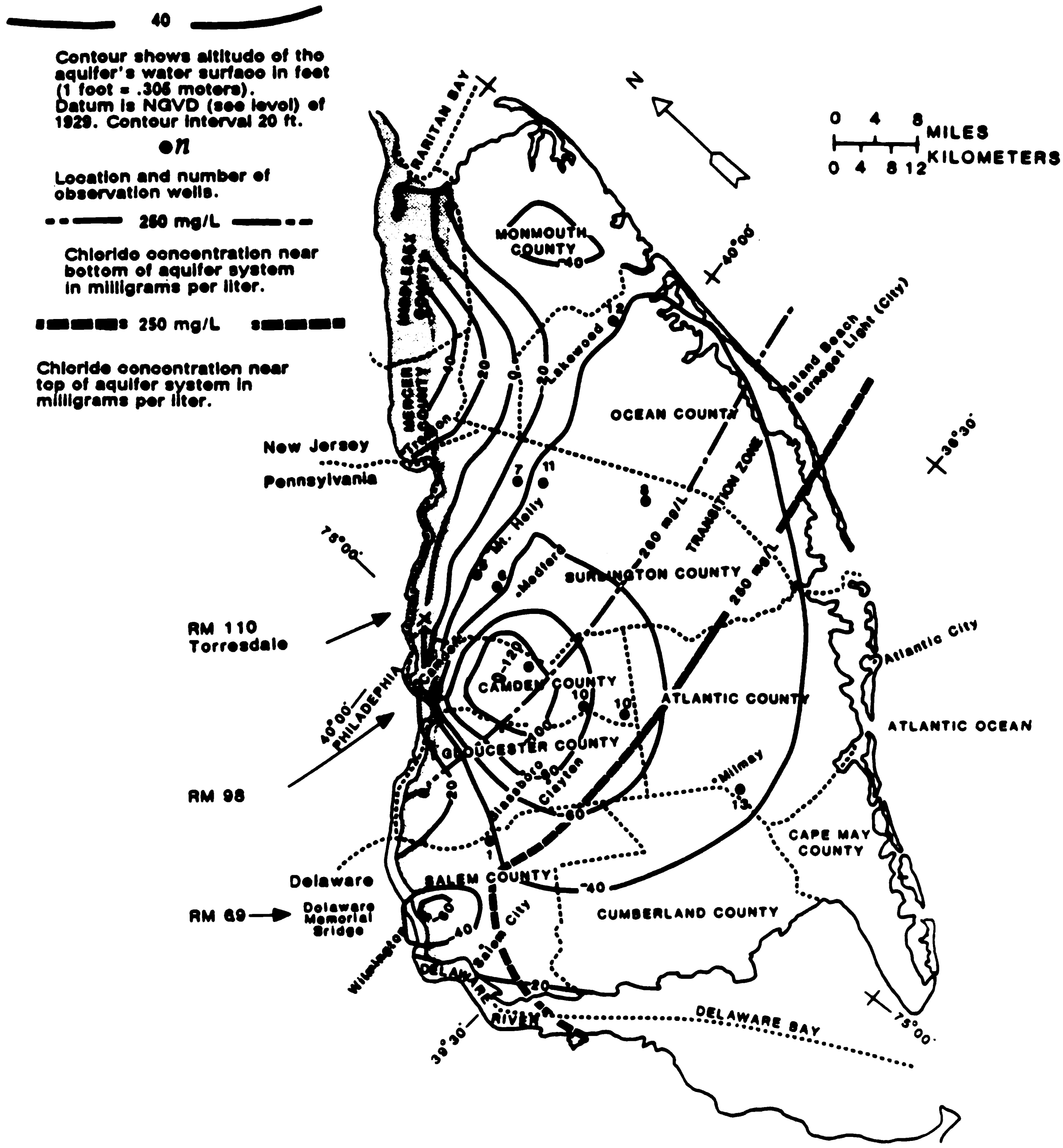
POTENTIOMETRIC SURFACE OF THE POTOMAC-RARITAN-MAGOTHY AQUIFER SYSTEM, NOVEMBER-DECEMBER 1973



Source: LUZIER, J.E., 1980. Digital-Simulation and Projection of Head Changes in the Potomac-Raritan-Magothy Aquifer System, Coastal Plain, New Jersey. U.S. Geological Survey Water Resources Investigations, 80-11.

FIGURE 14

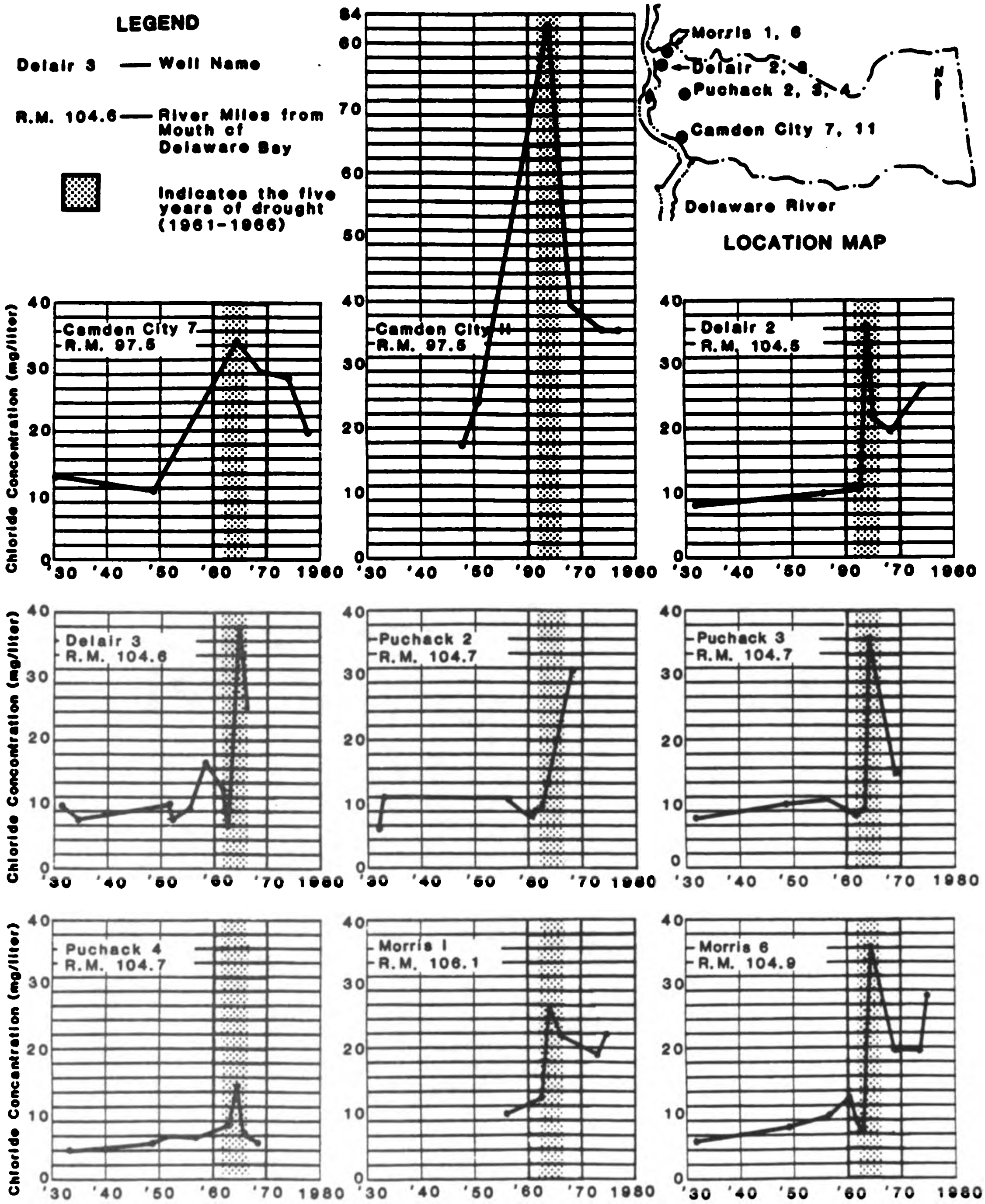
POTENTIOMETRIC SURFACE OF THE POTOMAC-RARITAN-MAGOTHY AQUIFER SYSTEM AT YEAR 2000 WITH ANNUAL EXTRACTION GROWTH RATE OF 1.7 PERCENT



Source: LUZIER, J.E., 1980. Digital-Simulation and Projection of Head Changes in the Potomac-Raritan-Magothy Aquifer System, Coastal Plain, New Jersey. U.S. Geological Survey Water Resources Investigations, 80-11.

