Metro East Coast Study
Water Sector Report
Public Comment Draft
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Comments on this public review draft should be sent to: Columbia University Center for Climate Systems Research, 2880 Broadway, New York NY 10025.

Figures and Tables

I. Introduction

This report assesses potential impacts of climate change on the New York City and some related regional water supply systems in the Metro East Coast region and adjoining areas. It suggests types of adaptive measures that might be undertaken to cope with the effects of climate change. It is now generally assumed that global climate change is likely and that it will include temperature increases, changes in precipitation, and a measurable rise in sea levels. These changes will have impacts both on demand and on supply in the New York City water supply system and other water supply systems in the region, including those of Long Island and the Delaware River downstream from New York City's reservoirs. While temperature increases and sea level rises are expected, there is a range of forecasts with respect to the timing and level of these variables. Moreover, forecast changes in regional precipitation vary widely, from positive in some GCMs to negative in others. Thus there is a substantial degree of uncertainty about climate change and its impacts on regional water systems. Urban water supply systems have large infrastructures, substantial customer bases, and long lead times for planning. Planning must therefore be a matter of considering what elements of the system might be impacted by global warming, what information will be needed to make adaptations, and what the timing of such adaptations should be. In most cases, both institutional and infrastructure responses will be required, for example in increasing the interconnectivity of regional systems.

A. Background

The New York City Water Supply System stretches from upland reservoirs in the Catskills down through all parts of New York City. Figure 1A-1 shows this system. Water is collected from upland watersheds, held in storage reservoirs, and sent via a system of tunnels and aqueducts through balancing and distribution reservoirs to distribution mains in the city and other user areas. User areas are shown in Figure 1A-2. The system operates almost entirely by gravity (the highest reservoir, Neversink in the Delaware system, has its spillway at 1440 feet above mean sea level). About 97% of the total water supply is delivered to the distribution system by gravity; only 3% is electrically pumped to maintain desired delivery pressures.

THE NEW YORK CITY WATER SUPPLY SYSTEM

FIGURE IA-1 : Watersheds, Reservoirs, and Aqueducts of the System

Water is collected and stored in three upland reservoir systems: Croton, which began service in 1842 and was completed as a system prior to World War I; Catskill, completed in 1927; and Delaware, completed in 1967. The total area of the watersheds is nearly 2000 square miles. The three systems meet respectively about 10%, 40%, and 50% of the total daily system demand. The systems deliver water to the City via the New Croton Aqueduct, the Catskill Aqueduct, and the Delaware Aqueduct. The New Croton Aqueduct delivers water from the Croton System to the Jerome Park Reservoir in the Bronx. Catskill and Delaware water flows via Kensico Reservoir to Hillview Reservoir, just north of the City line.

From Hillview Reservoir, City Tunnels #1 and #2 deliver system water to the City distribution system, which includes some 6,000 miles of mains varying in size from 6 to 96 inches in diameter. City Tunnel #3 is now under construction. Its first stage, which runs from Hillview Reservoir in Yonkers through the Bronx and Manhattan and under Roosevelt Island to Queens, was put into service in 1998. When the tunnel is completed through its second stage it will provide not only additional capacity but also the opportunity to shut down City Tunnels #1 and #2 for inspection and rehabilitation. The 18 impounding reservoirs, three controlled lakes, aqueducts, tunnels and water mains that make up the city water supply and distribution systems together constitute a monumental hydraulic and civil engineering achievement. Detailed descriptions of the system can be found in the documents issued in connection with proposed bond sales (New York State Environmental Facilities Corporation, 1998); see also Major (1992); New York City Mayor's Intergovernmental Task Force on New York City Water Supply Needs (1992); U.S. Geological Survey (1997).

The total storage capacity of the upland system is 547.5 billion gallons. The safe yield of the upstate elements of the system is currently estimated to be 1,290 million gallons per day (mgd), with 240, 470, 480 and 100 mgd available from the Croton, Catskill, Delaware and Rondout watersheds, respectively. (Rondout watershed is in the Hudson River Basin but is operationally part of the Delaware System.) In addition, there are now 33 mgd of safe yield from the formerly investor-owned groundwater well-based systems in Southeast Queens. Safe yield is defined as the amount of water that could be supplied on a continuous basis by the system should there be a recurrence of the worst drought of record (in the mid-1960's). System safe yield could be lower than that currently calculated as a result of future droughts and changes in the City's releases to meet Supreme Court and New York State requirements (New York City Mayor's Intergovernmental Task Force on New York City Water Supply Needs, 1992).

Mean annual precipitation on the city's watersheds has been approximately 44 _ inches (1130 mm) during the period of record (about 60 years). During this period, maximum yearly precipitation was 55.67 inches (1414 mm), in the l977-78 water year (the system water year begins on June 1), and the minimum precipitation was 27.97 inches (710 mm) in the l964-65 water year, during the drought of record. The maximum precipitation was thus almost exactly twice the minimum.

Water from the system is used to supply all of New York City, including supplies to the service area of the former Jamaica Water Supply Company in Queens. In addition, the City system supplies 85% of the water used in Westchester County and 5-10% of the water used in Orange, Putnam, and Ulster Counties. There are also upstate communities that do not regularly use water from the City system but are connected to it for emergency use. Upstate municipal corporations and water districts in counties (except Dutchess) in which the City has water supply facilities have certain legal entitlements to provide connections to the system and to take water, at a price set by the New York State Department of Environmental Conservation, in quantities no greater than their populations times the city's per capita use.

