# ASSESSMENT OF THE POTENTIAL EFFECTS OF CLIMATE CHANGE ON WATER RESOURCES OF THE DELAWARE RIVER BASIN: WORK PLAN FOR 1988-90

By Mark A. Ayers and George H. Leavesley

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U.S. GEOLOGICAL SURVEY

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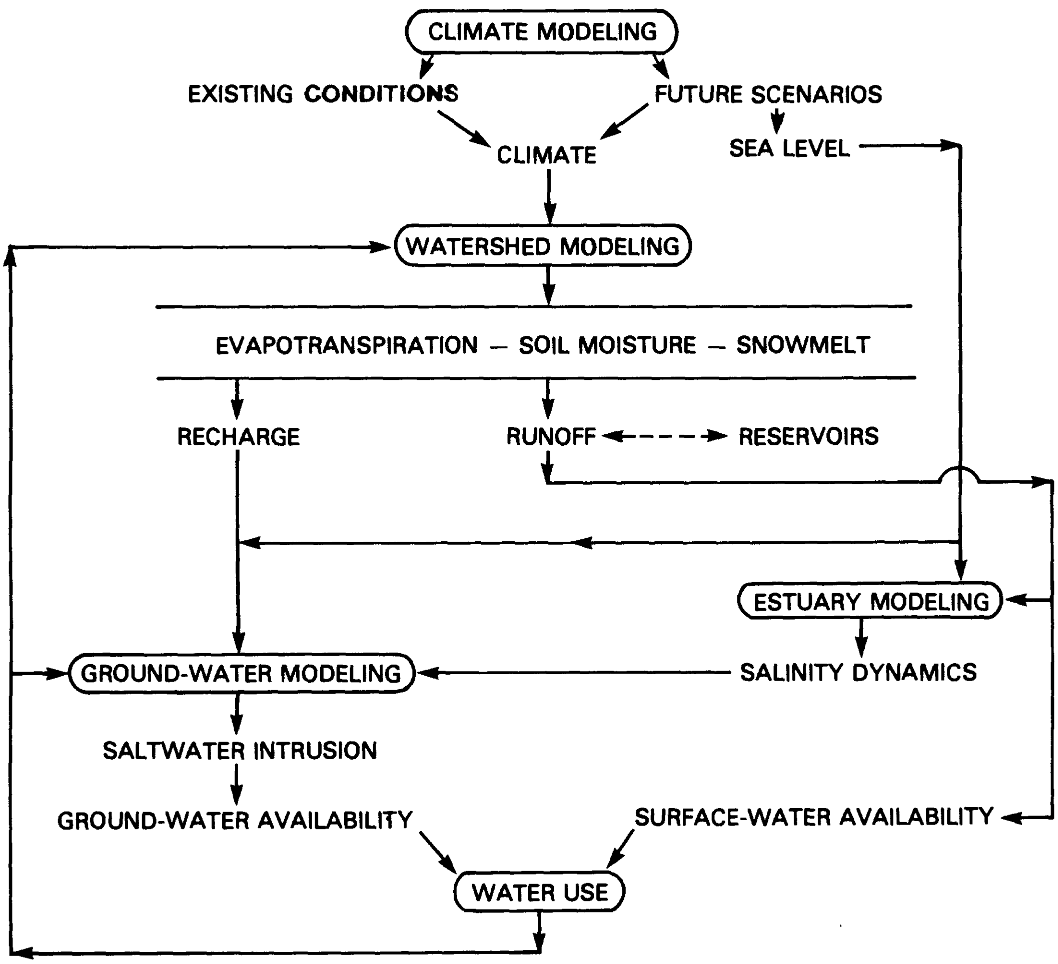


West Trenton, New Jersey
**1989**

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# ASSESSMENT OF THE POTENTIAL EFFECTS OF CLIMATE CHANGE ON WATER RESOURCES OF THE DELAWARE RIVER BASIN: WORK PLAN FOR 1988-90

By Mark A. Ayers and George H. Leavesley

## ABSTRACT

The current consensus is that some global atmospheric warming will occur as a result of increasing "greenhouse" gases. However, there is considerable uncertainty about the hydrologic implications of such a change. Water-resource scientists, planners, and managers are very concerned about the potential effects of climate change on water supplies and what planning might be necessary to mitigate the effects. Clearly, mitigation is possible only if the magnitude of the changes are definable and the relation between the changes in climate and water supply are understood. Collaborative studies between climatologists, hydrologists, biologists, and others are needed to gain this understanding. The Delaware River basin study is an interdisciplinary effort on the part of the U.S. Geological Survey that was initiated to improve understanding of the sensitivity of the basin's water resources to the potential effects of climate change.

The Delaware River basin is 12,765 square miles in area, crosses five physiographic provinces and three ecoregions, and supplies water for an estimated 20 million people within and outside the basin. The basin's runoff processes are naturally diverse, but human activities related to the movement and storage of water add complexity to the investigation of basin hydrology.

Climate change presumably will result in changes in precipitation and temperature and could have significant effect on evapotranspiration, streamflow, and ground-water recharge. A rise in sea level is likely to accompany global warming and, depending on changes in freshwater inflows, could alter the salinity of the Estuary and increase saline-water intrusion into adjacent aquifer systems. Because the effects of any climate changes on the hydrologic response of the basin are not well understood, this report discusses how the potential effects of climate change on the water resources of the basin might be defined and evaluated.

The overall objective of the Delaware River Basin Climate Change Project is to investigate the hydrologic response of the Delaware River basin, under existing water management policy and infrastructure, to various scenarios of climate change. Specific objectives include defining the temporal and spatial variability of basin hydrology under existing climate conditions, developing climate-change scenarios, and evaluating the potential effects and sensitivities of four aspects of the basin's water availability to these scenarios.

The four aspects of major concern include (1) the streamflow and water storage associated with the New York City and other basin reservoir systems, (2) the maintenance of U.S. Supreme Court mandated and "Good Faith" agreement streamflow requirements, (3) the upstream movement of saline water in the Delaware Estuary resulting from sea-level and freshwater-inflow changes, and (4) the resulting saline-water intrusion into aquifers adjacent

to the Estuary. In addition to the development of techniques and models specific to the Delaware River basin, a complementary goal of the study is to develop analytical tools and scenario approaches that can be applied easily to a variety of climate-hydrology, planning, or management analyses in this and other climatic and physiographic regions. The objectives of the Delaware River Basin Climate Change Project will be accomplished through a series of interrelated work elements as follows:

Element 1-- Modeling Basin Climate and Developing Scenarios
Element 2-- Modeling Watershed Systems and Assessing Changes
Element 3-- Modeling Estuary Salinity Dynamics
Element 4-- Modeling Aquifer/Estuary Interactions
Element 5-- Analyzing Water-Use and Geographical Information Systems

# INTRODUCTION

## Background on Potential Effects of Climate Change

Changes in global climate caused by increasing concentrations of atmospheric carbon dioxide and other trace gases could alter various hydrologic processes and cycles within many regions of the globe (National Academy of Sciences, 1977). The current consensus is that some global atmospheric warming (1.0 to 4.5 °C (degrees Celsius) for a doubling of atmospheric carbon dioxide) will result from increasing concentrations of "greenhouse" gases (Smagorinsky, 1982; Lamb, 1987) and cause changes in the water availability in some areas. Sensitivity analyses of water-resource systems to climate variation have been performed (Beard and Maristany, 1979; Nemec and Shaake, 1982; Klemes, 1985). However, many technical questions are unanswered including (1) where, in what direction, and in what magnitude will the climate changes occur; (2) what is the timing (particularly interannual) of the changes; and (3) what data are needed to develop climate-change scenarios for assessing regional water-supply effects.

Considerable efforts in climatology are underway to clarify the ramifications of increasing atmospheric carbon dioxide and other gases through the use of extremely complex, physically based, computer models of global atmospheric circulation, referred to as general circulation models or GCM's (Lamb, 1987). GCM research appears to be gaining confidence on where regional-scale changes in temperature are expected (primarily for certain larger regional areas, like the northern latitudes, by consensus of results among different models) and, perhaps, on the general direction of change for those areas. The timing and magnitude of any temperature changes for smaller regional areas and for individual model nodes are still very speculative, at best. Confidence in modeled change for precipitation and other variables is perhaps less. As such, Rind (1988) warns that consensus results from current GCM's may represent risky projections of future water availability.

Cloud processes are modeled very simplistically in current GCM's. Boundary-layer processes, such as land- and ocean-atmospheric interactions, are represented as very general parameterization schemes of boundary conditions in order to reduce the computational requirements of the GCM's. As such, topographic, hydrologic, and biologic controlling factors involved in the land-atmospheric interactions have been greatly simplified.

A GCM study by Peng and others (1987) indicated that a transient, rather than equilibrium, approach with a coupled two-dimensional ocean circulation component led to a 9- to 35-year delay in an equivalent temperature rise for a doubling of atmospheric carbon dioxide. The temperature distributions for transient and equilibrium approaches, however, were very similar. This study supports the general thinking that GCM's without the detailed ocean- or land-surface components are not accurately accounting for these important buffers to changes in atmospheric temperature. Verstraete and Dickinson (1986) reported that the land interactions are nearly as significant as ocean interactions. Because of the importance of surface processes and the problems of GCM's in handling them, there is considerable need for research in improving the GCM parameterization schemes of ocean- and land-surface processes (Rind, 1988; Verstraete and Dickinson, 1986).

Water-resource scientists, planners, and managers are concerned about the potential effects of climate change on water supply (Klemes, 1982; Gleick, 1986) and the mitigation of these effects (Schaake and Kaczmarek, 1981). Clearly, mitigation is possible only if the magnitude of the changes are definable and the relation between the changing climate and water resources are understood. A better understanding of climate-change effects on water resources can be obtained only through collaborative studies among climatologists, hydrologists, biologists, and others (Kilmartin, 1979). The Delaware River Basin Climate Change Project is an interdisciplinary effort initiated by the U.S. Geological Survey to improve understanding of the sensitivity of the basin's water resources to the potential effects of climate change.

## Purpose and Scope

The purpose of this report is to document the current (1988) plans for the newly initiated Delaware River Basin Climate Change Project. The report focuses on how the potential effects of climate change on the water resources of the basin might be defined and evaluated. The project will follow a general framework for the systematic investigation of the potential effects of climate change on water-resources systems (Moss, in press), specifically applied to the Delaware River basin. The approach will be flexible, allowing for improvements throughout most of the project. The project will provide an initial assessment of the potential for climate change to affect the water resources of the Delaware River basin by October 1990.

Significant contributions to sections of this report were made by G. C. Gravlee, H. F. Lins, A. M. Lumb, M. E. Moss, A. S. Navoy, G. N. Paulachok, C. V. Price, R. A. Sloto, G. D. Tasker, and R. A. Walters, all from the U.S. Geological Survey.

## Description of, and Potential of Climate Change in, the Delaware River Basin

The Delaware River basin is 12,765 square miles in area and crosses five major physiographic provinces and three different ecosystem types (fig. 1). The watershed runoff processes differ considerably over the basin. The Coastal Plain physiographic province has relatively flat, thick, sandy soils and exhibits very delayed responses to rainfall; in fact, most Coastal Plain runoff is derived from ground-water discharge. The New England and Piedmont physiographic provinces have relatively steep, thin, clayey soils and exhibit very flashy responses to rainfall, predominantly as direct runoff. The Appalachian Plateaus and Valley and Ridge physiographic provinces have relatively steep, thick, well-drained soils and exhibit responses to rainfall between the two extremes. Human activities influence the movement and storage of water in the basin (fig. 2) adding considerable complexity to the hydrologic response characteristics of these physiographic provinces. Urbanization in the lower portions of the basin has significantly altered the runoff response of this region (fig. 3).