FIGURE 15

CHLORIDE CONCENTRATIONS AT WELLS IN THE CAMDEN CITY VICINITY



Source: CAMP DRESSER and McKEE, INC., 1982. Groundwater Management Plan for Study Area 1: Coastal Plain Formations. Prepared for Delaware River Basin Commission, West Trenton, New Jersey.

TABLE 4

RECHARGE OF DELAWARE RIVER WATER INTO POTOMAC-RARITAN-MAGOTHY AQUIFER SYSTEM AND MAXIMUM SALINITY LEVELS OF RECHARGE

River Reach	Length of Reach (Miles)	River Mile	Estimated Reach Recharge to Aquifer System (cfs)**	Percent of Total River Recharge to Aquifer System	Maximum 30-Day Average Chloride Concentration (mg/l)		
					No Rise*	73-cm Rise*	250-cm Rise*
1	8.0	123 - 131	-	-	-	-	100
2	6.2	117 - 123	2.1	2.1	-	-	200
3	5.0	112 - 117	6.6	6.1	-	-	350
4	2.5	109.5 - 112	1.3	1.3	-	50	500
5	2.7	106.5 - 109.5	4.0	3.5	50	50	650
6	2.9	104 - 106.5	23.0	20.0	50	100	900
7	2.8	101 - 104	19.1	16.6	100	200	1200
8	2.8	98 - 101	9.4	8.2	100	250	1450
9	2.8	95.5 - 98	4.9	4.2	150	350	1700
10	4.5	91 - 95.5	13.1	11.4	250	450	2000
11	2.5	88.5 - 91	11.9	10.4	350	700	2500
12	6.5	82 - 88.5	11.8	10.5	600	1050	3050
13	5.4	76.5 - 82	1.4	1.3	1100	1650	3950
14	5.4	71 - 76.5	5.1	4.6	2250	2950	5400

* Post-1965 rise in sea level superimposed upon a recurrence of the 1964-65 drought flows.

** Total 1978 river recharge was approximately 43% of total water entering the aquifer system (Luzier 1980).

ten years; once introduced into the aquifer salinity contamination tends to remain (Camp Dresser and McKee 1982).

From such observed data, aquifer salinity distributions can be generated. Simulating the salinity distribution in the aquifer for the sea level scenarios requires a predictive numerical model. However, a first-order approximation can be deduced by considering (1) the estuary's salinity distributions for selected sea level rise scenarios (see Figure 9); and (2) the distribution of inflow into the aquifer (see Table 4).

Table 5 shows the penetration distances during the time that chloride concentrations exceed 250 and 78 mg/l, respectively, for the fifteen-month drought simulation. Although we simulated only fifteen months of the five-year 1961-1966 drought, these fifteen months were the worst part of that drought, with the lowest river flows and the highest estuarine salinities. Therefore, the computed chloride concentrations of recharge water would be no greater if we simulated the entire five-year drought. The estimates in Table 5 are based on groundwater velocities near the advancing edge of the saltwater front, estimated for each river reach based on 1978 water levels from Walker (1983) and aquifer properties affecting water velocities from Luzier (1980). The inflow rate obtained by Vowinkel and Foster (1981) was divided by the available cross-sectional area and porosity, providing an alternative method of computing groundwater velocities. The velocity ranges were extended to include both these estimates.

For the baseline scenario (recurrence of the 1964-65 drought flows with no sea level rise), the thirty-day average 250-mg/l isochlor in the estuary penetrates into reach 10 (river mile 91.0 to 95.5) with chloride concentrations in the estuary in excess of 50 mg/l extending up into reach 5 (river mile

106.5 to 109.5). Although the 250-mg/l line would not penetrate to reach 8, penetration distances of over ninety meters (three hundred feet) are predicted for the 78-mg/l line in reaches 6, 7, and 8 (Table 5). If in subsequent years the salinity in the recharge water decreased again to normal levels, the slug of high-salinity water would continue to move toward the area of lower water levels, that is, toward the center of the major cone of depression in Camden County (see 1973 water levels in Figure 13). As this slug slowly moves, however, the chloride concentration would decrease because of diffusion, dilution by lower salinity recharge water (including precipitation), and withdrawal from the aquifer. Nevertheless, levels in excess of the New Jersey drinking water standard (50 mg/l sodium, corresponding to 78 mg/l chloride) could occur for several years in areas within a mile or two of the river.

For the 73-centimeter sea level rise scenario, water with chloride concentrations slightly in excess of 250 mg/l (corresponding to a sodium concentration of 145 mg/l) would begin to recharge the aquifer system in the vicinity of reach 8 (river mile 98 to 101). The dilution and diffusion of the salt water as it moves through the aquifer would undoubtedly reduce the chloride concentration below 250 mg/l within a very short distance of the Delaware River. Above reach 8, the chloride concentrations are predicted to be below 250 mg/l. Thus, like the baseline case, no significant region of the aquifer adjacent to the Delaware River above river mile 98 should experience sustained chloride concentrations above 250 mg/l. Sodium concentrations greater than 50 mg/l would be present in the recharge water as far as reach 4 and would penetrate several hundred feet in reaches 6, 7, and 8.

For the more severe 250-centimeter sea level rise scenario, a significant zone (reach 3 and seaward) of the aquifer system would be recharged by water

TABLE 5

VELOCITIES, CONTACT TIMES, AND PENETRATION DISTANCES FOR GROUND WATER WITH ELEVATED CHLORIDE CONCENTRATIONS

River Reach	Estimated (1978) Ground-Water Velocity Range (meters/year)	Time that 30-Day Average Chloride Concentration Exceeded 78 mg/l and 250 mg/l (days)					Maximum Aquifer Penetration Distance for Duration of Contact Time (meters)				
		78 mg/l		250 mg/l			78 mg/l		250 mg/l		
		BASE	73 cm	BASE	73 cm	250 cm	BASE	73 cm	BASE	73 cm	250 cm
1	0-90	-	-	-	-	-	-	-	-	-	-
2	0-90	-	-	-	-	-	-	-	-	-	-
3	90-150	-	-	-	-	120	-	-	-	-	50
4	30-60	-	30	-	-	130	-	5	-	-	20
5	90-180	-	100	-	-	140	-	50	-	-	70
6	270-580	60	130	-	-	150	95	205	-	-	240
7	460-550	110	150	-	-	160	165	225	-	-	240
8	240-370	140	160	-	100	170	140	160	-	100	170
9	120-150	160	170	-	120	180	65	70	-	50	75
10	180-400	170	180	100	140	190	185	195	110	150	205
11	300-370	180	190	120	160	200	180	190	120	160	200
12	90-150	190	200	140	180	400	80	80	60	75	165
13	0-30	200	210	160	200	400	15	15	15	15	35
14	60-90	230	250	180	220	400	55	60	45	55	100

Note: A chloride concentration of 78 mg/l corresponds to a sodium concentration of 50 mg/l, the New Jersey drinking water standard.

from the river with thirty-day chloride concentrations in excess of 250 mg/l. The slug of high-salinity water would move significant distances before dispersing to insignificant background levels.