The average daily system water supply provided to users in recent years has been on the order of 1400 mgd, reflecting a downward trend since 1989. In 1997, system supply was 1307 mgd, which is attributable in part to metering and conservation measures. In addition to water supply to New York City and other user areas, the system also provides augmentation and conservation releases upstate and to the Delaware Basin. The annual demands on system yield are in order of magnitude: demands from New York City; augmentation and conservation releases; and upstate demands. The percentages of use for water year l988-89, for example, were 78% for New York City water supply; l5% for the two categories of releases; and 7% for outside community water supply.

The water quality of the system has been high, and the only treatment procedures routinely used to maintain quality have been detention, screening, addition of caustic soda for pH control, and chlorination for disinfection. Fluoridation is also used, and alum is applied in the Catskill Aqueduct to control turbidity when necessary. Corrosion inhibitors may also be added to control corrosivity in the water. There are laboratories that monitor water quality in the system; about 80,000 samples a year are collected, and approximately l,000,000 analyses made. Routine checks are made for some 60 substances. There are inspectors who maintain surveillance of the watersheds and City owned and operated upstate sewage treatment plants to prevent the discharge of untreated sewage into the watersheds.

The City maintains a drought management plan to control water use and supplement water supply during periods of drought; this is currently being updated. Generally, drought management has included three phases, invoked sequentially as a drought becomes more serious. (The phases and stages are summarized in New York State Environmental Facilities Corporation, 1998, pp. B-51, B-52.) The three phases are Drought Watch, Drought Warning, and Drought Emergency. The last includes four stages with increasingly severe mandated use restrictions. Several droughts of recent years have brought the system to the third of these four stages, which includes serious water restrictions, encompassing bans on outdoor water use and the prohibition of air conditioning using public water supplies unless room temperatures are kept at 78° F or above (New York City Department of Environmental Protection, 1991, 1999). In addition, the City has an emergency water supply available from the Chelsea Pumping Station, located on the east bank of the Hudson River in Dutchess County. This station can pump up to 100 mgd from the Hudson River into the Delaware Aqueduct. It was used in the summer and fall of 1985 and for two weeks in May, l989, under emergency approval from the New York State Department of Health.

The City has long used reservoir simulation models to operate and evaluate the system; these including the principal model, the Reservoir Systems Analysis simulation model (RSA model). A version of this model, based on a model originally developed by the New York State

Department of Environmental Conservation, is described in Laedlein and Mayer (l985). The RSA model is a monthly simulation model designed to analyze the entire New York City water supply system. In addition to the RSA model, the City maintains its Daily Simulation Model of the Delaware System for the purpose of evaluating specific system functions, in particular the impacts of conservation release requirements on hydroelectric operations. In addition, the Delaware River Basin Commission's Daily Flow Reservoir Operation Model, developed originally for the U.S. Army Corps of Engineers (l980), is used to evaluate the effects of proposed operation policies and projects on the Delaware River. These models can be used to evaluate changing stream flow patterns resulting from climate change impacts.

The Delaware reservoirs of the New York City system are managed in conjunction with the Delaware River as a whole, but not with all of the elements of water supply in the Delaware River basin (see Section IIE, below). This joint management is pursuant to decrees of the United States Supreme Court, and is under the jurisdiction of the Delaware River Basin Commission, a Congressionally chartered compact, with a river master, generally a United States Geological Survey employee.

The water systems of New York City, the Delaware Basin, and other adjacent systems to the west in New Jersey and to the east on Long Island are generally mature infrastructure systems with well-developed institutions that include city, state, and county agencies and the Delaware Basin River Commission, an intergovernmental agency chartered by the U.S. Congress, and an intergovernmental group formed as a result of the work of the New York City Mayor's Intergovernmental Task Force on New York City Water Supply, the Southeastern New York Intergovernmental Water Supply Advisory Council. The systems are operated by agencies already used to dealing with substantial, albeit short term, natural variation in weather. These characteristics make the implementation of institutional and infrastructure adjustments to increase resilience more feasible. System descriptions are in Delaware River Basin Commission (1983); Major (1992); New York City Mayor's Intergovernmental Task Force on New York City Water Supply Needs (1992); U.S. Geological Survey (1997); and New York State Environmental Facilities Corporation (1998).

Changes in the system from 1950 to 2000 have involved: massive infrastructure expansion; a downward impact on estimates of system yield due to the drought of the 1960s; demand management; and more recently, active watershed management for water quality protection.

After World War II the system was substantially expanded to include the Delaware reservoirs, which now supply 50% of the system’s water. These include the largest storage reservoir in the system, Pepacton (in service date 1954), as well as Cannonsville, Rondout, and Neversink. This expansion brought not only the reservoirs, but also the regulation of the Delaware according to Supreme Court decrees, and the formation of the Delaware River Basin

Commission.

Water systems are often characterized by the concept of “safe yield,” which is calculated to estimate the yield of the system that could be maintained during the drought of record. This has declined substantially for the New York City system in the last half century, as a result of the 1960s drought. Previously, safe yield had been calculated at 1800 mgd; after the 1960s drought, this dropped to 1290 mgd. (It is now at 1323 as a result of the acquisition of the Jamaica Water Company.) And, of course, a new drought of record would affect this further.