The Delaware River provides water for an estimated 20 million people (Delaware River Basin Commission, 1986) within and outside the basin (figs. 3 and 4). Water availability is enhanced by complex systems of reservoirs for storage and wells, pipes, tunnels, and canals for diversion and delivery. Two large diversions out of the basin (fig. 2) are through the New York City aqueduct system (up to 800 Mgal/d (million gallons per day) to New York City) and the Delaware and Raritan Canal (up to 100 Mgal/d to northeastern New Jersey).

The freshwater part of the tidal river below Trenton, the Delaware Estuary, serves as a major source of ground-water recharge for aquifer systems supplying water to southern New Jersey and, also, as an important water-supply source for the City of Philadelphia and many industries by direct diversion. It is critical for these water supplies that the Delaware Estuary remain potable in these reaches, even during periods of prolonged low flow (droughts). The Delaware River Basin Commission (DRBC) has established a current interim standard for salinity (Delaware River Basin Commission, 1985) whereby the maximum 30-day average concentration at river mile 98 (fig. 2) can not exceed 180 milligrams per liter chloride.

Historically, the salinity problems in the Estuary have been an issue affecting the New York City diversion rights. The U.S. Supreme Court (1931; 1954) required the City reservoir system to maintain a streamflow at Montague, New Jersey of 1,750 $ft^3/s$ (cubic feet per second, fig. 5) to compensate downstream interests in the basin, mainly for salinity control in the Estuary. Releases are managed and designated by the Delaware River Master. "Good Faith" agreements among the States and the City since have included management of other reservoir system releases to maintain a streamflow at Trenton, New Jersey of 3,000 $ft^3/s$, as determined by the DRBC (1985). During the drought of record in 1961-65 (Anderson and others, 1972) and twice since 1980, emergency water-use restrictions were mandated basinwide to meet the basic water-supply demands and streamflow requirements.

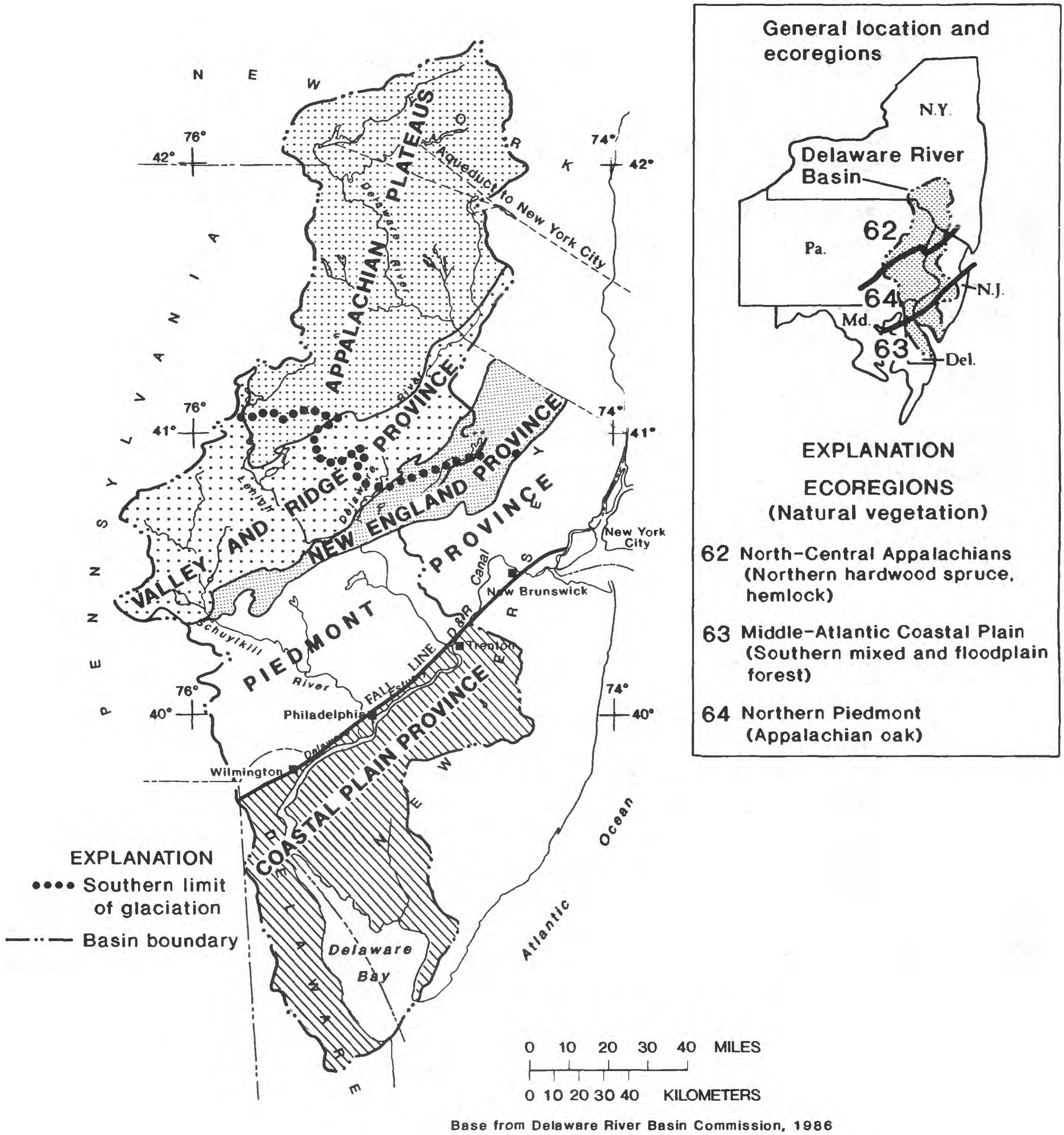


Figure 1.--General location, physiographic provinces (from Parker and others, 1964), and ecoregions (from Omernik, 1986) of the Delaware River basin.

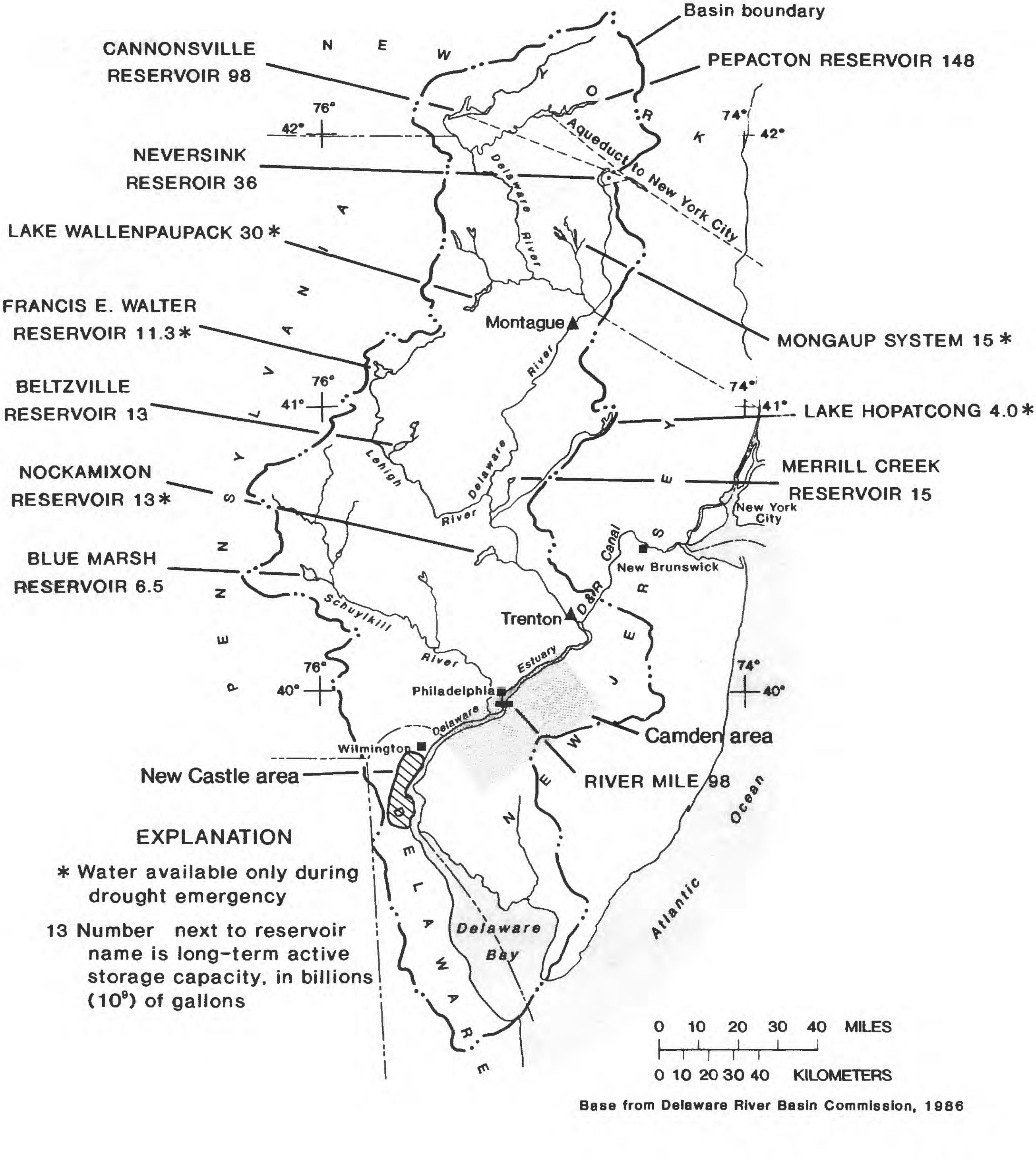


Figure 2.--Major water-supply features and long-term active storage capacity of major reservoirs in the Delaware River basin.