In summary, a recurrence of the 1960s' drought with a higher sea level would cause increased sodium and chloride levels in parts of the Potomac-Raritan-Magothy aquifer. These increased levels would persist for long periods--probably several decades--as the high-chloride water dispersed and propagated toward pumping wells. For many years, some wells would experience elevated sodium levels that could make the water unfit for many purposes, including human consumption, in which case, water from alternate sources could be required.

Improved Estimates

Although we used the DRBC salinity model to estimate surfacewater impacts, no similar model was available for assessing groundwater impacts without an investment of resources exceeding what was available for this study. To more adequately evaluate the impact of the estuary salinity distributions on the groundwater system will require a solute transport and dispersion model, such as the one presented by Konikow and Bredehoeft (1978). A significant field investigation should be conducted, including an in-depth review of existing field data. Because of the complex hydrogeology, a numerical model is required. The model must contain such features as salinity concentration at the boundaries, which can vary in time and space. Although a two-dimensional representation may prove adequate, a three-dimensional model may be necessary. During drought conditions, high-chloride water will recharge the aquifer far up the estuary for a limited period of time. The output of a numerical model will allow tracking of the slug of high-chloride water as it propagates and moves through the aquifer in the down-gradient direction.

V. RESPONSES TO SALINITY INCREASES

In spite of the severity of projected salinity increases, the major impacts are far enough in the future to be incorporated into planning by the DRBC, state governments, and the private sector. The options fall primarily into two categories: preventing increased salinity or adapting to it. This section briefly discusses such options. A determination of the most appropriate responses to be undertaken is outside the scope of this report.

Preventing Salinity Increases

Increasing river flow can offset salinity increases. The DRBC currently maintains capacity to release fresh water from reservoirs and has regulatory authority to decrease consumptive use of water during droughts.

Hull and Tortoriello (1979) determined that the thirteen-centimeter (five-inch) rise in sea level expected for the period 1965-2000 (based on recent trends) would require an increase in reservoir capacity of fifty-seven million cubic meters (forty-six thousand acre feet). The DRBC's comprehensive plan provides for such an increase in capacity.

A conservatively low extrapolation of the results from Hull and Tortoriello (1979) implies that for the thirty-centimeter (one-foot) rise in sea level expected through 2025, the required additional reservoir capacity would be approximately 140 million cubic meters (110 thousand acre feet), about one fourth the capacity that would be provided by the proposed Tocks Island reservoir. Table 6 lists reservoirs that are currently in the DRBC's long-range comprehensive plan, with a combined reservoir capacity of 730 million cubic meters (592 thousand acre-feet). These reservoirs would augment streamflow during droughts enough to offset salinity increases caused by sea

TABLE 6

UNSCHEDULED RESERVOIRS IN DRBC'S PLAN THAT COULD BE
USED TO OFFSET SALINITY INCREASES IN THE DELAWARE ESTUARY a/

Name of Project	Location b/	Increment of Long-Term Storage Capacity: Cubic Meters (millions)	Billions of Gallons	Acre-Feet (thousands)
(1)	(2)	(3)	(4)	(5)
Tocks Island Reservoir	Delaware River (217.2)	525	139	425.6
Aquashicola Reservoir	Aquashicola Creek (183.66 - 36.3 - 4.6)	30	8	24
Maiden Creek Reservoir	Maiden Creek (92.5 - 86.7 - 9.6)	91	24	74
Evansburg Reservoir	Skippack Creek (92.47 - 32.3 - 3.0 - 1.0)	29	8	23.5
Newark Reservoir	White Clay Creek (70.7 - 10.0 - 12.0)	37	10	30
Icedale Reservoir	W. Branch Brandywine Cr. (70.73 - 1.5 - 20.0 - 25.6)	18	5	14.6
Total		730	194	592

a/ These multipurpose projects are currently (1985) in the DRBC's Comprehensive Plan, but this does not guarantee ultimate construction, which will depend on further analysis of water demand, environmental impact, and financial feasibility. Such analysis may result in deauthorization of some of these projects. They are generally in reserve status--for development after year 2000, if needed.

b/ Statute miles, measured along the axis of Delaware Bay and River from the mouth of the bay. Second and subsequent mileages indicate distances above the mouths of tributaries.

level rise and increased water consumption well into the 21st century. However, most of these dams have not yet been scheduled for construction.

Although reservoirs are generally not built before they are needed, incorporating future reservoirs into the Comprehensive Plan long before construction can help to limit eventual costs. Otherwise, the best sites may be developed for other uses, increasing the cost of purchasing the land, perhaps to the point where a dam at that site becomes economically infeasible, which could necessitate selection of an alternative reservoir site that is less environmentally or economically attractive.

The advantage of adding reservoir capacity is that such an approach fits within the current policy framework. The limitations, however, must also be considered. Although dams can mitigate environmental disruption caused by consumption of water, environmental disruption can result from the dams themselves, a factor of no small importance in the opposition to the proposed Tocks Island Lake, the consideration of which has been deferred until after the year 2000. Moreover, the capacity of reservoirs must keep pace with increased consumptive use of water, as well as sea level rise. Finally, each additional dam tends to cost more than the previous one, as the least costly sites are usually developed first. Thus, even ignoring environmental questions, there is a limit to the ability of reservoirs to counteract saltwater intrusion in a cost-effective manner.

Increased private storage capacity could augment public reservoirs. As mentioned in Section 3, electric utility companies in the Delaware Basin are already required to develop enough storage capacity to offset their new consumptive uses during low-flow conditions. Actions could be taken to encourage other users to develop storage or decrease consumption.

Decreasing the depletive use of water from the river would also prevent salinity from increasing. The DRBC has used its special powers during several drought emergencies since 1965 to curtail diversions to New York City and northeastern New Jersey and other depletive uses. In 1983, the DRBC (1983b, 1983c) adopted regulations that automatically cut back consumption within the basin and diversions out of the basin during droughts.

Decreasing depletive uses of water has been one of the DRBC's tools for combatting saltwater intrusion. Nevertheless, there are practical and physical limits on the ability to offset salinity increases caused by a large rise in sea level. Although conservation has been exploited to a high degree within the basin, consumptive use is expected to grow with population. Curtailing diversions of Delaware River water to New York City and other areas may impose increasing hardships on these areas as alternate supplies such as the Hudson River also become saltier. Moreover, even if all depletive uses of water were eliminated, a substantial rise in sea level would eventually increase salinity in the estuary, as it has since the last ice age.

Adapting to Increased River Salinity: Surfacewater Users

If measures are not undertaken to prevent a salinity increase, water users will have to adapt to it. The City of Philadelphia could adapt to increased salinity by moving its intake upstream. This approach was actively considered as a temporary measure during the 1960s' drought, when the Torresdale intake was threatened by saltwater intrusion (Hogarty 1970).

Although Philadelphia will almost certainly continue to rely on the Delaware River for part of its water supply, other users may be able to shift to alternative supplies. The Chester (Pennsylvania) Municipal Authority has already done so. Formerly taking its water supply from the tidal Delaware

River below Philadelphia, the Authority was forced to abandon this source in 1951 because of frequent high salinities related to low river flows. The Authority now obtains its water supply from the Susquehanna River Basin. However, the Susquehanna River flows cannot be reduced without limit to help Delaware Basin water users avoid increasing salinity; the Susquehanna has its own problems, including the need to maintain adequate low flows for salinity control in upper Chesapeake Bay (Schaefer 1931; Susquehanna River Basin Commission 1973).