The ultimate impact of conservation measures, principally metering and low-flow fixtures, in offsetting demand growth is still unknown, but many observers feel that the effects so far have been significant (for example, New York City Department of Environmental Protection, 1998, 1). The most important of these measures are the Universal Metering Program and the associated move from flat rate pricing to metered per-unit pricing. Under the metering program, all connections in the city will soon be metered; about 23%, mostly industrial and commercial connections were metered prior to the start of the program. Other important conservation programs include the City's low-flow fixtures law and retrofit programs and its aggressive leak detection program.

Looking further into the future, there are a variety of factors that might change total demands on the system in addition to global warming impacts considered below. These include demand growth in existing use areas, the addition of new user communities both upstate and on Long Island, and additional conservation flow demands (to maintain fisheries, for example) by the State. A wide range of planning issues is presented in the reports of the Mayor's Task Force (New York City Mayor's Intergovernmental Task Force on New York City Water Supply Needs, 1986, 1987a,b, 1992). The Southeastern New York Intergovernmental Water Supply Advisory Council, a stakeholder in the present study, is continuing much of this work.

B. Role of climate

Climate is an important determinant of the design and operation of water supply systems; every system is affected by variation in hydrologic conditions, droughts, floods, and temperature (including its impacts on evapotranspiration and demands). Global climate change is now likely, and will be accompanied by temperature increases, changes in precipitation, and a rise in sea levels (Intergovernmental Panel on Climate Change, 1996a,b, c). On the other hand, it is accepted that there are many uncertainties, both at the global and regional levels. At regional scales relevant to the New York City system, for example, current global climate change models cannot forecast rainfall patterns with sufficient accuracy to indicate what will happen to precipitation in the New York City system watersheds. Thus, although there are potential impacts of global warming both on demand and on supply in the New York City system, planning must be a matter of considering what elements of the system might be impacted by global warming, what information will be needed to make decisions, and what the timing of such decisions should be. Urban water supply systems have large infrastructures, substantial customer bases, and long lead times for planning. For these reasons, it is important to evaluate the potential effects of global environmental change.

The climate changes most likely to affect water demand and supply include temperature changes, precipitation changes, and sea level rise impacts. In most cases, both institutional and infrastructure responses will be required. These can be small to substantial (although it should be remembered that with respect to the New York City water system, relatively small changes can be large in absolute terms). The changes may also be both within an individual system, such as the New York City water system, and between systems, as for example possible water exchanges between the New York City system and Long Island groundwater systems. In addition, the different impacts of climate change can interact, which will affect the mix and size of the adaptive measures required.

Temperature Changes. Increases in mean regional temperatures can be expected to affect demands for air-conditioning and recreational demands for water, such as increased releases to maintain fishing habitat. On the supply side, there will be increases in evaporation that will reduce available flows; it is the effect of temperature change on evapotranspiration that is the key relationship between temperature change and water supply.

Precipitation Changes. A principal effect on demands would be for outdoor sprinkling, a substantial water use in areas of one and two family homes. This could fall or rise depending on the direction of precipitation change. A drop in precipitation and runoff would affect average reservoir storage and thus would also affect operating rules: a severe drop in precipitation would be a serious problem in terms of water supply. The frequency of droughts would increase, the safe yield of the system would be substantially reduced, and there could be the need for both institutional changes and new infrastructure investments.

A substantial increase in precipitation would cause local flooding problems, but on the other hand increased flows may help with some ecosystem and recreation problems associated with sea level rise. Modeling results indicate that precipitation changes can be either positive or negative; the spatial and temporal resolution of the models does not permit a more secure forecast within current modeling and computational techniques.

Sea Level Rise. Sea level rise can affect coastal systems such as the New York City water system in several ways. A rising sea will push salt intrusion further up the Hudson (and the Delaware) estuaries. The Hudson River salt front (defined as 100 mg/l chloride) is gauged by the United States Geological Survey. Normally, the salt front ranges between the area from about river mile 35 (Haverstraw Bay, with the southern tip of Manhattan = river mile 0) and upper Newburgh Bay, at about river mile 60, but extreme high freshwater stream flows can push the salt front all the way out of the river and extreme drought conditions can send the salt front above the water intake for the city of Poughkeepsie. In addition, rising sea levels can result in salt-water intrusion into aquifers, such as those on Long Island, resulting in the degradation of water supplies from groundwater. Finally, rising sea levels can be expected to impact ecosystems.

C. Sector stressors other than climate

There are a variety of factors in addition to climate change that might change total future demands on the system. As mentioned, these include demand growth in existing use areas due to population and income growth, the addition of new user communities both upstate and on Long Island, and additional conservation flow demands by the State. In addition, income and population growth also have affects on water quality; this occurs particularly through the development of second homes in watershed areas, and the construction of larger primary residences in the closer-in watershed areas. These effects will continue to be relevant even with demand management measures.

II. Potential Impacts of Climate Change on Sector

A. Research questions

The research questions relevant to this sectoral study are based on the nature of the systems involved, the role of climate, and the possibilities of adaptation. The New York City and adjacent water systems have rarely been studied as related elements of a larger system, except for the joint management inherent in the Delaware Supreme Court decrees. The research questions essentially deal with the examination of the shared ability of these mature infrastructure systems, built for specified purposes and conditions, to be coordinated and dynamically adapted to new conditions of climate change. The questions include:

What are the likely effects in direction and amount of climate change on demand and supply in the region’s systems?

What feasible infrastructure adaptations to climate change can be undertaken to exploit currently unused joint operation opportunities in these interregional systems, taking into account current and future hydrologic and demand conditions?