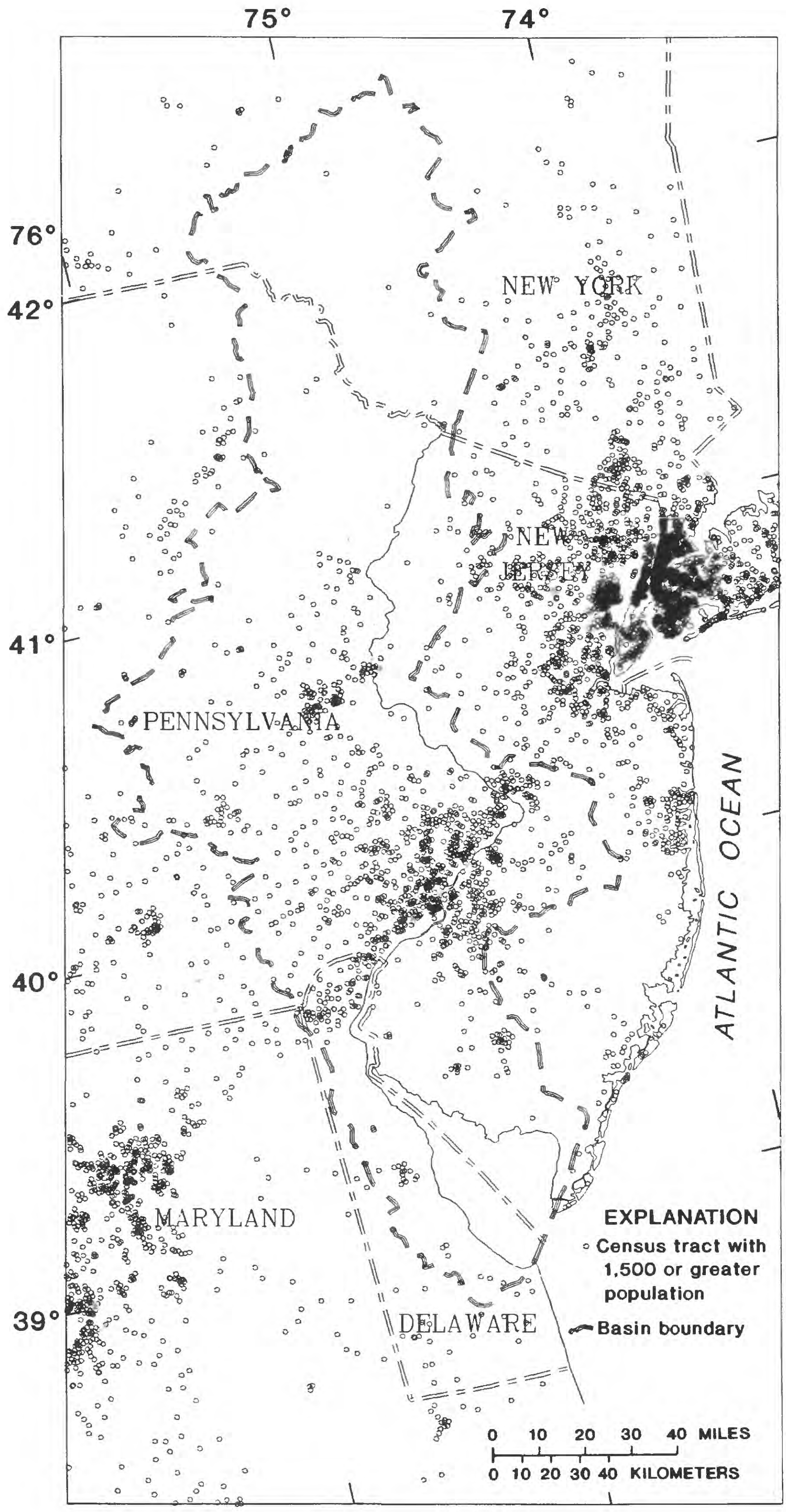


Figure 3.--Population distribution in the vicinity of the Delaware River basin.

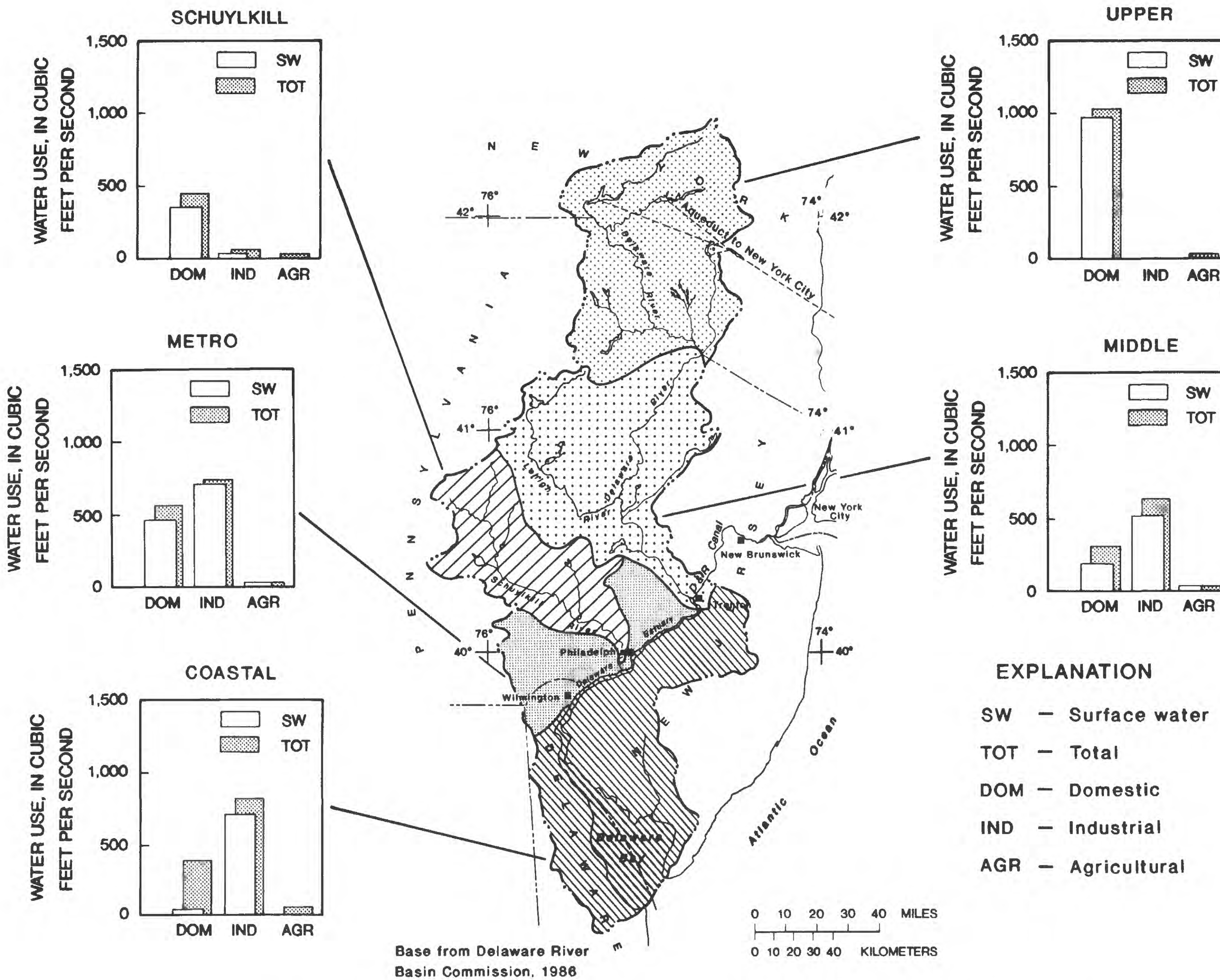


Figure 4.--Water use by subbasin for the Delaware River basin.

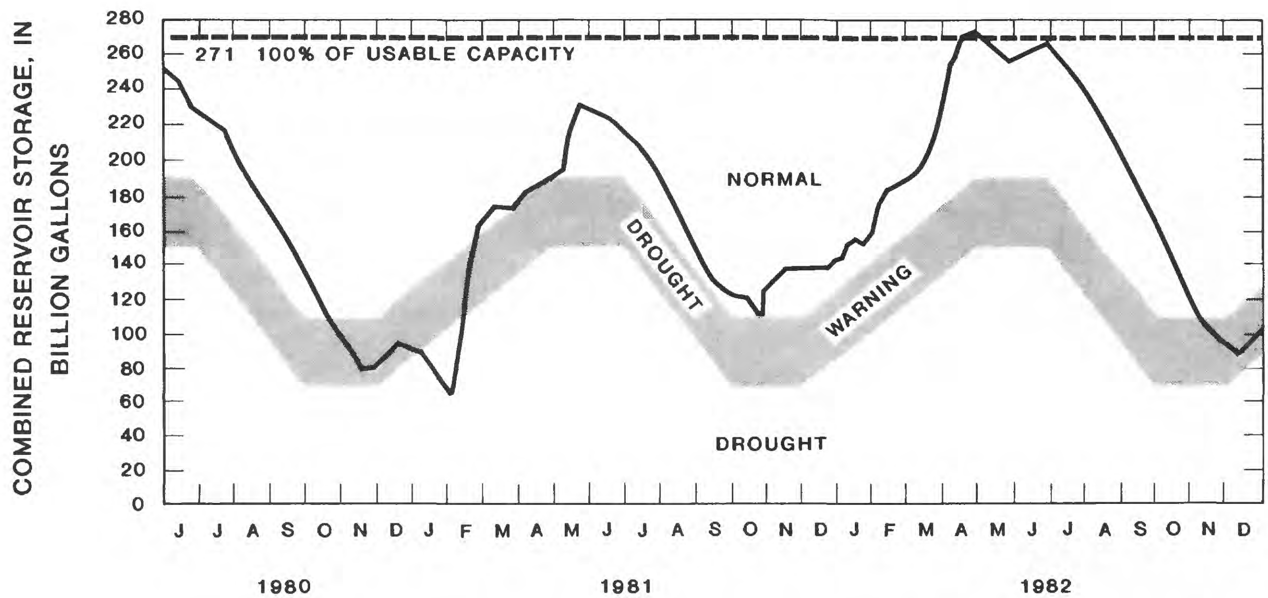


Figure 5.--Operating curves for the New York City reservoir system in the Delaware River basin compared with the actual contents of the reservoirs for June 1980 through December 1982 (from Delaware River Basin Commission, 1982). Note drought conditions in 1981.

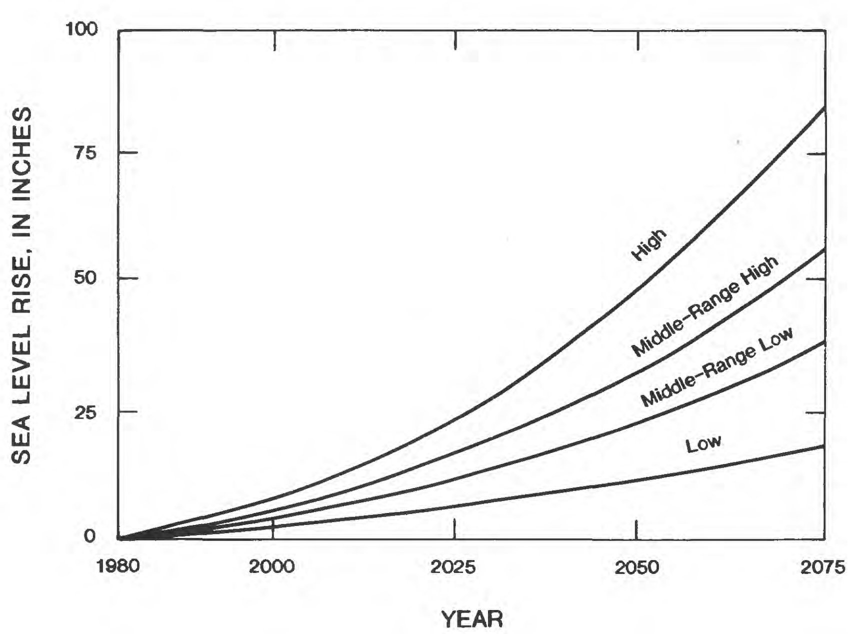


Figure 6.--Projected global sea-level rise scenarios (from Titus, 1986).

Climate-change effects on the Delaware River basin water supply will stem largely from changes in precipitation and temperature, although changes in cloud cover, wind, humidity, and other weather conditions all would have some effect. Precipitation changes could change the amount and temporal distribution of streamflow and ground-water recharge, and the frequency and duration of extreme events, such as major storms and droughts. Changes in temperature and other climatic variables could affect rates of evapotranspiration in warm seasons and amounts or timing of snow or snowmelt in winter, and subsequently alter both streamflow and ground-water recharge. A rise in sea level (fig. 6) also is likely to accompany global warming (Titus, 1986), and combined with potential changes in freshwater inflows, could significantly alter the salinity of the Estuary and increase saline-water intrusion into adjacent aquifer systems. The hydrologic effects of any climate changes in the basin potentially could be significant, but are not well understood. This project will investigate the basin's hydrologic response to various climate-change scenarios.