Some industries along the Delaware estuary may eventually find it impossible to obtain adequate freshwater supplies. Such industries may be forced to relocate to areas where fresh water is available. Others may be able to survive at their present locations by shutting down river pumps during periods of high salinity and switching to municipal water distribution systems with access to fresher sources. This has happened in past droughts in the area along the Delaware estuary served by the Chester Municipal Authority. However, alternative sources may be prohibitively expensive.

Although water conservation measures could make only a limited contribution toward preventing salinity increases, they could also play a role in adapting to decreased availability of fresh water. Nevertheless, they would face institutional barriers that could substantially delay an effective response. Additional regulations of water use would require identification of additional activities to be controlled. Although higher prices could theoretically induce an economizing shift toward conservation, public agencies would find it difficult to raise water prices, particularly for those whose water is supplied by wells on their own property.

Finally, companies and individuals may adapt by using water with higher salinity. Companies that use water for cooling may experience increased corrosion of pipes and machinery, or may invest resources in corrosion-resistant materials. Some individuals may shift to bottled water during droughts,[7] while others may choose to drink water with elevated salt content rather than go to the expense of distilling water. Health-conscious people may respond to salt-laden drinking water by reducing salt intake from other sources. Nevertheless, the health hazard of elevated sodium in water ingested by persons subject to hypertension and other diseases requiring low-sodium diets is an argument for avoiding high salt content in public drinking-water supplies, so that susceptible persons will not be forced to save money by sacrificing health.

Adapting to Increased River Salinity: Groundwater Users

Groundwater users can adapt to increased salinity in ground water by many of the same methods by which surfacewater users can respond. In addition, efforts may be undertaken to prevent the river from recharging the aquifers with salt water. The methods include physical barriers, extraction barriers, freshwater injection barriers, and increased recharge from sources other than the estuary. Modified pumping patterns could also be employed.

Physical barriers. Subsurface physical barriers, such as sheet pile cutoff walls, clay slurry trenches under earth dams, and impermeable clay walls, are routinely used by engineers to control the movement of water and

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[7] A large fraction of citizens in New Orleans use bottled water or purchase home distillers; the salt-intrusion problem in Louisiana probably will continue to be more severe than that in the Delaware River Basin.

other liquids, including hazardous waste materials. It is also possible to inject materials that form a zone of low permeability.

Extraction barriers. Extraction barriers consisting of a line of pumping wells parallel to shore have been used in various locations in order to prevent or reduce saltwater intrusion (Stone 1978). Extraction barriers may withdraw some fresh water that would otherwise be useful and thus may not be a viable option where water supplies are scarce.

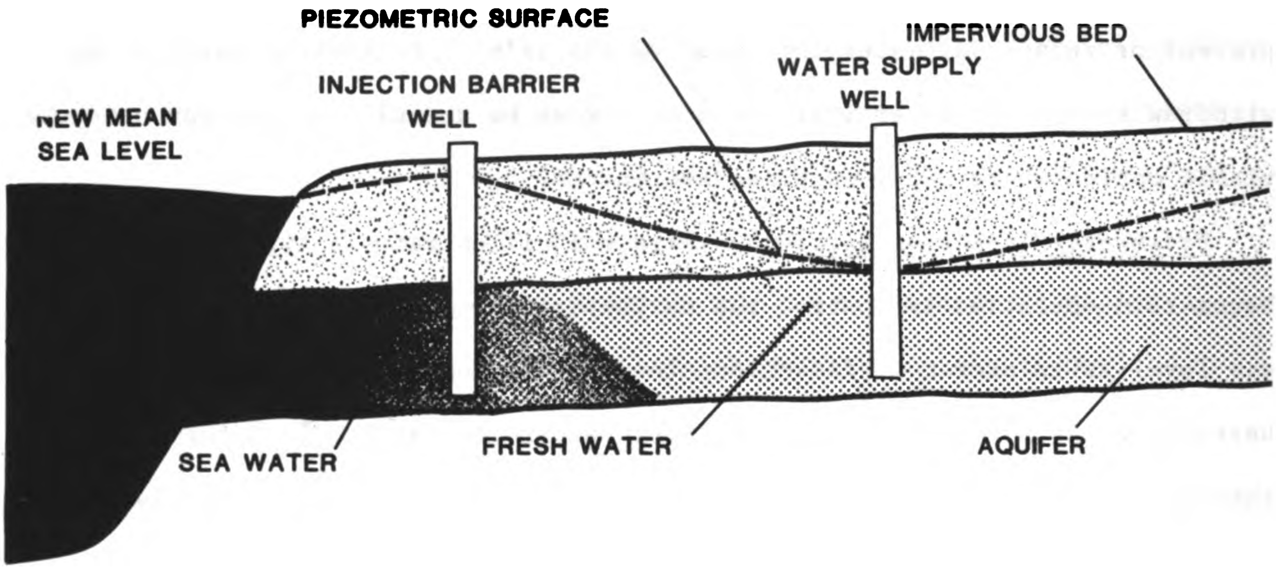
Freshwater injection barriers. Figure 16 illustrates a typical injection barrier in operation to control the saltwater intrusion for cases where the sea level is in excess of freshwater levels. In contrast to the extraction barrier, with an injection barrier, fresh water is injected into the aquifer through a line of wells along the shoreline. The higher groundwater levels along the injection barrier prevent saltwater intrusion.

Increased recharge. In many coastal locations in the United States, sufficient amounts of fresh water are available for recharge during periods of high precipitation. Although some water is captured during these periods and stored in surface reservoirs, very little water is artificially recharged to groundwater reservoirs for use during droughts. This extra water, which is "wasted" to the ocean, could be used to replenish the aquifer, build up groundwater levels, and slow or stop saltwater intrusion.

Modified pumping patterns. For aquifers where moderate pumpage already occurs and the effect of a sea level rise is projected to be important, a phased shutdown of wells can be designed as the monitored saltwater intrusion progresses. Instead of a disorganized search for alternate water as the chloride concentrations increase, logical permitting of new wells or new economical surfacewater distribution schemes can be implemented. Because a

FIGURE 16

INJECTION-TYPE SEAWATER INTRUSION BARRIER



Source: SORENSEN, R.M., R.N. WEISMAN, and G.P. LENNON, 1984. Control of Erosion, Inundation and Salinity Intrusion Caused by Sea Level Rise. In Greenhouse Effect and Sea Level Rise: A Challenge for This Generation, edited by M.C. Barth and J.G. Titus. New York: Van Nostrand Reinhold.

saltwater slug will pass through the aquifer even when the drought that caused the high river salinity has passed, the well could be reopened after the aquifer has become fresh again. However, such natural purging of a contaminated aquifer may require decades, if not centuries.

Although it is technically possible to use physical, extraction, or injection barriers to prevent saltwater intrusion in the Potomac-Raritan-Magothy aquifer system, the large expense probably would not be justified. Harbaugh, Luzier, and Stellerine (1980) present technical information on how an injection barrier could be employed in the aquifer system to reduce the existing saltwater intrusion. However, Camp Dresser and McKee (1982) provide cost estimates showing that the implementation of such a groundwater barrier is not feasible because of the large area needing protection. Although these types of barriers may be considered, they probably cannot be justified economically.

Increased recharge in the aquifer's outcrop could be employed at a reasonable cost, as could modified pumping patterns, which would shift the pumping away from the critical areas. The State of New Jersey is currently studying alternative water systems for the critical area of excessive drawdown in Camden County. Among alternatives being considered is the improvement of the water distribution system, which would transfer water to the area of heavy drawdown from other sources, thus relieving pumping stress in the critical area.