What feasible institutional adaptations to climate change can be undertaken to exploit currently unused joint operation opportunities in these interregional systems, taking into account current and future hydrologic and demand conditions?

What are the benefits, costs and optimal timing of available adaptations?

A broad long-term research approach along these lines for considering the impacts of climate change on water supply systems and developing an adaptation strategy includes the following elements:

(1) Forecasts and estimates of the effects of climate change on flow, including estimates of extreme events;

(2) Forecasts and estimates of demand on the system, incorporating a range of economic, demographic, and technologic elements;

(3) Combined assessment of the first two, in order to examine the potential range of variation of demand/supply combinations in future years;

(4) Examination of the elements of a system in order to identify those that are likely to be impacted by the above variation; and

(5) Development of a strategy of adaptation, including infrastructure and institutional changes, staged over time, and intended to be cost-effective in coping with the variability of climate change (in addition to natural variability).

This study begins the investigation of many of these questions and elements of strategy.

B. Literature on previous studies on climate change impacts on sector

There has been relatively little work on climate change and the New York City water system. The Mayor’s Task Force noted the need to be aware of climate change impacts on the system a decade ago (Mayor's Intergovernmental Task Force on New York City Water Supply Needs, 1987a, 17), a point taken note of in Schneider (1990), although there has not been as yet an extensive effort to consider these impacts in any systematic way; this project fills a part of this gap. A short review of relevant considerations is in Alpern (1996). On the other hand, the system does have one of the few concrete adaptations to global warming in any large water supply system, an outflow pipe for the Third City Tunnel on Roosevelt Island built higher than originally planned explicitly to take into account the possibility of rising sea levels (Hurwitz, 1987; Schwarz and Dillard, 1990, 348). (The redesign was not total, however; the designers raised the outlet to the extent possible within existing design constraints, rather than redesigning completely.)

There has, on the other hand, been work on the impacts of climate change on the Delaware system, and other work on urban water demands and climate change. A review focusing on the uncertainty of effects in the Delaware Basin is in Lins *et al.*, 1997. Boland (1997) studied the affects of climate on water demands in the Washington, D.C., area, concluding that foreseeable effects could be offset by conservation measures (p. 175).

The most comprehensive recent demand forecasts for the New York City system (Hazen and Sawyer, 1989) showed large increases in demand under some assumptions, using a model based on population and income forecasts, but with substantial reductions forecast from the implementation of potential conservation measures (Figure IIB-1). For 1995, for example, total demand without conservation was projected at 1631.3 mgd, and with assumed additional conservation measures such as metering and plumbing fixture replacement, 1445.0 mgd. For 2015, the same study projected daily demands of 1845.1 mgd without conservation, and 1461.6 with conservation (Hazen and Sawyer, 1989, p. 1-16). Since that study, effective demand management programs have in fact been put into place, offsetting upward demand pressures from population and income (see the assessment in New York City Department of Environmental Protection, 1998). However, for the reasons given above, demands may once again increase.

ESTIMATED EFFECTS OF CONSERVATION MEASURES ON DEMAND IN NEW YORK CITY (MGD)

	NYC Demand - Met By NYC Sources				
	1995*	2005	2015	2025	2035
Projected Demand Without Conservation	1611.3	1739.1	1845.1	1952.6	2061.4
Savings Due to Conservation Measures					
o Reduced Use Due To Initial Conversion Of Flat Rate Accounts	35.0	35.0	35.0	35.0	35.0
o Reduced Use Due To Price Increases	48.5	76.6	104.6	133.4	163.0
o Reduced Use Due To Replacing Plumbing Fixtures	33.6	69.8	106.5	143.6	181.1
o Reduced Use Due To Multi-Family Residential Conservation	23.4	50.2	78.9	109.2	141.0
o Savings Due To Improved Programs Dealing With Leakage, Abandoned Buildings and Vacant Lots	45.8	53.7	58.5	63.4	68.3
Savings Sub-Total	186.3	285.3	383.5	484.6	588.4
Projected Demand With Conservation	1425.0	1453.8	1461.6	1468.0	1473.0

* In 1995, total New York City Demand Without Conservation is projected to be 1631.3 mgd of which 20.0 mgd is assumed to be met by Jamaica Water Supply Company wells. Total projected demand with conservation is 1445.0 mgd.

TABLE IIB-1
SOURCE: HAZEN & SAWYER 1989

C. Data and methods

The aspects of climate change most relevant to water supply planning are temperature increases, changes in precipitation, associated increases in extreme events, and rise in sea levels. These changes may have a wide range of impacts on both the demands for and the supplies of water from the region's systems. The estimates of physical parameters (below) show something of the range of uncertainty involved, as does a consideration of future demands, which could increase or decrease depending on expansion in users of system water, climate change impacts, and the impacts of conservation.

The data used in the study, except for the GCM forecasts (see earlier) and the PDSI forecasts below, was taken from available studies of the New York City and adjacent water systems. It should be noted that these studies, while numerous and helpful, were in general not originally undertaken with a view to examining climate change impacts, and therefore do not provide the full information required for detailed assessment of adaptation alternatives. The procedure therefore has been to identify the main elements of climate change that impact water demand and supply, and to identify likely infrastructure and institutional changes that might be made to adapt to these effects. The analysis is framed by the basic understanding that, at least for water systems and barring (possible) surprises, the effects of climate change can best be seen as an additional source of uncertainty imposed upon the substantial hydrologic and demand uncertainties with which water systems must regularly deal (Stakhiv, 1993).