## OBJECTIVES OF THE STUDY

The overall objective of the Delaware River Basin Climate Change Project is to investigate the sensitivities in hydrologic response of the Delaware River basin, under existing water management policy and infrastructure, to various scenarios of climate change. Specific objectives include defining the temporal and spatial variability of basin hydrology under existing climate conditions, developing various projections of climate change, and evaluating the potential effects and sensitivities of four aspects of basin water availability to various projections.

The four aspects of major concern involve potential changes in (1) the streamflow and water storage of the New York City and other basin reservoir systems, (2) the maintenance of the U.S. Supreme Court mandated and "Good Faith" agreement streamflow requirements, (3) the upstream movement of saline water in the Delaware Estuary caused by changes in sea level and freshwater inflows, and (4) the saline-water intrusion into aquifers adjacent to the Estuary resulting from salinity changes. In addition to the development of techniques and models specific to the Delaware River basin, a complementary goal of the study will be to develop analytical tools and scenario approaches that can be applied to a variety of climate-hydrology, planning, or management analyses for this basin and in other climatic and physiographic regions.

## APPROACH OF THE STUDY

The objectives of the Delaware River Basin Climate Change Project will be accomplished through a series of concurrent and interrelated work elements (fig. 7). Each element in this report has an expanded discussion of background information, element objectives, specific approaches, and the relation of each element to other elements. The five work elements are as follows:

- Element 1-- Basin Climate Modeling and Scenario Development
- Element 2-- Modeling Watershed Systems and Assessing Changes
- Element 3-- Modeling Estuary Salinity Dynamics
- Element 4-- Modeling Aquifer/Estuary Interactions
- Element 5-- Analyzing Water-Use and Geographical Information Systems

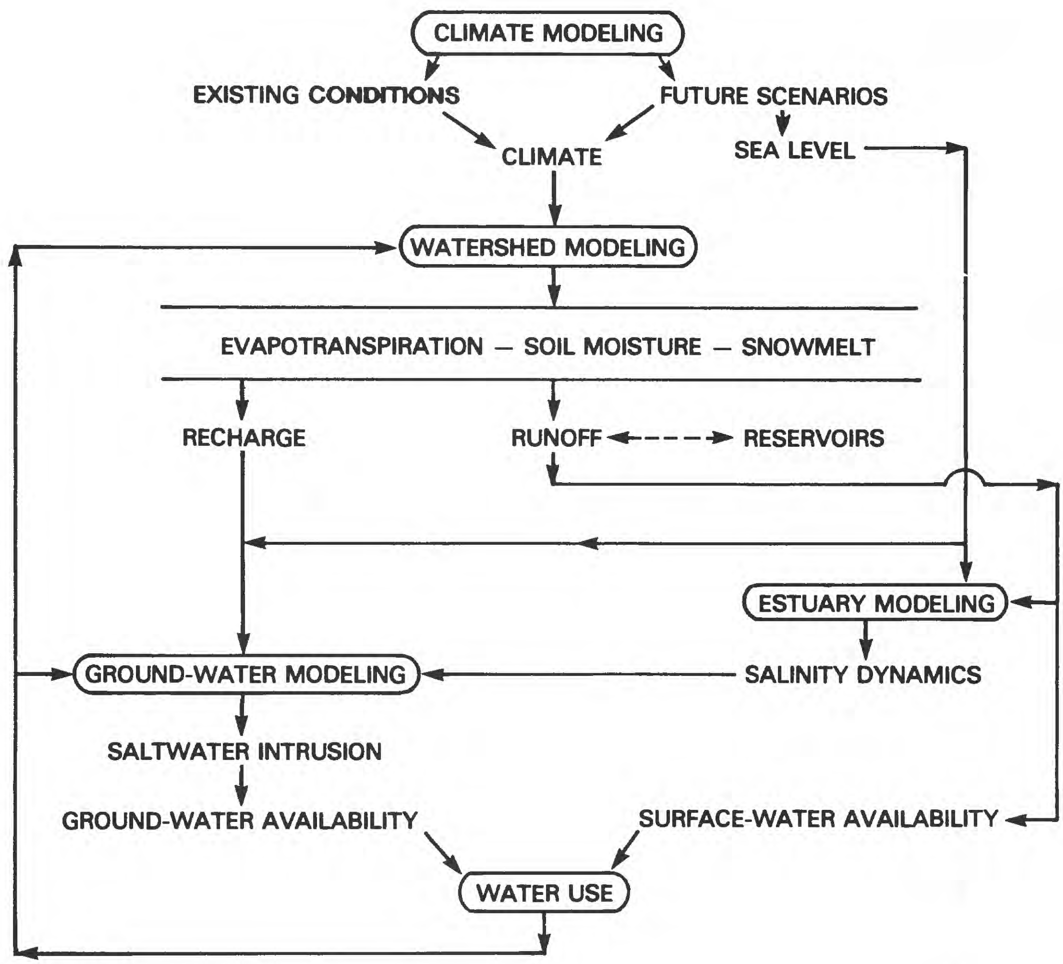


Figure 7.--Summary of modeling tasks for the Delaware River Basin Climate Change Project.

## Element 1-- Modeling Basin Climate and Developing Scenarios

### Background

Concern about a global acceleration in atmospheric warming stems from records of increasing concentrations of carbon dioxide, methane, chlorofluorocarbons, and other gases released primarily by human activities (Titus, 1986). These gases and water vapor in the atmosphere trap Earth's reradiated energy, primarily in the infrared range, rather than allowing it to pass into space. The result is an increase in ambient air temperature much the same as what occurs with glass trapping reradiated energy in a greenhouse, hence the term, "greenhouse effect". This is an important mechanism for supporting earth's life systems as we know them, for without the greenhouse effect of the atmosphere, the earth would be about 33 °C colder than present (Hansen and others, 1984). However, a doubling of current atmospheric carbon dioxide concentrations is expected to cause an increase in global average temperature of 1.0 to 4.5 °C (Lamb, 1987).

The release of carbon dioxide from such activities as fossil fuel combustion, deforestation, and cement manufacturing have contributed significantly to a rise in atmospheric carbon dioxide of about 20 percent since the industrial revolution (Titus, 1986). The atmospheric concentrations of methane and other "greenhouse" gases also are increasing significantly (Lacis and others, 1981). Scientists generally expect a global warming to result (Smagorinsky, 1982; Lamb, 1987). The warming may cause other changes, possibly creating feedback effects that add to the warming (fig. 8). However, there is not a clear consensus that this will occur, and some factors, such as cloud height and/or cover may actually reduce the amount of warming.

Many of these indirect climatic feedbacks are expected to amplify, others possibly could cancel, the direct effect of the greenhouse gases (Hansen and others, 1984; Titus, 1986). Of the available climate models, only the GCM's, with coupled ocean/land boundary condition models, have the physical detail to address the complexity of the problem (Lamb, 1987). Surface climate data sets generated by GCM's are complete for many variables in space and time and, thus, possess an important quality of good internal physical consistency between variables that may encourage the systematic extraction of statistics important to the development of climate-change scenarios (Gates, 1985). Monthly or seasonal statistics, such as duration of wet or dry periods, mean wet days, mean dry days, maximum or minimum temperatures, barometric pressure gradients, and average wind direction, are examples.

The assessment of water-supply effects caused by climatic change requires a definition (modeling) of current climatic variability and runoff relations for the basin that is sensitive to the scenarios developed. A general summary of current climatic conditions and variability for the Delaware River basin is available from Jenner and Lins (in press), but a detailed model analysis of the current climatic variability is not available. However, techniques are available which should find application for this effort (Richardson and Wright, 1984; Woolhiser and Osborn, 1985). Furthermore, spatial details on the changes of regional climatic variability

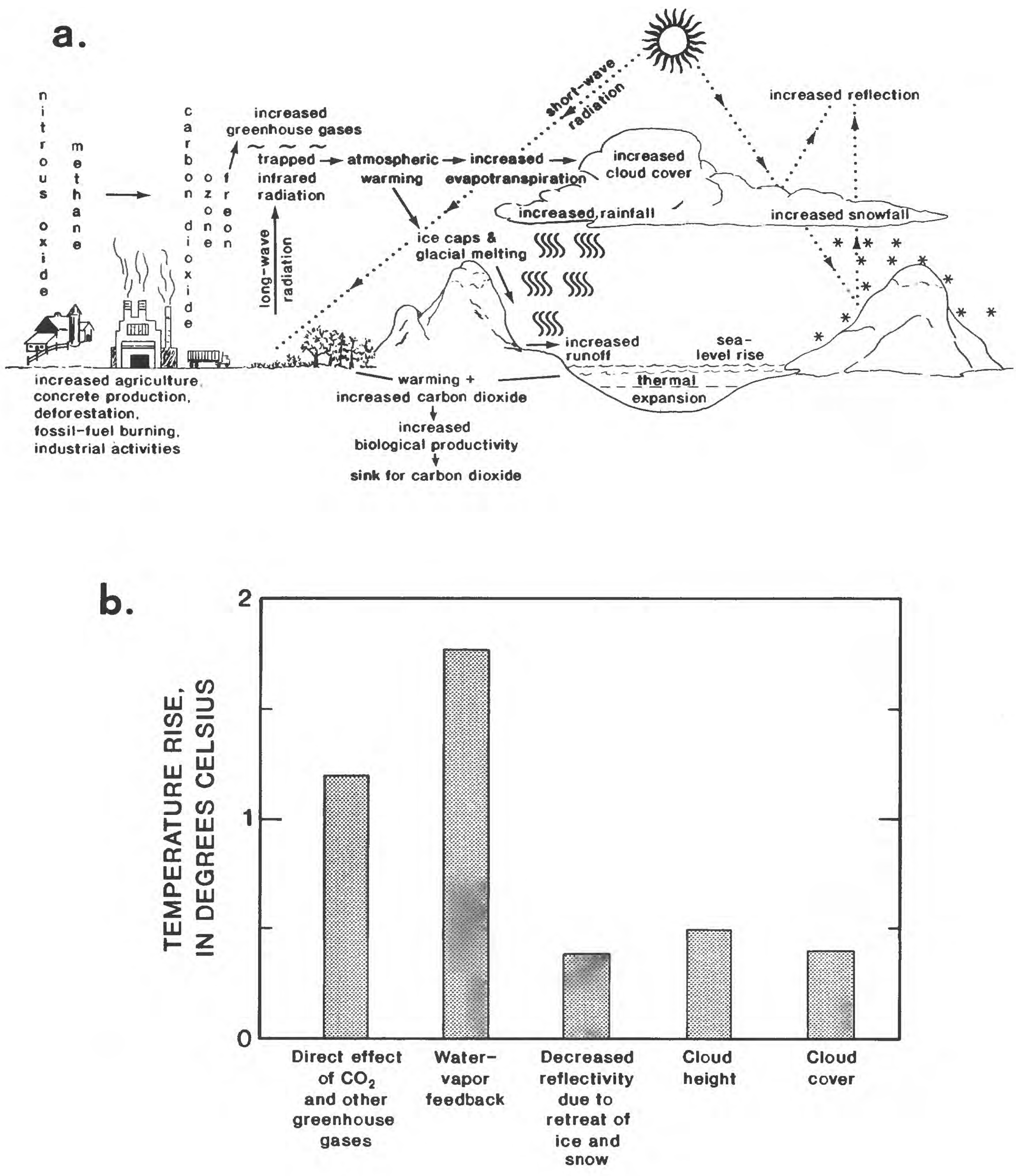


**Figure 8.**--Conceptual diagram of various feedback mechanisms (a) and potential magnitudes of feedback (b, modified from Titus, 1986) resulting from increases (doubling) in greenhouse gases.

for the basin are not directly available from any of the GCM research efforts. Considerable work is needed to extract information from the course grid of the GCM's and spatially disaggregate it based on historic climate records. Therefore, scenario development will require an analysis of historic climatic variability both temporally and spatially and an integration with GCM and other projections specific for the regional area of the basin.