VI. NEXT STEPS

Considering Climate Change

Although this paper focuses on the impact of sea level rise on salinity, other consequences of the greenhouse effect may accelerate or delay the consequences of sea level rise. For example, if droughts become more severe in the future, the resulting reduction in river flow would also allow salinity to increase. Although projections of drought conditions cannot currently be made for specific regions, general circulation models suggest that drought frequencies may change substantially.

Rind and Lebedeff (1984) examined model calculations of the change in drought frequency, caused by a doubling of atmospheric CO_2, for four regions of the continental United States, one of which included the Delaware River Basin. Two of the regions would change slightly, one would experience half as many droughts, while the other would experience ten times as many. Although the Delaware River Basin is largely in the latter region, the authors strongly warn that their model does not accurately project climate for particular regions.

This report focuses on rising sea level because our ability to project it is far superior to our ability to predict future precipitation change. Nevertheless, planning for hydrologic shifts may be more important than planning for sea level rise. It is possible to plan around a gradual rise in sea level; even waiting until the 1990s for a confirmation of the predicted global warming would allow time to prepare for the most severe consequences. By contrast, a drought can occur suddenly, and several droughts may have to occur before people know that their area is more prone to drought than it was in the past. Thus, successful planning for changes in the hydrologic cycle will probably have to start before those shifts are well understood.

Chen, Boulding, and Schneider (1983) have thus argued that in this situation, water resource officials should rely on "robust" strategies--policies that are less vulnerable to large changes in conditions and can accommodate a shift in either direction. In the case of the Delaware River Basin, two types of policies readily come to mind. Reservoirs provide more water storage for increased drought frequency, but they can also be used to prevent flooding that would occur from an increased frequency of extremely wet periods. Market mechanisms can also help for shifts in either direction because they encourage individuals to adapt quickly to new information rather than to wait for the government to formulate its response.

Although policies have been identified that would reduce the vulnerability of the water supply in the Delaware River Basin to future climate change, it would be infeasible and unwise to implement these policies until a comprehensive assessment of the likely impacts and possible solutions has been undertaken.

The DRBC's long-range comprehensive plan includes numerous measures that would reduce the vulnerability of the region's water supply to salinity increases resulting from rising sea level or changes in climate. Comprehensive assessments of the likely impacts and possible solutions should be undertaken to provide adequate lead time for implementing these measures if and when they become necessary.

Necessary Research

The highest priority is to determine the impact of various climate change scenarios on river salinity and the streamflow modification required to maintain acceptable salinity levels in the face of climate change. An examination of the costs and benefits of various response options should then be undertaken for each of these scenarios. By examining each option for a variety of possible sea level and precipitation changes, it may be possible to identify which solutions are likely to be robust and which are likely to be clearly inferior. A particularly important question for such an analysis is what amount of resources could be saved by planning in the 1980s, compared with delaying the planning until the 1990s or later.

A second research priority that concerns other parts of the nation as well as the Delaware River Basin is to develop better estimates of future sea level rise and climate change. In addition to undertaking the research, it is essential that the results be made available to decision makers and the public at large. For the private sector to make locational and design decisions that are consistent with expected water availability, people must become informed about future conditions.

Improvements in the models for estimating salinity changes will also be necessary. The model used in this report to estimate river salinity would benefit from a more in-depth assessment of the impact of sea level rise on shoaling and the estuary's width and cross-sectional geometry. Increasing salinity of the Potomac-Raritan-Magothy aquifer system is already a research priority of the U.S. Geological Survey. Current efforts should be supplemented with analysis of the implications of rising sea level on that system.

Conclusion

The expected rise in sea level and climate changes caused by the greenhouse effect are likely to have profound impacts on the quality and availability of water in the Delaware River Basin. Although the greatest impacts are decades in the future and cannot be predicted precisely, assessments of how to respond should start now. Public officials responsible for water quality will have to decide whether to adapt to salinity changes or attempt to prevent them. Such assessments may require lengthy public debates, after which planning, design, and implementation may take decades. Furthermore, even current trends may necessitate management changes by the year 2000.

An important impediment to implementing the farsighted policies that will be necessary is the relatively short planning horizon of 15-20 years generally used by the DRBC, as well as other agencies. This time horizon has been appropriate in the past because decisions have involved such phenomena as economic growth and technology that did not require a longer lead time. But given the longer-term impacts of climate change and sea level rise, the longer lead time required to prepare for the consequences, and the potential magnitude of the impacts, a longer time horizon is warranted.

We cannot rule out the possibility that our current understanding overlooks factors that will substantially reduce the saltwater intrusion expected from the greenhouse effect. Perhaps the Delaware River Basin will be one of the regions that experience fewer droughts in the future. Should one conclude that preparations are not necessary? Can we afford to gamble with our water supplies on the hope that problems will not emerge in the future? Such issues are outside the scope of a technical report and must be addressed by policy makers and the public at large.

APPENDIX A

TECHNICAL DESCRIPTION OF DELAWARE ESTUARY SALINITY MODEL

Governing Equations: Knowns and Unknowns

The model is based on the general, one-dimensional equations of open channel hydraulics and conservation of salt as coupled through an equation of state that relates density to salinity and to temperature. The unknowns of these equations are the surface elevation, the velocity (discharge divided by area), and the salt concentration. Known quantities are the geometry, the time-varying tributary inflows and tributary salinities, the temperature, and the tidal elevations at the ocean boundary throughout the period being modeled. The time scale of calculation is sub-tidal so as to properly account for the estuarine dynamic response to the driving force of the ocean tidal oscillation and to ensure that the mixing can be represented as accurately as possible. The use of such a small time-scale is essential, as sub-tidal variations play an important role in long-term and short-term salinity concentrations (Najarian et al. 1983; Elliot 1978). The equations on which this model is based are as follows.

Continuity equation:

$$b\frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} - q = 0 \qquad \text{(a-1)}$$

Longitudinal momentum equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial (QU)}{\partial x} + gA\frac{\partial h}{\partial x} + g\frac{Ad_c}{\rho}\frac{\partial \rho}{\partial x} + g\frac{Q|Q|}{AC^2R_h} = 0 \qquad \text{(a-2)}$$

Salt balance equation:

$$\frac{\partial(A_t s)}{\partial t} + \frac{\partial(Qs)}{\partial x} = \frac{\partial}{\partial x} \left(A_t E \frac{\partial s}{\partial x}\right) \qquad \text{(a-3)}$$

Equation of state (relation between density, salinity, and temperature):

$$\rho = \alpha_T + \beta_T s \qquad \text{(a-4)}$$

In the above equations: b = total surface width; h = depth from water surface to horizontal datum; Q = cross-sectional discharge; q = lateral inflow per unit length; U = longitudinal velocity averaged over the cross section of the core area; A = core area; g = acceleration of gravity; d_c = distance from the water surface to the centroid of the cross section; ρ = mass density of water; R_h = hydraulic radius of core area; C = Chezy coefficient; A_t = the total area of the cross section, including that of storage areas; s = salinity averaged over the total cross section; and E = the longitudinal dispersion coefficient. All of the aforementioned quantities (except g) are functions of longitudinal location (x), and time (t). The coefficients α_T and β_T depend only on temperature.

The continuity equation (a-1) and the momentum equation (a-2) are essentially in the form used by Harleman and Lee (1969) to describe the unsteady tidal hydraulics of estuaries and canals. Thatcher and Harleman (1972) incorporated an additional term into the momentum equation that includes the effect of the longitudinal density gradient due to salinity. This term, $gA(d_c/\rho)\ \partial\rho/\partial x$, couples the two hydraulic equations to the salt balance equation through the equation of state (a-4).