D. Use of climate change and socioeconomic scenarios

Several future physical parameters of climate, including temperature and precipitation, that can be expected to affect regional water systems were projected for the MEC region While such projections cannot be expected to provide credible estimates for specific locations, the use of a scenario approach with GCM outputs can be used to demonstrate the effects that climate change might bring to the system (Boland, 1997, 171, 174). The GCM scenarios described in an earlier section of the Metro East Coast report were used to consider climate change impacts on water supply with the Palmer Drought Severity Index (PDSI) for the region. The PDSI calculations for the region are done not only for the four GCM run results, but also for a range of sensitivity on the temperature and precipitation parameters; this provides a wider look at the range of possible outcomes than using the GCM outputs alone. It should be noted that the concept of drought in the PDSI is a purely physical concept; by contrast, in speaking of a Drought Management Plan, water supply managers refer to the intersection of physical drought and the use of water in a specified time period.

Palmer Drought Severity Index (PDSI)

The Palmer Drought Severity Index (PDSI) (Palmer, 1965) compares anomalous dry and wet years to normal years; it is used to identify relative droughts and floods at particular places. It uses a simple overall water balance approach. Runoff occurs whenever the soil profile is full, and there is evaporation at the potential rate whenever there is enough water present. Higher temperatures result in increased drought through increases in potential evapotranspiration (PET) and evapotranspiration (ET). Increased precipitation causes increased flooding. Input into the PDSI model is monthly mean temperatures and precipitation (interpolated for the MEC region from GCM results) . In addition, other inputs are the soil water capacities and the Thornthwaite (1948) parameters, which are a function of the mean temperature and latitude. potential evaporation approach is used, together with a simple water balance scheme. The program used for calculations is (Karl, n.d.). Outputs are the monthly PDSI and other climatic variables. The PDSI classes for wet and dry periods are given below:

> 4.00	Extremely wet.
3.00 to 3.99	Very wet.
2.00 to 2.99	Moderately wet.
1.00 to 1.99	Slightly wet.
0.50 to 0.99	Incipient wet spell.
0.49 to -0.49	Near normal.
-0.50 to -0.99	Incipient drought.
-1.00 to -1.99	Mild drought.
-2.00 to -2.99	Moderate drought.
-3.00 to -3.99	Severe drought.
< -4.00	Extreme drought.

It should be noted that this model is particularly sensitive to temperature changes, as the results below indicate. A listing of recent droughts in both the New York City and Delaware River Basin Commission areas is reported by New York City Department of Environmental Protection (1999).

In this work, the Palmer Drought Severity Index was calculated for the Metro East Coast region as a whole, using historic data and an interpolation from GCM outputs. The period of record (1990-1997) and daily data for each of 23 sites used in the study was downloaded from the National Climatic Data Center at:
http//www.ncdc.noaa.gov/ol/climate/research/ushcn/daily.html.
(This page also presents the data inventory and format.) The data set is the United States Historical Climate Network (USHCN) set; more information on the data can be found at: http//www.ncdc.noaa.gov/ol/climate/research/ushcn/ushcn.html. The 23 sites of daily data were combined using all available data; there were somewhat fewer sites available during the beginning yearas of the assessment than in the later years. (For the Palmer analysis the 23-site daily

averages were used to compute monthly means needed by the PDSI program). A discussion of the PDSI can be found in Rind et al., 1990.

E. Results

The results of the study indicate that there are substantial opportunities for adaptation in the New York City and adjacent systems. These adaptations are likely to be valuable both for natural variability in the current climate, and for anthropogenic climate change. There will almost certainly be affects on Metro East Coast water systems of climate change, through precipitation, temperature and its effects on evapotranspiration, and sea level rise, and these changes have to be monitored and appropriate adaptations undertaken over time. Moreover, the water sector interacts with the other sectors of the MEC study, and these interactions must be taken into account in adaptations. Possible adaptations and their locations are identified below.

Palmer Drought Severity Index. The PDSI (Figure IIE-1) generally suggests more droughts in the region; this is because of rising temperatures as well as, in the Canadian Centre model, less precipitation. In the Hadley Centre model, more precipitation modifies this effect, with conditions becoming generally wetter throughout the new century. These results, by emphasizing both variability and uncertainty, suggest that the adaptations described in this work are important elements for study. Drought and flood probabilities for future years are also shown (Figures IIE-2, 3). These indicate the key role of precipitation, the most difficult parameter to forecast at the regional level: depending on the GCM model, both floods and droughts can increase or decrease. Sensitivity results, showing drought and flood probabilities for stepwise changes in temperature and precipitation are shown in Figures IIE 4, 5 and Table IIE-1.