Another climate-change factor of interest to the water-supply availability of the basin is the likelihood of a rise in sea level accompanying a climatic warming (Hoffman and others, 1983; National Research Council, 1984; Titus, 1986). Several sea-level rise scenarios are available from the current literature. Titus (1986) provides an excellent review with particular reference to the Delaware Estuary (fig. 6).

## Objectives

The objectives of Element 1 are (1) develop stochastic models of current climatic conditions in the basin area for use with the watershed models; (2) develop stochastically based approaches for defining basinwide, climate-change scenarios, for doubled carbon dioxide conditions, for use with the watershed models; (3) define a probabilistic set of sea-level rise and tidal-oscillation scenarios at the mouth of the Delaware Bay, for doubled carbon dioxide conditions, for use with the salinity models; (4) research the disaggregation of climatic-change variables, especially precipitation, to shorter than daily time steps (1 to 6 hours) to assess the sensitivity of processes controlling basin runoff; (5) begin development of a mesoscale modeling approach directly linked to the GCM research efforts to provide more accurate projections of changes in climatic variables for the basin.

## Approach

Using a synoptic climatological approach (Kalkstein and Corrigan, 1986; Kalkstein and others, 1987) and stochastic methods similar to Richardson and Wright's (1984), the stochastic properties of about 80 climatic stations in the vicinity of the Delaware River basin area will be used to model the temporal (at sites) and spatial variability (between sites) of the basin. Stochastic properties of the data sets will relate to the frequency and duration of occurrences, time between occurrences, magnitudes and distribution within occurrences of precipitation, temperature, solar radiation, and any other climatic variables. Other properties could be used that are related to mechanisms controlling weather patterns over the basin, such as barometric gradients, monthly average wind speed or direction, and orographic effects (Craig and Roberts, in press). The initial analyses will use daily values of the variables. Stochastic models that synthesize these variables for each climatic station will be developed and tested against the available record. Then, significant model parameters will be analysed for their spatial relations, leading to regionalized stochastic models of climatic variables.

Concurrently, several approaches for developing climate-change scenarios will be developed using a variety of sources. The GCM research will be one of the sources, but climatic records (Wigley and others, 1986) and dendrochronology (Cook, in press) also will be used.

A GCM-derived, monthly coefficient approach is being used currently by the U.S. Environmental Protection Agency in four regional ecosystem impact studies (Joel Smith, U.S. Environmental Protection Agency, oral commun., 1988). Monthly time-series outputs (for model nodes adjacent to the study areas from three different GCM's) of various climate parameters for "single" and "double" carbon dioxide conditions were used to compute monthly coefficients for the "double" carbon dioxide scenario. The coefficients derived from each of the GCM's then were applied to the historic, daily-time series for the period 1951-1980 for use in the four regional analyses. This approach also might be available for use in the Delaware River basin study.

Another approach is one that would produce a stochastically based set of "single" and "double" climate-model parameters from a GCM time series, similar to those for the historic record, for which a coefficient of change in model parameters then could be applied to the stochastic models of the basin. The first test of this approach would be if the GCM time series currently (for "single" carbon dioxide conditions) preserves the dependence in time, the correlation between variables, and the seasonal characteristics of the actual climate records for the basin area.

Because of the uncertainties in the GCM approaches, the project will focus on quantifying the ranges of uncertainties and determine the sensitivities to climatic changes using analysis techniques based on selected percentage changes in climatic variables (Nemec and Shaake, 1982) using climatologic records and dendrochronology. The several GCM-derived scenarios also offer a range of conditions, but the sensitivity analysis approach will be the first step of this assessment, irregardless of the results of the stochastic and GCM related efforts. Both the daily and monthly flow modeling efforts in Element 2 will need climate variable inputs for current and "double carbon dioxide" conditions.

Another task of Element 1 is to prepare a set of plausible sea-level changes resulting from a doubling of atmospheric carbon dioxide. The historical rate of sea-level rise and one or more other rates (fig. 6) will be determined by a consensus among several "experts". Then, a tidal series for several sea-level conditions will be generated for input to the estuarine model of the freshwater-saltwater interface for the Delaware Estuary in Element 3.

An effort will be made to investigate the disaggregation of climatic variables, primarily precipitation, to shorter than daily time steps (1 to 6 hours) in order to assess the potential for improved sensitivity of shorter time steps to processes controlling basin runoff. The approach might follow one investigated by Woolhiser and Osborn (1985) utilizing a dimensionless, nonhomogeneous Markov process to disaggregate equal time increments of a total elapsed storm.

If possible, some effort will be made to begin a mesoscale or sub-grid modeling approach (Lamb, 1987). The model would be directly linked to one of the GCM research efforts and would be used to provide considerably more accurate projections of changes in climatic variables for the basin.

There will be considerable use made of Geographical Information Systems (GIS) to prepare spatial coverages of analyses and to analyze spatial relations of climatic and other variables. Element 5 describes the GIS efforts for the project.

### Relation to Other Elements

The generation of climatologic data in Element 1 is functionally linked to the success of each of the other Elements in the Delaware River Basin Climate Change Project. Therefore, the data requirements of the models operated in other Elements will be coordinated with Element 1.

Three distinct data outputs from this Element are as follows:

1. A synthetically generated data base consisting of at least daily maximum, minimum, and mean temperature and daily total precipitation for points (stations) within the Delaware River basin spanning a period of time sufficient for the generation of current conditions.
2. A similar, synthetically generated data base sufficient to simulate the effects due to climate change.
3. An estimated series of daily sea-level/tidal-stage values for the mouth of the Delaware Bay.

## Element 2-- Modeling Watershed Systems and Assessing Changes

### Background

Effects of climate change on the Delaware River watershed systems will stem largely from changes in precipitation and temperature, although changes in cloud cover, wind, humidity, and other weather conditions all would have some effect. Precipitation changes could change the amount and temporal distribution of streamflow and ground-water recharge, and the frequency and duration of extreme events, such as major storms and droughts. Changes in temperature and other climatic variables could affect rates of evapotranspiration in warm seasons and amounts or timing of snow or snowmelt in winter, and subsequently alter both streamflow and ground-water recharge. It is important to reiterate that the assessment of effects of climatic change on water supply requires a definition (modeling) of current climatic variability and runoff relations for the basin through watershed models that are sensitive to the climate-change scenarios developed in Element 1.

The large area of the basin, the different physiography and ecology (fig. 1), the diversity of watershed runoff processes, and human influence on the movement and storage of water (fig. 2) make the task of modeling watershed systems extremely complex. There are anticipated problems associated with the scale of the processes and the basin, with the parameterization of model components, and perhaps with some of the streamflow records and other data. However, a combination of empirical and physical model components and a strong GIS dependence are planned and should overcome most of these problems.

## Objectives

The objective of developing models of watershed systems for the Delaware River basin is to gain the knowledge of possible effects that climate change would have on the generation of watershed runoff. In this Element, three of the four aspects of basin water availability are related directly to the role of watershed runoff and changes in (1) the basin reservoir systems, (2) the maintenance of streamflow at Montague and Trenton, and (3) the upstream movement of saline water in the Delaware Estuary.

Specifically, the watershed models will be used directly to evaluate changes in streamflow and other water-balance components that could affect the allocation of water resources of the basin. Indirectly, the watershed modeling also will allow for the evaluation of potential saline-water intrusion and changes in ground-water availability of Coastal Plain aquifers caused by changes in freshwater inflows and estuary salinity conditions (see Elements 3 and 4 for details).

## Approach

Two general categories of watershed system models for the basin will be developed. The modeling approaches differ in the type of data they will output for analysis (monthly or daily) and also in the complexity of their respective data needs and methodologies. The two modeling approaches will provide water-supply models for the climate-change analyses in this project and for planning and operational decision making by the various agencies in the basin.

### Monthly Flow Modeling

Monthly flow models have proven useful for water-supply analyses of critical low-flow or drought periods (Alley, 1985). Because droughts occur over extended periods of time with relatively little day-to-day variation in streamflow, the monthly flow approach is appropriate for some analyses like water-supply and water-balance analyses (Alley, 1984). The obvious advantages of the approach are its relative simplicity and less stringent data requirements. The disadvantage of the approach is the lack of resolution required for assessing the effects of climate change on the more dynamic processes like flow generation during storm events or evapotranspiration and soil-moisture accounting between storms. The monthly flow model approach includes three tasks: (1) the compilation of all pertinent data, (2) the development of regional regression equations for estimation of monthly streamflow statistics under existing and changed climate conditions, and (3) the development of monthly flow models for strategic points in the basin for the evaluation of streamflow changes that could affect the allocation of basin water resources.

First, gaged and ungaged sites in the basin will be selected and monthly flow models will be developed. At least 20 sites from the existing network of more than 100 gages will be chosen and most will match the sites for the daily flow modeling. Next, physical descriptions of all reservoirs, diversions, and other important hydrologic structures within each subbasin will be compiled. Basin characteristics, such as slope, land cover, drainage density, and other physical attributes of the subbasins, will be compiled using GIS methods. Monthly streamflow for gaged subbasins and monthly values of diversions, returns, and reservoir releases for all subbasins will be loaded into computer files along with the basin characteristics. Streamflow will be adjusted for various water uses to produce unregulated monthly values. Detailed descriptions of normal reservoir operating rules, drought warning/emergency water-use restrictions, and any other rules for water use or release also will be compiled for use in making streamflow adjustment algorithms in the models.

Using monthly flow and basin characteristics from the gaging stations, regional regression equations will be developed for estimating unregulated monthly flow statistics at ungaged sites. Climate-change scenarios will be provided by Element 1 and will be used to develop monthly data under changed climate based on projected changes in temperature, precipitation, and any other climate variables used in the water-balance models (Gleick, 1986).

Next, a monthly flow model for critical points in the basin; such as at each major reservoir, at Montague, at Trenton, and perhaps for various inflows to the Delaware Bay will be developed. The model will be driven by a multisite streamflow generator based on the monthly flow statistics estimated above and capable of generating long records of flows for both the current and projected climate scenarios. The long series of monthly synthetic flows at critical points in the basin can be compared and analyzed statistically for changes in streamflows. Analyses could be geared for an assessment of instream storage requirements relative to projected water demand, if so desired and if projected water-demand data can be supplied.