The one-dimensional salt balance equation (a-3) can be obtained by spatially integrating the three-dimensional convective-diffusion equation for turbulent flow, as demonstrated by Okubo (1964) and Holley and Harleman (1965).

Longitudinal Dispersion Relationship

The longitudinal dispersion coefficient, E, represents the combined effect of internal circulation induced by saline density gradients and mixing due to boundary shear. The boundary shear effect is assumed to be represented by a dispersion relation similar to that formulated by Taylor (1954). The density gradient effect is assumed to be proportional to the absolute value of the local, longitudinal salinity gradient. This assumption implies that density-induced circulation is greatest in the region in which the longitudinal salinity gradient is largest. This relationship, assumed by Thatcher and Harleman (1972), is

$$E(x,t) = K \left| \frac{\partial \mathring{s}}{\partial \mathring{x}} \right| + mE_T \qquad \text{(a-5)}$$

in which K is a stratification parameter that depends on the degree of vertical stratification in the estuary. The value $\mathring{s}$ is defined by the relation $\mathring{s} = s/s_o$, s_o being the maximum salinity at the ocean boundary. The value $\mathring{x}$ is defined by the relation $\mathring{x} = x/L$, L being the length of the estuary from the ocean boundary to the head of tide, and E_T is the Taylor-type dispersion coefficient applicable in the upstream freshwater portion of the estuary where $\partial\mathring{s}/\partial\mathring{x} = 0$. The coefficient m is used to account for channel irregularities and other effects not caused by density-induced circulation. The coefficient E_T is defined for free surface flow by

$$E_T = 77\ UnR_h^{5/6} \qquad \text{(a-6)}$$

(where n is Manning's n)

The local salinity gradient is expressed in dimensionless form and the stratification parameter, K, has the dimensions of a dispersion coefficient, l^2/t. The stratification parameter, K, is assumed to be independent of distance and time within a particular tidal period. However, K may vary from one tidal period to the next, depending on the degree of stratification. In order to make the model more predictive, it is necessary to relate this stratification parameter to the gross estuary properties that determine the degree of stratification. This is done by a correlation between K and a densimetric estuary number as defined by

$$\mathbb{E}_D = \frac{P_t \mathbb{F}_D^2}{Q_f T} \qquad \text{(a-7)}$$

in which P_t is the tidal prism, calculated by integrating the flow at the ocean boundary during the flood portion of the tidal cycle; Q_f is the freshwater inflow upstream of the salt front; and T is the duration of the tidal period. The densimetric Froude number, $\mathbb{F}_D$, is defined by

$$\mathbb{F}_D = \frac{U_o}{\sqrt{g \frac{\Delta \rho_o}{\rho} h_o}} \qquad \text{(a-8)}$$

in which $\Delta\rho_o$ represents the density difference between fresh water and ocean water; ρ the ocean density, and U_o and h_o are the maximum tidal velocity and the depth, respectively, at the ocean boundary.

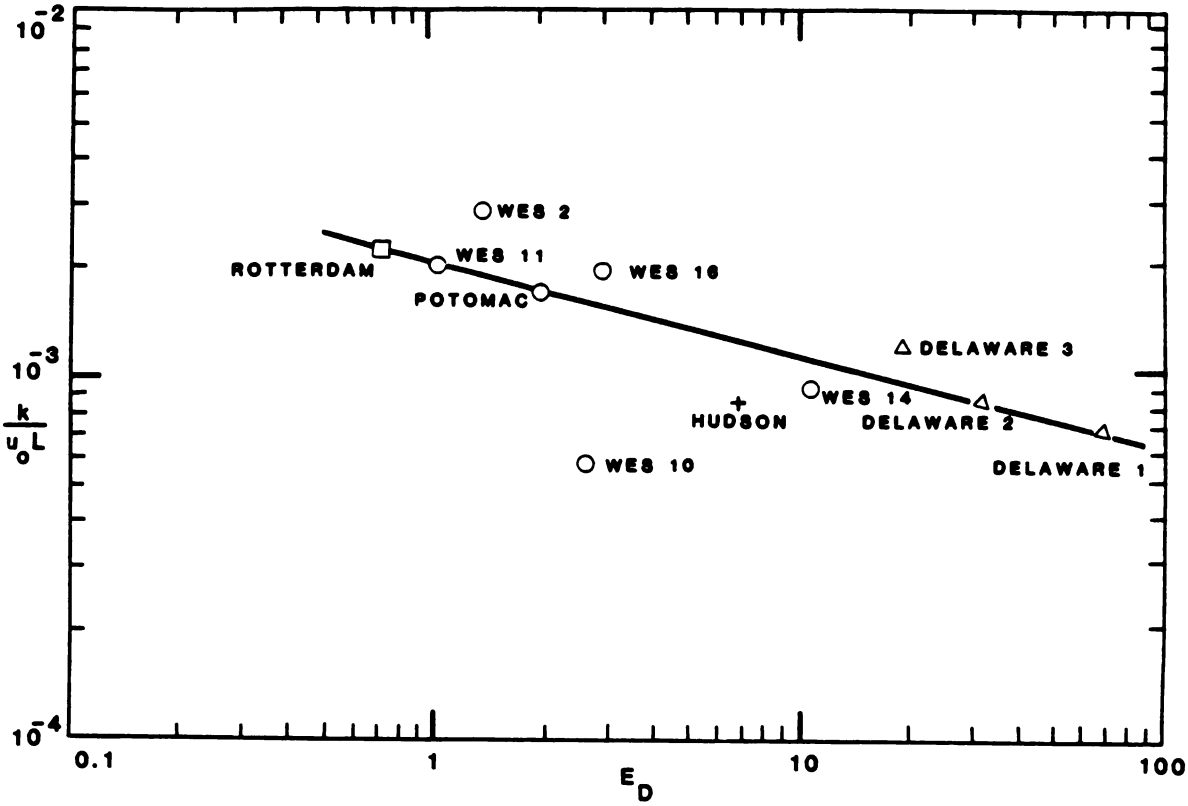
By using salinity data from laboratory flumes, estuary models, and field studies, Thatcher and Harleman (1972) found a correlation between the normalized stratification parameter, $K/(U_oL)$, and the estuary number, as shown in Figure A-1. The densimetric estuary numbers, $\mathbb{E}_D$, extend over two orders of magnitude ranging from relatively stratified conditions in the Rotterdam Waterway to fairly well-mixed conditions in the Delaware estuary. Within this range, the ratio $K/(U_oL)$ varies only by a factor of 5. The longitudinal dispersion coefficient is thus determined by equations (a-5) and (a-6) as a function of local parameters and global estuary parameters.

Numerical Solution of Governing Equations

Initial conditions and boundary conditions being specified, equations (a-1) through (a-4) can be solved by numerical techniques for the dependent variables, elevation, h; discharge, Q; and salinity, s; as functions of distance, x; and time, t. The finite difference scheme used to solve the tidal-dynamic equations is similar to that of Harleman and Lee (1969), and is a staggered explicit scheme wherein surface elevations and discharges are calculated at alternative locations in the space and time mesh. This scheme has been shown to be efficient in calculation, but the choice of Δx and Δt must be made in a manner that does not violate the approximate stability criterion,

FIGURE A-1

CORRELATION OF STRATIFICATION PARAMETER WITH ESTUARY NUMBER



$$\Delta t \leq \frac{\Delta x}{U + c} \tag{a-9}$$

where, Δx and Δt are the longitudinal distance and time increments of calculation, U is the average cross-sectional velocity, and $c = \sqrt{gh}$ is the wave speed at the same location as U.