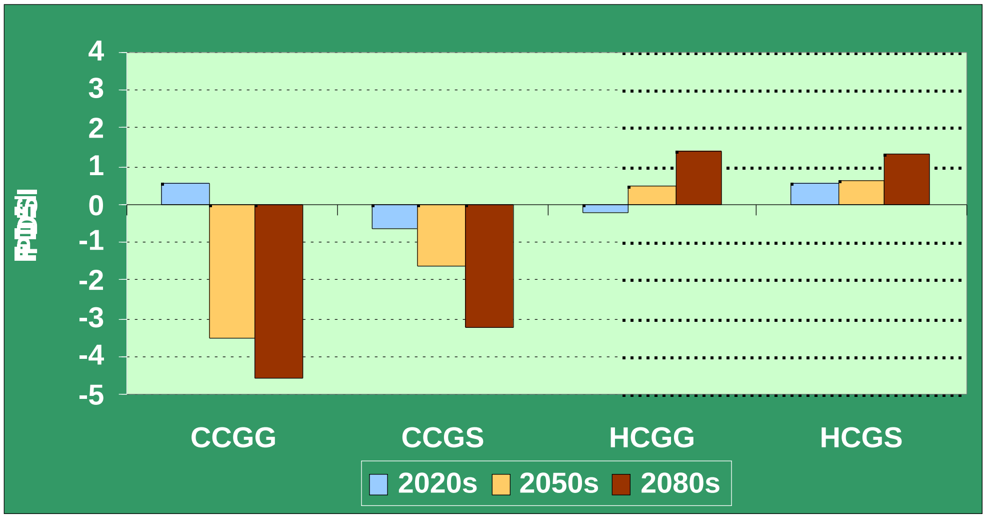

Figure IIE-1: Projected Change in PDSI, Metro East Coast Region

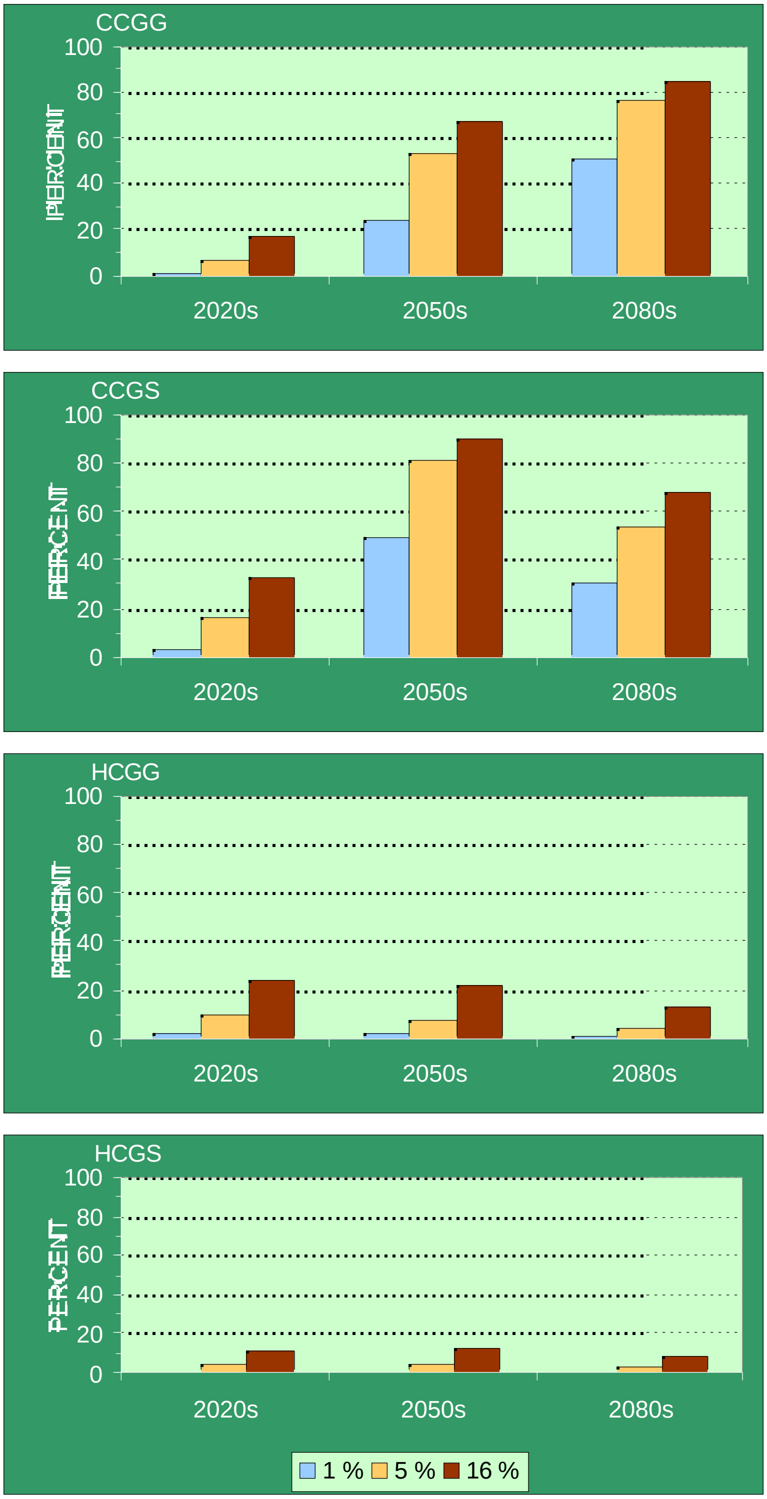

Figure IIE-2: Projected GCM Drought Probabilities, Metro East Coast Region

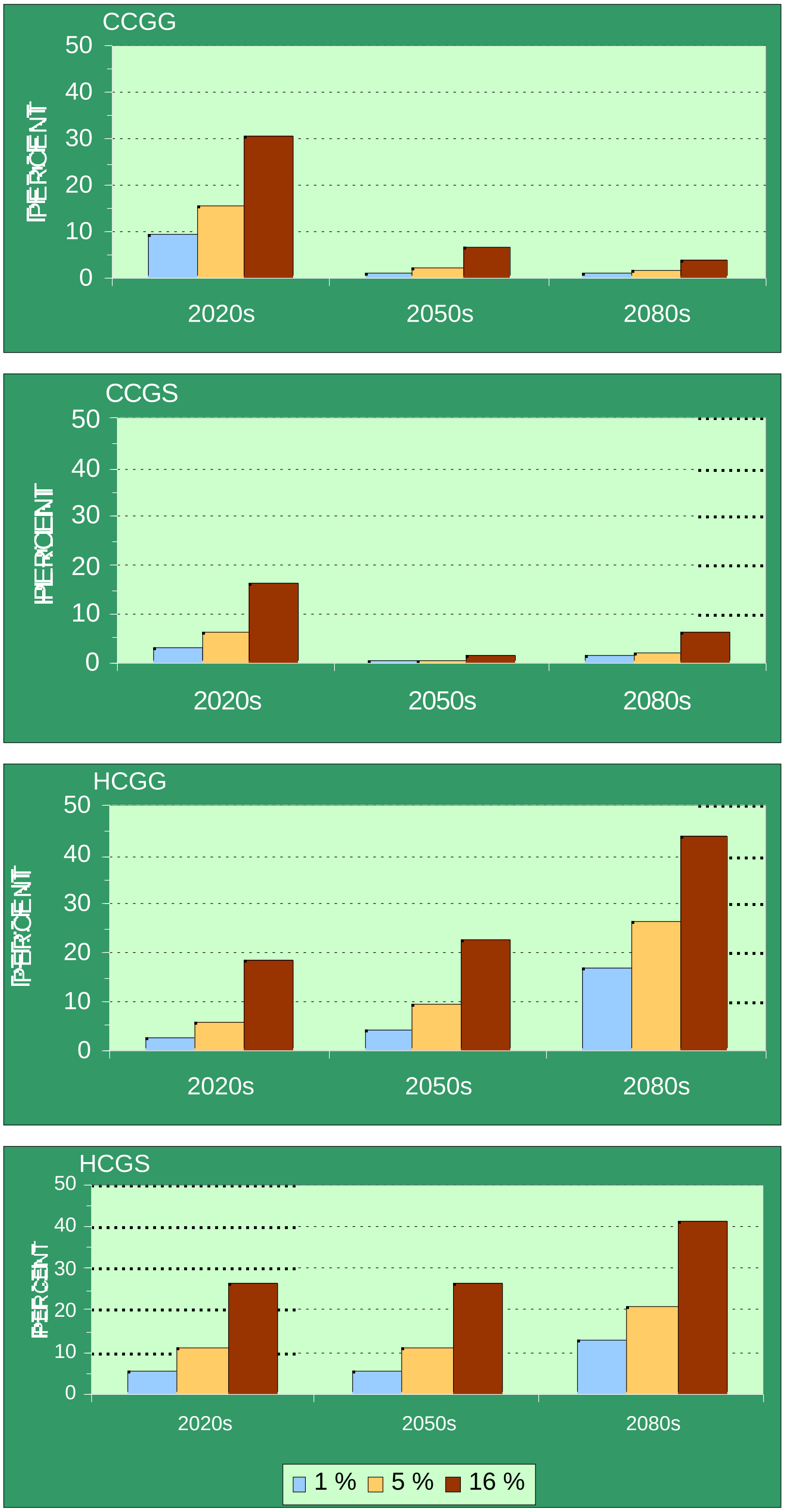

Figure IIE-3: Projected GCM Flood Probabilities, Metro East Coast Region

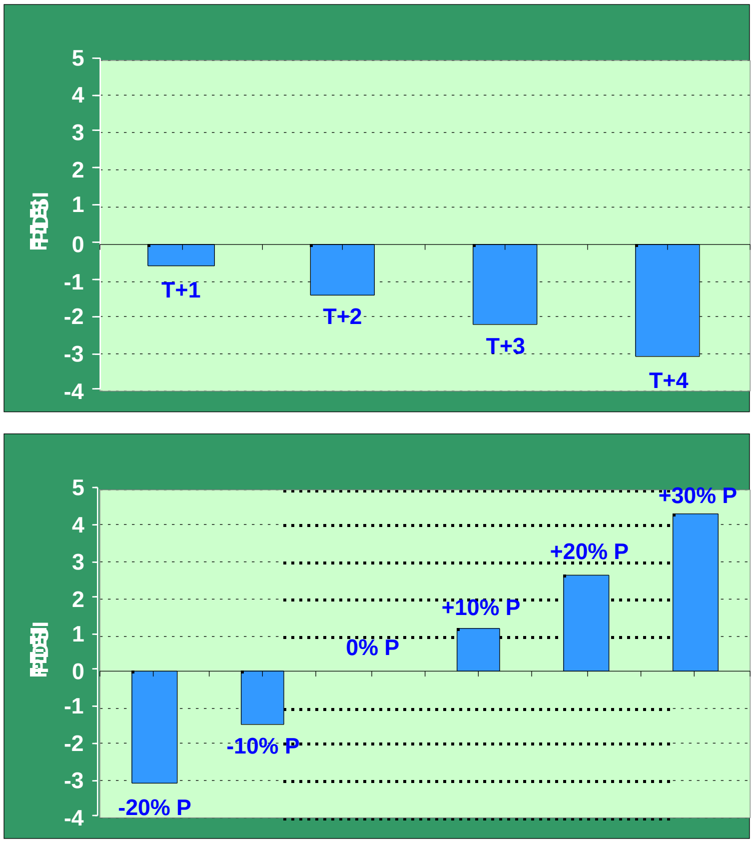

Figure IIE-4: PDSI Sensitivities, Metro East Coast Region

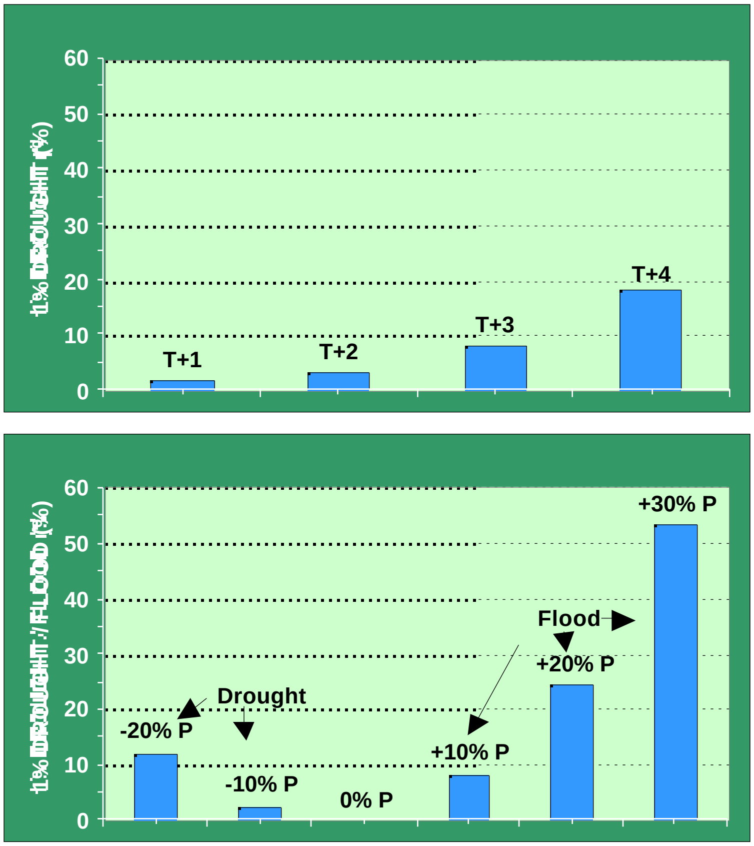

Figure IIE-5: 1% Drought and Flood Probabilities, Metro East Coast Region

Table IIE-1: PDSI Sensitivities and Probabilities, Metro East Coast Region

Clim. Chg.	Mean		Drought			Flood	
(C,%	PDSI	1%	5%	16%	1%	5%	16%
T+1	-.61	1.6	10.5	22.0	.0	.8	10.5
T+2	-1.37	3.3	21.3	41.2	.0	.3	7.5