Daily Flow Modeling

The daily flow models will provide better time resolution of the flows at target locations; that is, at water-supply reservoirs, Montague, Trenton, and other inflows to the Delaware Estuary and Bay. The daily flow models will utilize a system of physically based and empirically based modules of Hydrologic Simulation Program--Fortran (HSPF), (Johnson and others, 1980), Precipitation-Runoff-Modeling-System (PRMS), (Leavesley and others, 1983), and Topographic model (TOPMODEL) (Beven, 1985). Physically based modules simulating various watershed processes (for example, the runoff generator of Beven, 1985) will be investigated and likely could replace or augment selected empirically based modules (for example, the runoff generator of the HSPF model). Also, empirical calibration of some parameters could be avoided and modules would be more physically based by using parameters estimated from GIS linkages to digital coverages of topography, soils, geology, and land cover rather than by calibration. Parameters that can be estimated more directly from GIS-measurable basin characteristics and by regionalization would be more desirable for assessing climate change. All modules will be tested for sensitivity to current climate conditions and runoff, and those that are most appropriate will be used for the basinwide model.

The approach is intended to be flexible in application of those modules which are more appropriate or more accurate for the intended task. The approach also should have more transfer value. Considerable input from the U.S. Geological Survey's Office of Surface Water and Branch of Regional

Research will be needed to structure and develop the modeling system packages for this project. GIS techniques and satellite imagery (Element 5) will play a significant role in the daily flow modeling for use in defining, distributing, and applying parameters directly to the physically based modules or in generalizing (regionalizing) parameters for implementation of empirically based modules.

In coordination with Element 1, all daily climate data for the Delaware River basin will be entered into a computer data base, probably Watershed Data Management System (WDMS) (Lumb and others, in press). Likewise, all daily values of streamflow, reservoir levels, and water withdrawals and return flows for the basin will be entered into WDMS. If needed and appropriate, values for periods of missing record for the data will be estimated. Solar radiation and potential evapotranspiration data will be generated as needed from other climate data. The period from about 1950 through 1987 will be the target data set (current conditions), realizing that there will be some difficulty in obtaining good records of water withdrawals before 1970 and returns before 1980. At least 10 years of record will be required for a streamflow station in the model.

The basin will be segmented, using GIS techniques, on the basis of physiography, geology, soils, land cover, climate station coverage, reservoirs, and target locations on streams and rivers. The model input data will be compiled for both empirical and physical modules for each segment based on characteristics from the GIS and from channel cross-section data. The linkage of subbasins will be accomplished through the HSPF channel and reservoir routing module.

Using a selected number of GIS-distributed, physically based and empirically based techniques, rainfall-runoff and snowmelt parameters will be developed for each subbasin used in the calibration of gaged subbasins. Flows will be simulated for at least a 10-year period with all the parameter-estimation techniques at about half (about 50) of the gaged sites. Using approaches similar to Klemes' (1986), split samples of the time series of each calibration subbasin will be used to test the sensitivity of each of the parameter-estimation techniques; then the remaining one-half of the gaged subbasins will be used for a proxy-basin verification of parameter transfer and as additional sensitivity to parameter estimation modules. Flows will be simulated at a couple of mainstem Delaware River stations for a long (longer than 60 years) period of record for additional verification. Various statistical routines will determine model prediction errors and sensitivities.

Determining sensitivity of individual modeling approaches to climate controls, primarily precipitation and temperature is a goal of this Element. The sensitivity of temperature will be related to its effect on evapotranspiration, soil moisture, snow accumulation, and snowmelt. The sensitivity of precipitation will be related to its effect and reasonableness of fit over a wide range of precipitation, antecedent moisture, and flow conditions.

Once the subbasin modeling approach is verified, a basinwide modeling approach will be developed using the parameter estimation techniques that are successful in the generation of streamflow for all subbasins in combination with the streamflow and reservoir routing module. The basinwide modeling will simulate flows for a long period of record using existing climate data and reservoir rule curves. Model output at target locations will be stored and flow statistics will be computed.

With the various climate-change data from Element 1 and the basinwide model, flows will be simulated for a long period of record. Model output at target locations will be stored and flow statistics will be computed for each scenario and used for comparison and analysis with current conditions.

### Relation to Other Elements

The streamflow data generation activities of Element 2 are linked functionally, are dependent upon the output from Element 1, and will determine the success of Elements 3 and 4. It is imperative, therefore, that the data requirements of the models being operated in other Elements be closely coordinated with Element 2.

Three distinct data outputs from this Element are as follows:
1. Two synthetically generated data bases consisting of monthly and daily streamflow for points (stations) within the Delaware River basin spanning a time period sufficient for the generation of current conditions.
2. Two similar, synthetically generated data bases will be used to simulate the effects due to climate change and as input to the estuarine modeling effort in Element 3.
3. Estimated evapotranspiration values for the climate-change scenarios to be used to estimate new values of ground-water recharge for the aquifer systems to be modeled in Element 4.

## Element 3-- Modeling Estuary Salinity Dynamics

### Background

The Delaware Estuary region is highly dependent upon the freshwater resources of the estuary and adjacent aquifers for public and industrial supply. The primary source of water supply for the City of Philadelphia is the Delaware River, taken from the freshwater part of the Estuary at the Torresdale intake. Across the river, New Jersey is developing strategies to augment ground-water supplies, possibly with surface water, to halt declining water levels in Coastal Plain aquifers (Whipple, 1987). Many industries on both sides of the Estuary obtain their water supply directly from the Estuary. Salinity intrusion caused by changing conditions could jeopardize existing water supplies and could influence the location of New Jersey's water intakes in the Estuary.

The Potomac-Raritan-Magothy aquifer system in the Cretaceous Potomac Group and the overlying Raritan and Magothy Formations of New Jersey and the Potomac aquifers in the Cretaceous Potomac Formation of Delaware both receive significant recharge from the Estuary and are vulnerable to saltwater intrusion (fig. 9). A rise in sea level (fig. 6; Titus, 1986) or decrease in freshwater inflows could change the position of the salt front

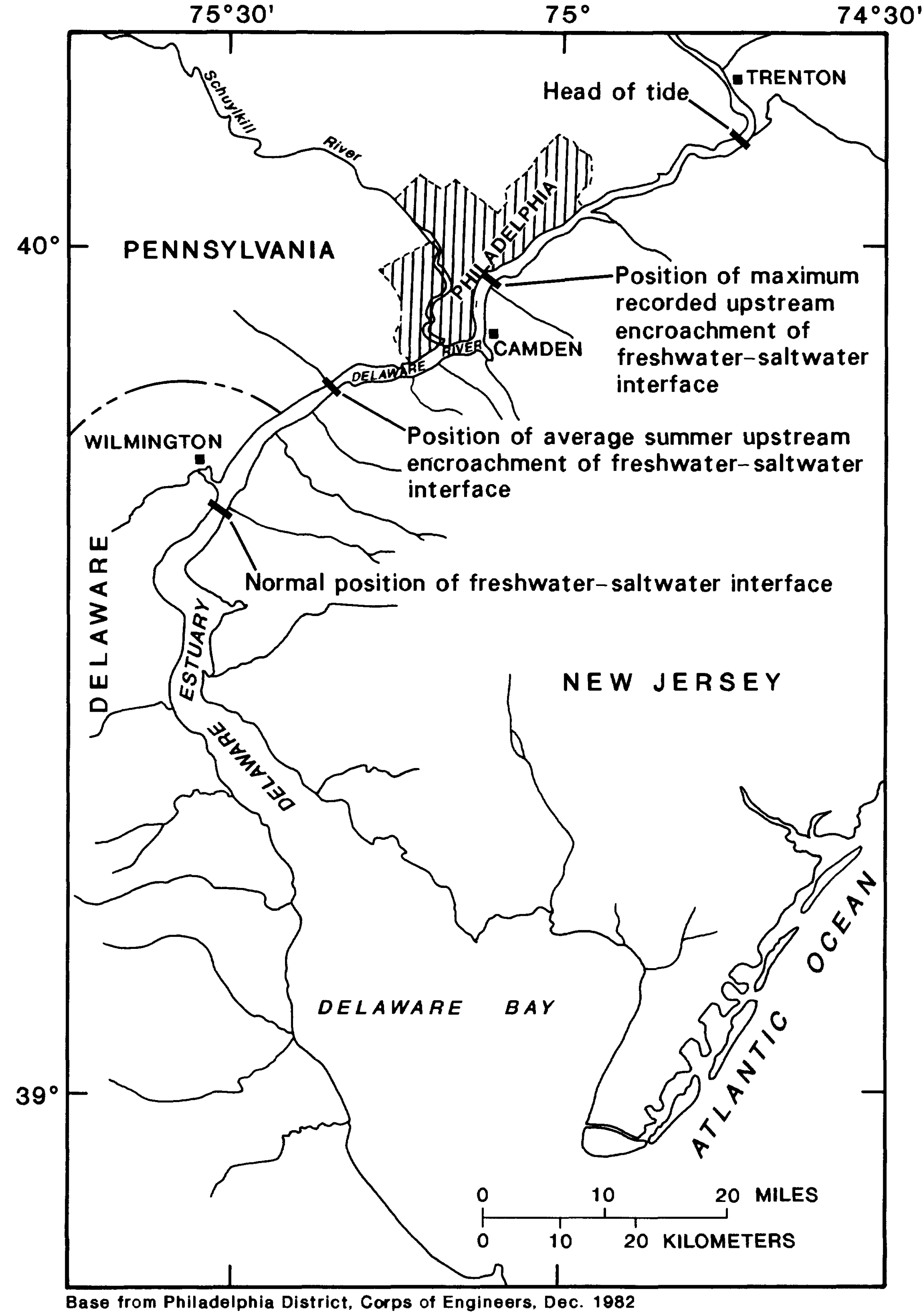


Figure 9.--Location of various freshwater-saltwater interface positions in the Delaware Estuary.

and cause saltwater intrusion to increase in these Coastal Plain aquifers (see Element 4 for more details). Therefore, it also is necessary to evaluate the effect of climate change on the dynamics of saltwater intrusion in the Delaware Estuary.

## Objective

The objective of Element 3 is to investigate changes in the spatial distribution of salt front in the Delaware Estuary resulting from climate-induced changes in freshwater inflows and in sea level.

## Approach

The approach adopted for this study is composed of two parts: (1) the analysis of existing physical data in order to derive a basic understanding of the estuarine salt dynamics, and (2) the numerical simulation of future conditions based on this understanding.

The data analysis is prompted by the existence of an extensive data set for a variety of physical variables and the lack of previous studies to define the magnitudes of the various salt transport processes. The data of interest include stage and salinity data from the U.S. Geological Survey and DRBC; and tide, salinity, current meter data from the National Oceanic and Atmospheric Administration, National Ocean Service. From this data, rates of the various salt transport processes can be calculated, such as the horizontal residual transport, tide-induced dispersion, and transport from estuarine circulation. Finally, changes in these rates can be related to changes in freshwater inflow, wind stress, mean sea level, tides, and other factors. Knowledge of these rates and their changes relative to changing conditions is an essential input to the numerical simulations.

The method to be adopted in the simulations for this Element is to use the projected sea-level and tide scenarios for the mouth of the Delaware Bay (from Element 1), along with the current and projected freshwater inflows to the Delaware Estuary and Bay (from Element 2), as input to a multidimensional flow and salinity model. One such model is the three-dimensional, time-stepping model of Blumburg and Mellor that was recently developed for the Delaware Estuary and Bay (Johnson and others, in press). The fact that the model is a state-of-the-art, strongly physically based approach, and is operational, make it most appropriate for this type of analysis and for this task. The model should be able to provide the data to statistically analyze the salinity dynamics resulting from sea level and freshwater inflow changes. These results then can be compared with the corresponding data analysis.