The finite-difference scheme employed for solution of the salt-balance equation (a-3) is a six-point implicit scheme based on the minimum-error investigation of Stone and Brian (1963). This scheme has a truncation error with terms proportional to $(\Delta x)^2$ and $(\Delta t)^2$ and thus is of second order. The truncation error contains no term proportional to $\partial^2 s/\partial x^2$, which means it has no numerical dispersion term as found in some first-order schemes (Bella and Grenney 1970).

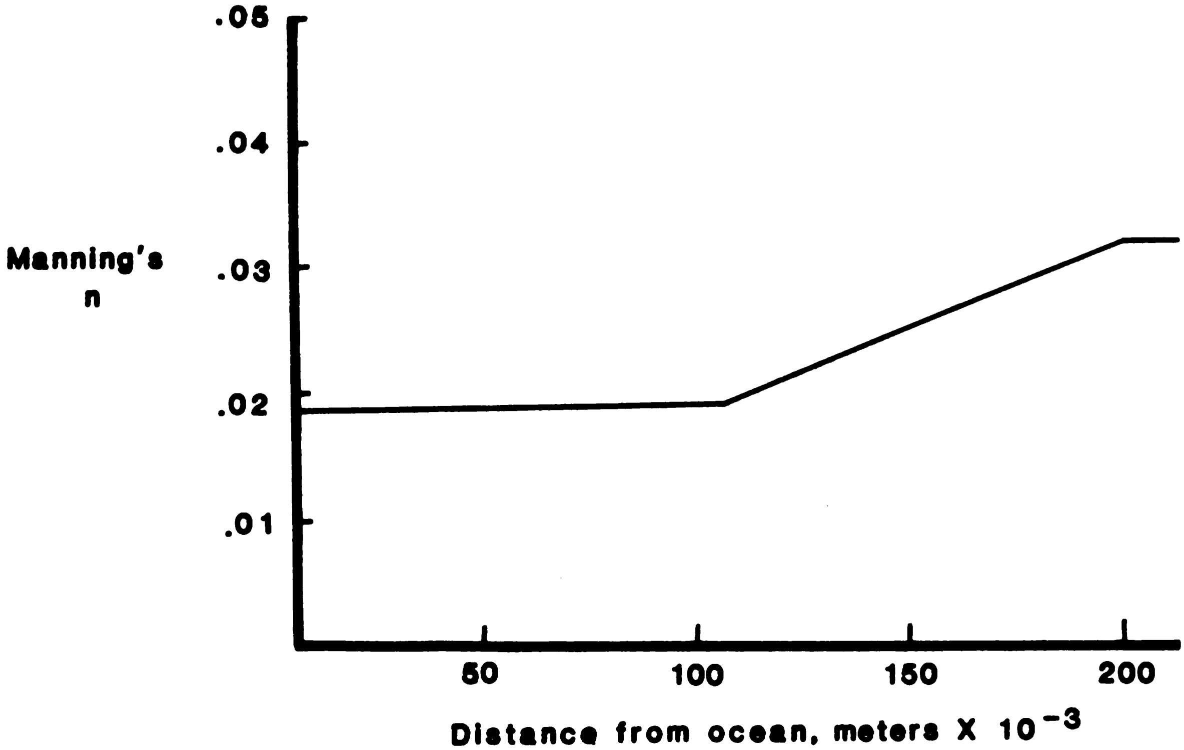
Calibration Parameters

Three parameters are treated as calibration coefficients for this model. The first is the friction parameter used to determine the Chezy coefficient. This is achieved through a Manning's "n" distribution for the estuary. Using observed values of high and low tidal elevations throughout the estuary, the calibration distribution of Manning's "n" was determined. This distribution (Figure A-2) was then used in all subsequent calculations.

The second and third parameters relate to the longitudinal dispersion relationship of equation a-5, specifically to the determination of parameters K and m. The slope of the $K/(U_o L)$ vs. $Æ_D$ relationship (Figure A-1) was assumed to be that shown, e.g., -(1/4). The intercept of this relationship was treated as a calibration parameter. Sensitivity analyses and comparison

FIGURE A-2

CALIBRATION DISTRIBUTION OF MANNING'S "n"



of a three-month calculated set of salinities with observed values provided calibration values of

$$\frac{K}{U_oL} = 0.0015\ \mathbb{E}_D^{-1/4} \qquad \text{(a-10)}$$

$$m = 35$$

Additional Sources of Information

Further details about the model's development and application can be found in the two-volume report made to the Delaware River Basin Commission by Thatcher and Harleman (1978). This report includes data sources for calibration and verification as well as the results of sensitivity studies. Further applications by the Commission have been documented in DRBC reports. Thatcher and Harleman (1981) have presented some of the model results in a paper published in the Journal of the Environmental Engineering Division of the American Society of Civil Engineers. This paper was discussed by Fischer, August 1981, and by Hull, December 1981. The authors' closing response can be found in the February 1983 issue of that journal.

APPENDIX B

MODIFICATION OF SALINITY-MODEL GEOMETRY FOR LARGE RISES OF SEA LEVEL

The salinity model represents estuarine geometry by a schematization to a double rectangular section as shown in Figure B-1. The flow-carrying rectangle is referred to as the core area and the adjoining rectangle (if any) represents the storage area. The schematization in use by the Delaware River Basin Commission is based on the U.S. Army Corps of Engineers "Table of Mid-Tide Volumes." This source of geometry is accurate, but is limited to near present conditions of sea level because of the rectangular schematization in terms of a constant width. As shown in Figure B-2, to schematize a significant rise in sea level, Δz, would require new widths, whereas the schematization based on the Table of Mid-Tide Volumes can accommodate only new depths. A procedure for modifying this rectangular schematization for a sea level rise of approximately seven or eight feet is presented as follows.

Figure B-3 shows the basic relationships leading to a second rectangular schematization of a typical estuary cross section that would be filled to the elevation of inundation. To create a rectangle whose width is the distance between contours of inundation, and whose area is the sum of the present core area plus the additional inundated area, would result in a new depth that would be very shallow in comparison with reality. This is because the shallow inundated region can be very wide compared to the present width of the estuary. To use such a shallow depth would distort the model calculations because the speed of propagation of the tidal wave is primarily dependent upon

FIGURE B-1

ESTUARINE GEOMETRY SCHEMATIZATION

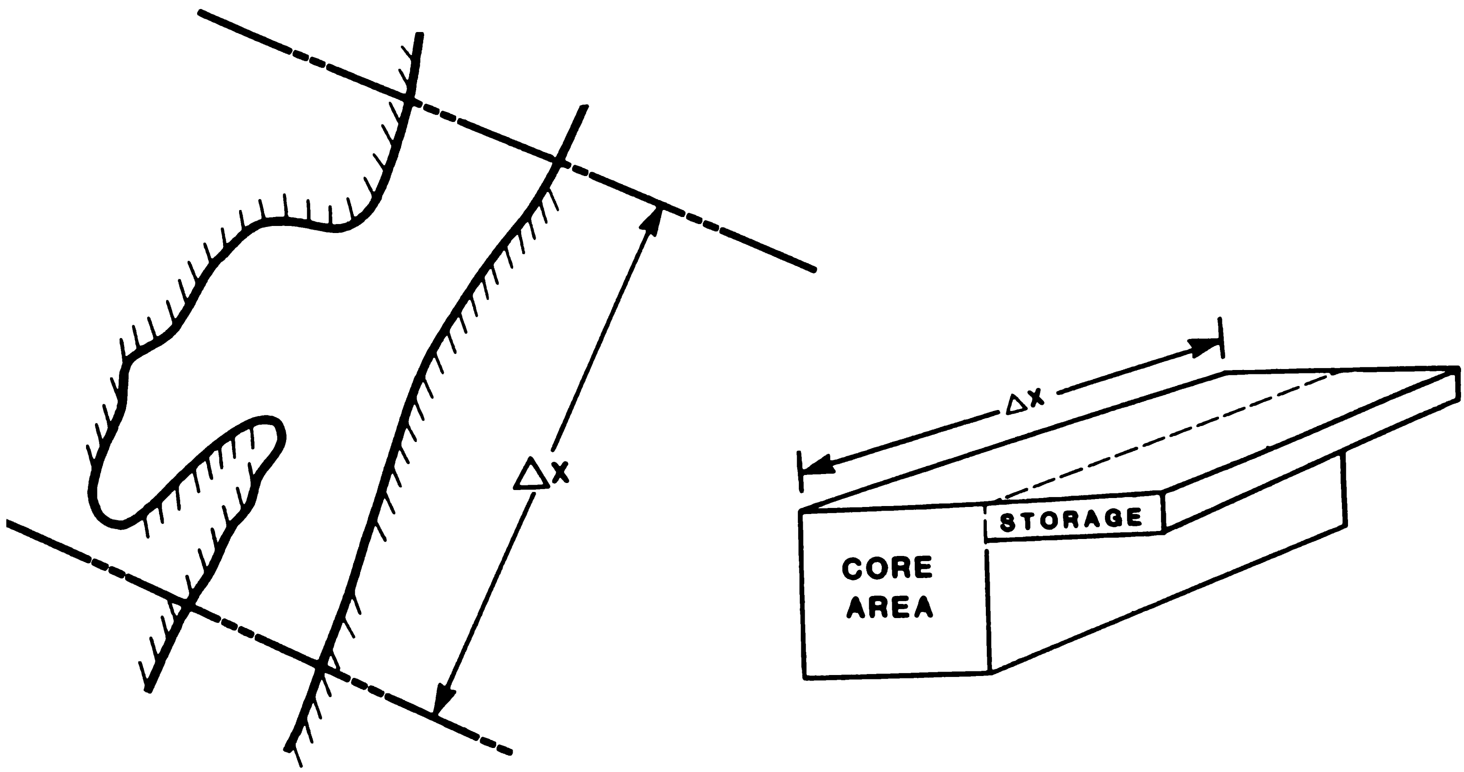


FIGURE B-2

TYPICAL ESTUARY CROSS SECTION SHOWING INCREASE IN WIDTH RESULTING FROM SEA LEVEL RISE

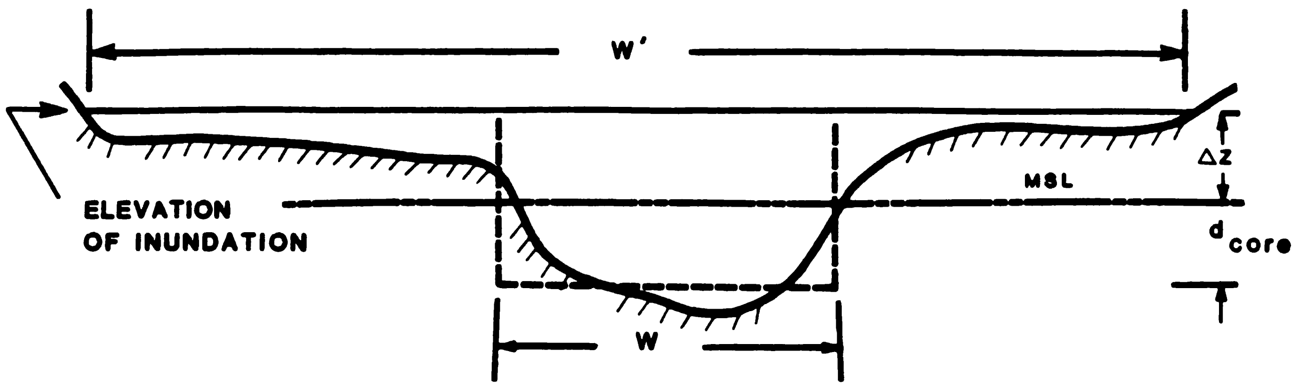
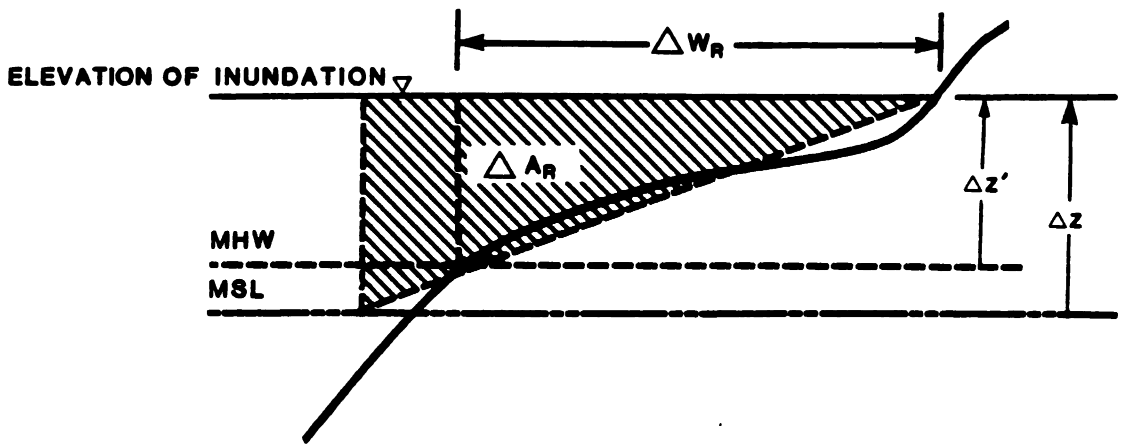


FIGURE B-3

TYPICAL ESTUARY CROSS SECTION SHOWING ADDITIONAL CROSS-SECTIONAL AREA (RIGHT-HAND SIDE) RESULTING FROM SEA LEVEL RISE



the depth. To maintain this most important parameter, depth, a second approach is presented.

The bottom elevation of the core area (sometimes called "conveyance area") will be maintained. Outside the core area, the additional cross-sectional area of inundation, ΔA, will be calculated in terms of the newly inundated width, ΔW, by assuming triangular cross sections adjacent to the rectangular core area. With reference to Figure B-3, this area is

$$\Delta A = \left(\frac{\Delta W}{\Delta z'} \right) \frac{(\Delta z)^2}{2} \qquad \text{(b-1)}$$

where, ΔA = the sum of left-hand area ΔA_L and right-hand area ΔA_R,

ΔW = the sum of left-hand width ΔW_L and right-hand width ΔW_R,

Δz = elevation of inundation - mean sea level, and

$\Delta z'$ = elevation of inundation - mean high water.

Note that the change in width, ΔW, was from mean high water to the elevation of inundation. These parameters come from topographical data related to mean high water. A linear slope was assumed, and this slope was utilized to calculate the additional area for a prescribed sea level rise. These calculations yielded a new Effective Width, W*

$$W^* = \frac{A_{core} + \Delta A}{d_{core} + \Delta z} = W + \frac{\Delta A}{d_{core} + \Delta z} \qquad \text{(b-2)}$$

where, A_{core} and d_{core} are the area and depth of the core.

The storage widths of the original schematization are maintained. As the measurement of width between contours of inundation was along the main stem of the estuary, this assumption is conservative. It is conservative because it is probable that new, significant storage areas would be opened up adjacent to the main stem under the sea level rise condition.

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