However, the costs associated with a fully three-dimensional model indicate that other approaches are necessary. Therefore, there will be an investigation of a currently operational one-dimensional, cross-sectionally averaged flow and salinity model (Thatcher and Harleman, 1978; Hull, 1981). The salt dispersion in this model is approximated with an empirically derived relation that will be compared with the results of the data analysis. In addition, there will be an investigation of a two-dimensional, vertically averaged model that uses a spectral decomposition in time (Walters, 1987). Either of the lower-dimensional models would greatly reduce the computational requirements of analyzing a large number of sea-level rise and freshwater inflow scenarios. The tasks might lead, then, to an improved approach (or improved confidence of the present approach) to drought warning analysis by the DRBC.

### Relation to Other Elements

Sea-level and tide information will be provided by Element 1, and freshwater inflows to the Delaware system will be provided by Element 2. Output from Element 3 includes salinity distributions in the Estuary that will be used as input to the ground-water models in Element 4.

## Element 4-- Modeling Aquifer/Estuary Interactions

### Background

Large withdrawals of ground water for public supply and industrial use in the Camden area of New Jersey and in the New Castle area of Delaware have caused water levels to decline and created extensive cones of depression in parts of the Coastal Plain aquifer systems adjacent to the Delaware Estuary. Consequently, these depressed water levels have resulted in considerable quantities of induced infiltration from the Estuary into the aquifer systems.

Climatic change could have a major effect upon ground-water supplies in the Delaware Estuary region (fig. 2). Precipitation changes will have a direct effect on recharge to the ground-water systems. Temperature changes would affect evapotranspiration rates and, therefore, also affect ground-water recharge. Changes in temperature and precipitation in the upstream portions of the basin could cause changes in freshwater inflows to the Estuary.

A change in global temperature also will have an effect on sea level (fig. 6). It has been postulated that a rise in sea level of approximately 0.4 to 2 feet by 2025, and 1.25 to 7 feet by 2075, could result from a global warming trend (Hoffman and others, 1983). Sea-level rise would have several basic hydrologic effects. It would cause a rise in the fundamental base level of the aquifer systems resulting in adjustments to the potentiometric surface and, thus, move the saltwater interface landward in coastal aquifers. It also would cause the saltwater interface in the Delaware Estuary to assume a more upstream position, unless countered by a concurrent increase in freshwater inflows to the Estuary.

The possibility of saltwater intrusion from the Delaware Estuary into the coastal freshwater aquifers of both the Camden and New Castle areas is a major concern. Such intrusion could result if saline water migrated upstream in response to decreases in freshwater inflow, rising sea levels, or worse yet, both. Because of the geographical and political separation, the hydrologic data bases and models for previous investigations of each area have not been integrated on a scale appropriate for the present investigation. Therefore, two independent work efforts are planned, one for each area.

Potomac aquifers near New Castle, Delaware

The Potomac aquifers in Delaware presently yield most of the ground water used north of the Chesapeake and Delaware Canal for public and industrial supply. A steady increase in pumpage since the mid-1900's has resulted in local and regional cones of depression centered around well fields in New Castle, Delaware (fig. 2). Ground-water levels as deep as 200 feet below sea level have been reported in some areas (Martin and Denver, 1982). Under current (1987) conditions, infiltration induced from the Delaware Estuary constitutes about 10 percent of the total pumpage from wells in the Potomac aquifers of northeastern New Castle County (S. W. Phillips, U.S. Geological Survey, oral commun., 1987). Clearly, any significant salinity increases in the Delaware Estuary could have serious consequences on the quality of water in these aquifers.

Coastal Plain aquifers near Camden, New Jersey

The metropolitan areas of southwestern New Jersey particularly are vulnerable to any significant changes in Estuary salinity. In particular, the water supply for the greater Camden metropolitan area (fig. 2) is derived from ground-water sources, primarily the Potomac-Raritan-Magothy aquifer system. Under current (1988) demand stresses, the Potomac-Raritan-Magothy aquifer system in the Camden area is being recharged from the adjacent Delaware Estuary coincident with the aquifer system's outcrop.

Approximately 100 Mgal/d (1985) is being pumped from the Potomac-Raritan-Magothy aquifer system in the Camden area. Luzier (1980) developed a two-dimensional, ground-water flow model for the Camden area and determined that approximately 70 Mgal/d is leaking from the Estuary to recharge the Potomac-Raritan-Magothy aquifer system under 1973 pumpage demands. Water use in the area has increased since 1973, thus, the current induced recharge from the Estuary is probably higher.

The area of induced recharge to the Potomac-Raritan-Magothy aquifer system is in the freshwater part of the Estuary. Normally, the freshwater-saltwater interface in the Estuary is located downstream of Wilmington, Delaware (fig. 9), fluctuates approximately 6 miles with each tidal cycle, and is a well-mixed front rather than wedge-shaped (J. Hull, Delaware River Basin Commission, oral commun., 1985). The average annual maximum upstream encroachment of the interface is approximately to Chester, Pennsylvania (fig. 9). During the drought of record (fig. 9), the maximum recorded upstream encroachment reached the Philadelphia, Pennsylvania area (Anderson and others, 1972). This maximum encroachment occurred in November 1964, during which time saltwater was adjacent to aquifer recharge areas in the Estuary and entered the aquifer. A slug of higher chloride water (but still potable) has been observed in the aquifer since that time. Figure 10 shows a time-series of maps in the vicinity of Camden that traces the slug in the Potomac-Raritan-Magothy aquifer system.

Although there were no long-term deleterious effects on Camden's water supply from this short-lived incident, and subsequent reservoir construction and management in the upper basin (Hull and others, 1986, p. 21-27) have

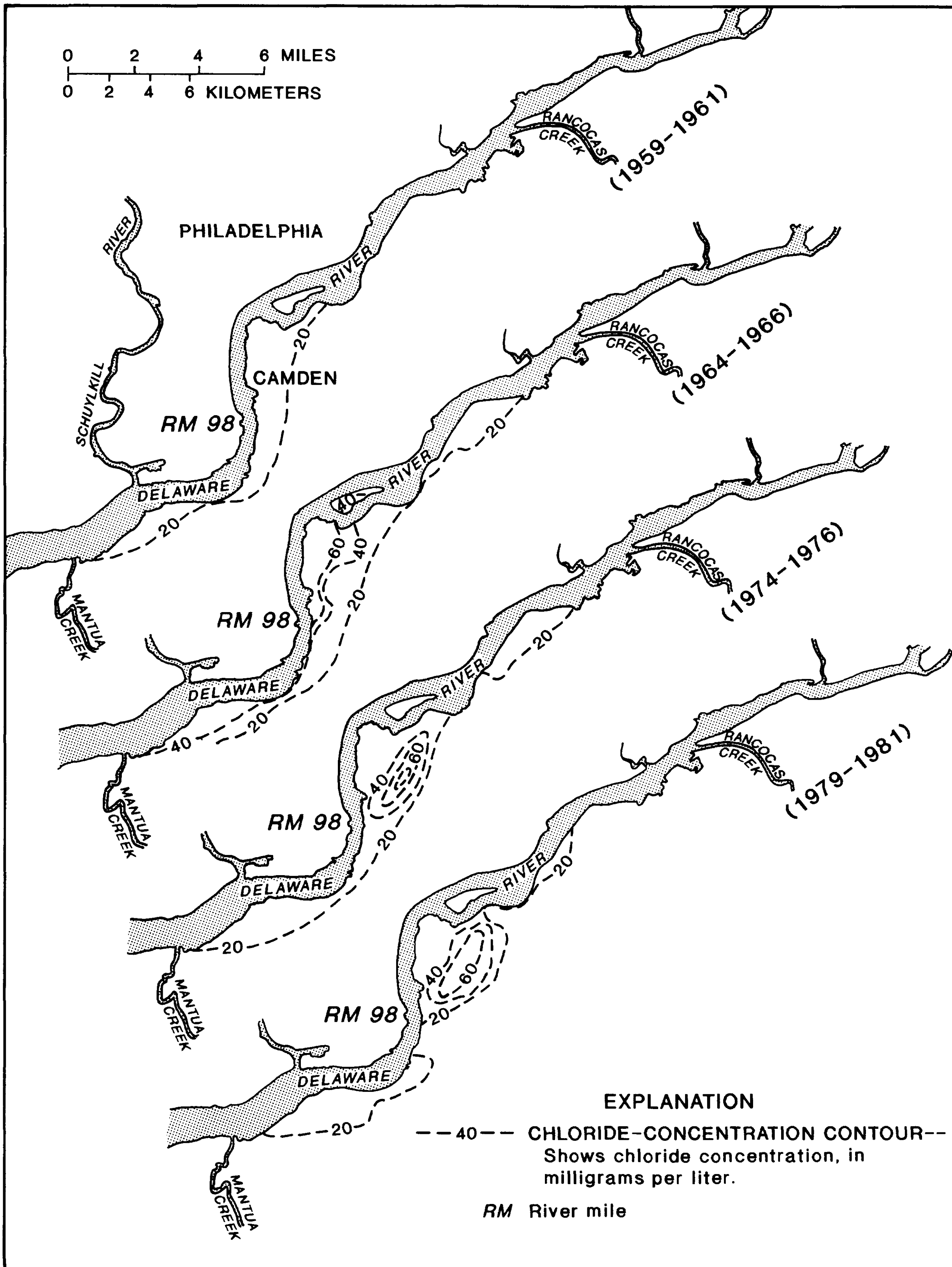


Figure 10.--Chloride concentrations in the Potomac-Raritan-Magothy aquifer system before and after the salty recharge episode resulting from the maximum recorded estuary saltwater encroachment of November 1964 (modified from Camp Dresser and McKee, Inc., 1984).

prevented a reoccurrence, this episode indicates the vulnerability of Camden's water supply to encroachment of the Estuary's interface. If climatic conditions were to change and encroachment were to extend beyond present mitigation capabilities, the primary source of water supply for the Camden metropolitan area would be threatened with contamination by saltwater.

## Objectives

The overall objective of Element 4 is to investigate the effect of climate change on the ground-water supplies in the Delaware Estuary region. Specific objectives include (1) determining the extent to which the aquifer systems will be affected by saltwater intrusion from the Delaware Estuary; (2) determining the extent to which ground-water recharge to the aquifers will be affected by changes in precipitation and evapotranspiration; and (3) estimating the rate of concentration change and movement of chloride in the aquifer systems associated with saltwater intrusion.

## Approach

The proposed approach for Element 4 will include similar but separate tasks for each of the two ground-water study areas. The tasks will be accomplished through the use of previously calibrated, three-dimensional, ground-water flow models and supplemented by use of a one- or two-dimensional, solute-transport model.

### Potomac aquifers near New Castle, Delaware

The approach for the New Castle area investigation will be based on two previously developed models. Martin (1984) prepared a model of ground-water flow in the Potomac aquifers in New Castle County, Delaware using the three-dimensional code of Trescott (1975). Although the modeled area covered 2,860 square miles in Delaware, Maryland, and New Jersey, this model was calibrated only within a 330-square-mile area in Delaware. Phillips (1987), using the spatial discretization and reformatted input data from Martin's model, applied the U.S. Geological Survey's modular, three-dimensional, ground-water flow model (McDonald and Harbaugh, 1984) to investigate the potential for intrusion of saline water from the Delaware Estuary into the Potomac aquifers in New Castle County.

Aquifer/estuary interactions for the New Castle area will be addressed through the use of Phillips (1987) ground-water flow model. Model simulations representing the modified hydrologic conditions will be analyzed for information on cell-by-cell fluxes, especially leakage, and the overall volumetric budget. The ground-water velocity field generated from these simulations will be used to predict the approximate extent, severity, and timing of chloride migration into the aquifers in response to new recharge, water levels, and salinity stresses in the Estuary.

Evaluating the distribution of chloride that would be expected in the aquifers under the modified hydrologic regime will be addressed through the use of a one- or two-dimensional, solute-transport model. One of several analytical, one-dimensional, steady-state models could be prepared readily to simulate chloride transport away from a line source by a direction and dispersion in a strong radial flow field. With some additional effort, a digital, two-dimensional, transient model (Konikow and Bredehoft, 1978) could be prepared with coarse-grid resolution to more accurately simulate the temporal and spatial distribution of chloride in the aquifers. The transport simulations will be analyzed to determine the maximum ground-water withdrawal rates that can be sustained without inducing an unacceptable quantity of saline Estuary water into the Potomac aquifers.

Coastal Plain aquifers near Camden, New Jersey

The approach to the Camden area (fig. 2) investigation also will be based on previously developed models and will determine the extent of the Potomac-Raritan-Magothy aquifer system that would be affected by saline water encroaching onto its recharge area. The changes in direct recharge resulting from changes in precipitation and evapotranspiration also will be evaluated.

Two ground-water flow models are available and appropriate for this analysis. The New Jersey Regional Aquifer System Analysis (RASA) model covering the entire New Jersey Coastal Plain (11 layers, 1,479 nodes) is calibrated and documented (Martin, 1987). The Camden and Vicinity Ground-Water Investigation, part of the New Jersey Bond Issue Studies (Leahy and others, 1987), currently has a high-resolution model (4 layers, 10,000 nodes) calibrated for the Potomac-Raritan-Magothy aquifer system in the Camden metropolitan area. Both the Camden model and the RASA model use the modular, three-dimensional, finite-difference code of McDonald and Harbaugh (1984).

The Camden model operates in a "nested" fashion with the RASA model and limits the Camden model's node size while retaining true hydrologic boundaries. The existing model input data set will be modified to handle the proposed climate-change data. The flow path of water entering the aquifer system from the Estuary can be delineated and the affected areas can be determined from the high-resolution Camden model. Steady-state concentrations of mixed aquifer and Estuary water can be roughly estimated from the flow model output. The effect of changes in recharge would be evaluated by analysis of head changes in the RASA model.

A ground-water solute-transport model, such as the method of characteristics model (Konikow and Bredehoeft, 1978), or one of various analytical solutions will be used to better evaluate the chloride transport. A flow path between the recharge area in the Estuary and the major pumping center will be determined from the flow model. The solute-transport model will be applied along this flow path to determine the timing and severity of the problem, in terms of water-supply potability.

## Relation to Other Elements

Because the extent, severity, and timing of chloride migration from the Delaware Estuary into the surrounding aquifers is dependent on the chloride concentration and water stage in the Estuary, the ground-water analyses are related to the estimates of sea-level rise (Element 1), to the watershed modeling efforts (Element 2), and to the salinity modeling efforts (Element

3). The information from these other Elements include the average stage in the Estuary, the frequency distribution of salinity concentrations in the Estuary, and the change in precipitation and evapotranspiration.

## Element 5-- Analyzing Water-Use and Geographical Information Systems

### Basinwide Water-Use Analysis

#### Background

The Delaware River is a source of water for an estimated 20 million people (Delaware River Basin Commission, 1986) both within and outside the basin (figs. 3 and 4). The waters of the Delaware River are critical to public water supply, commercial and industrial activities, electric utilities, and recreational use. The availability and distribution of water to users is based on many complex systems of reservoirs for storage and wells, pipes, tunnels, and canals for diversion and delivery. Even with all its water-supply facilities, the basin still is prone to shortages during extended periods of less than normal rainfall. Any significant changes in the temperature and precipitation regimes could have serious implications on the dependability of supplies for the region.

Total basin water use is about 9,000 Mgal/d (or 13,000 $ft^3/s$) (Bob Limbeck, Delaware River Basin Commission, written commun., 1988) and is mostly surface water. The New York City aqueduct system and the Delaware and Raritan Canal account for 900 Mgal/d of water exported out of the basin (fig. 2).

#### Objective

The objective of this part of the Element is to compile and analyze basin water use. Current usage and trends will serve as a basis for evaluating the water availability for various climate-change scenarios.

#### Approach

The approach will be to compile the monthly and daily (where available) water-use data in the following subareas: above Montague, Montague to Trenton, and the Estuary. The DRBC has 1986 annual usage data for all major users (over 50,000 gallons per day) within the basin, including the source, the use category, and estimates of the depletive (consumptive) use. Monthly variability for each significant water-use component within each subarea can be estimated from data in DRBC and other files. Many of the major surface-water users have reported monthly data from which to derive these estimates. Daily data are available for a few users, such as New York City and the Delaware and Raritan Canal diversions. Daily water use estimates that significantly effect the daily flow modeling will be estimated from the monthly data.

Water-use data will be compiled for each subarea for the following information:

- Total withdrawal by source, for ground and surface water, fresh and saline.

- Population estimates for users inside and outside of the basin.
- Seasonal demands and trends in use for public supply, electric power generation (thermal and hydroelectric), agriculture and irrigation, industrial, and commercial.
- Seasonal demands and trends in consumptive use and diversions in and out of the basin.

This quantification is important to the understanding of water use needs over time and the ability of the basin to meet and deliver the seasonal demands, and to the evaluation of effects of climate change on the dependability of the supply. From initial discussions with the DRBC, the types and length of available water-use data, other than the 1986 compilation, are scattered and mostly in paper form.

Relation to other Elements

Modeling of watershed runoff, estuary salinity, and aquifer/estuary interactions will depend upon accurate estimates of water use. The quantification of diversions and consumptive use in the basin are particularly important to the watershed modeling tasks in Element 2.

## Geographical Information Systems

Background

Geographical Information Systems have been found to be powerful tools in the management and analysis of spatial data. The ARC/INFO[1] GIS system has found considerable application within the U.S. Geological Survey, particularly in regional hydrologic studies that require the compiling, combining, comparing, summarizing, overlaying, analyzing, displaying, and preparing extensive amounts of data. Many of the tasks would be impractical without the GIS, however, applications are often dependent upon the availability of digital data or on the practicality of digitizing the needed coverages.

In the 12,765-square-mile Delaware River basin, the GIS has particular applicability for areal analysis of precipitation and other climatic data, for providing an efficient (and probably the only practical) way of building distributed daily flow models that clearly reflect runoff and evapotranspiration variability for a large area, for more accurate estimates of model parameters based on basin characteristics, and for summarizing and displaying interpretive outputs.

The GIS activities of the Project will develop the GIS coverages defining political and physical boundaries, land use/cover, topography, hydrology, geology, soils, and other basin characteristics. The GIS will be used to manage, analyze, and display data for modeling and other interpretive activities.

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[1] The use of trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Objective

The objective of the GIS part of this Element is to build the appropriate digital data bases and apply the spatial analysis tools of the GIS to the data analysis and modeling tasks of the project.

Approach

A general survey indicates a sparsity of directly available digital data, but most data are purchasable or within reach with a modicum of manpower expenditure. The approach will require the development of a digital data base and the application to various analysis tasks.

Developing the data base.-- General political boundaries, physiography, and hydrology coverages are available at the 1:250,000 and 1:500,000 scales and will find application for publications to follow. Larger scale coverages of land use (1973-74), political boundaries, census tracts, and federal lands are available through the Geographic Information Retrieval and Analysis System (GIRAS) digital data base at a 1:250,000 scale. This is the only digital source of land use. A separate effort should be made to secure another time coverage (mid-1980's) using Landsat imagery (see below) to account for the land-use changes, especially in the lower basin, caused by rapid urban growth.

Generalized geology of the basin has been digitized from 1:500,000 scale geologic maps of Parker and others (1964). Larger scales would contain more detail, but coverages are not complete for the basin and the matching of geologic units between maps classified differently would yield little additional information for the tremendous effort involved. Soils data will be digitized, probably at the same scales as geology, from the generalized state-wide soil maps of the U.S. Soil Conservation Service. Geology and soils coverages both are needed for the daily flow modeling effort, because it is not known which of the two will prove most useful for distributing or regionalizing model parameters.

The basin hydrology coverages have been purchased as digital line graphs (DLG's). The data are from 1:100,000 scale maps and provide the detail necessary for the distributed-flow modeling effort. Some additional work on the coverages will be necessary to put the coverages into ARC/INFO format and to assign hierarchical order attributes to the stream network.

The 1:250,000 scale digital elevation model data have been purchased. The 1:100,000 scale DLG hypsometry is more desirable, but not available. The coverages will be used to delineate watershed boundaries using techniques developed by Jenson and Domingue (in press) and to compute various topographic characteristics (Beven, 1985).

Geographical information systems analyses.-- Compiling, cleaning, and transforming the data are only part of the GIS effort. In addition, the GIS will be used to produce working copy maps, to aid in the areal analysis of the climatic data, to develop data for input to the distributed daily flow models of sub-basins, to regionalize model parameters, to process the model output, and to produce the publication graphics.

Expanding land-use coverage through satellite imagery.-- Digital imagery collected by earth observation satellites provide synoptic, repetitive coverage of large areas of the earth's surface since 1972. The most common imagery have been collected from the Landsat series of satellites. The imagery are reflected solar radiation data in the visible and near infrared regions of the electromagnetic spectrum, with a ground resolution range from 30 to 80 meters. Imagery are collected every 14 days at the same solar time (10:30 a.m.).

Classification of land cover from this imagery is an existing and proven technology (Allord and Scarpace, 1979; Cermak and others, 1979; Lins, 1987) and could enhance the U. S. Geological Survey's efforts in climate-change research and other watershed-modeling activities. The classifications take advantage of the fact that different surface materials have different reflectance characteristics. Landsat imagery generates detailed land-use/land-cover maps that are not equivalent to photointerpreted maps, but are commonly more consistent, especially in areal tabulations of land-cover types (Jackson and McCuen, 1979). These maps then can be imported into the GIS for analysis. Difficulties do exist with this translation of image classifications to directly update a GIS; however, satellite imagery can be a useful GIS input when timely cover data are unavailable and large areas are involved (Goodenough, 1988).

The Delaware River Basin Climate Change Project requires detailed land-cover information for input into hydrologic models. The land cover currently available is the 1973-74 GIRAS digital data. Land-cover maps from Landsat imagery could be generated as frequently as desired (since 1972) to analyze change in land cover through time. Input from this source would enhance the applicability of surface-water models which require land-cover changes over time to account for changes in runoff characteristics.

The Earth Resources Display and Analysis System (ERDAS) image processing system will be used. ERDAS has working software links to the ARC/INFO system. More importantly, the New Jersey Department of Environmental Protection has an archive of digital Landsat imagery covering most of the Delaware River basin area.

It is clear that Landsat data analyses could be another tool in our hydrologic toolbox. The use of remote sensing inputs to climate models is more common outside the U.S. Geological Survey, and given its experience with GIS, the U.S. Geological Survey should be involved in applying both together (Lins, 1987). An effort will be made to produce an additional time interval (mid-1980's) of land cover for the basin to overlap with the water-use data of the 1980's.

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