T+3	-2.19	8.0	36.9	60.8	.0	.0	4.2
T+4	-3.07	18.3	57.6	74.8	.0	.0	1.9
-20% P	-3.09	12.2	62.8	78.6	.0	.0	.0
T+1, -20% P	-3.92	28.5	76.3	88.8	.0	.0	.0
T+2, -20% P	-4.83	51.7	87.3	95.1	.0	.0	.0
T+3, -20% P	-5.72	72.3	93.4	98.6	.0	.0	.0
T+4, -20% P	-6.67	86.5	98.4	99.2	.0	.0	.0
-10% P	-1.43	2.6	21.8	44.2	.0	.0	1.9
T+1, -10% P	-2.21	6.1	36.8	64.9	.0	.0	1.6
T+2, -10% P	-2.99	13.4	57.9	76.4	.0	.0	1.4
T+3, -10% P	-3.85	30.8	74.4	83.0	.0	.0	.0
T+4, -10% P	-4.88	53.4	86.5	92.2	.0	.0	.0
+10% P	1.17	.0	2.5	6.3	8.4	15.9	35.5
T+1, +10% P	.57	.3	3.9	10.0	5.2	11.6	25.7
T+2, +10% P	.02	1.3	8.4	17.7	3.2	5.2	21.8
T+3, +10% P	-.61	2.3	12.0	23.6	.4	3.3	13.6
T+4, +10% P	-1.42	5.2	24.3	42.1	.0	.7	9.1
+20% P	2.65	.0	.3	4.0	24.5	36.5	62.0
T+1, +20% P	2.01	.0	1.5	4.8	16.6	29.0	53.8
T+2, +20% P	1.31	.1	3.5	7.5	12.7	20.5	46.7
T+3, +20% P	.61	.9	5.2	10.1	6.0	14.7	30.6
T+4, +20% P	-.05	1.9	9.3	19.0	4.5	9.4	24.4
+30% P	4.28	.0	.0	.2	53.4	68.2	88.4
T+1, +30% P	3.54	.0	.0	3.1	39.1	56.6	79.1
T+2, +30% P	2.79	.0	1.1	4.4	29.1	43.5	63.5
T+3, +30% P	2.00	.1	3.1	6.2	20.7	29.1	54.6
T+4, +30% P	1.22	.8	4.1	8.5	14.9	24.3	46.2

To check on the regionalization, the PDSI was calculated directly from historical data and the relevant GCM output at three points. The three points are: Mohonk, in the Catskills; Setauket, on Long Island, and Flemington, NJ, which is close to the boundary of the Delaware watershed. The results are shown in Figures IIE 6-8. The results are close in each case, which suggests that the regional calculation is appropriate for policy at this level.

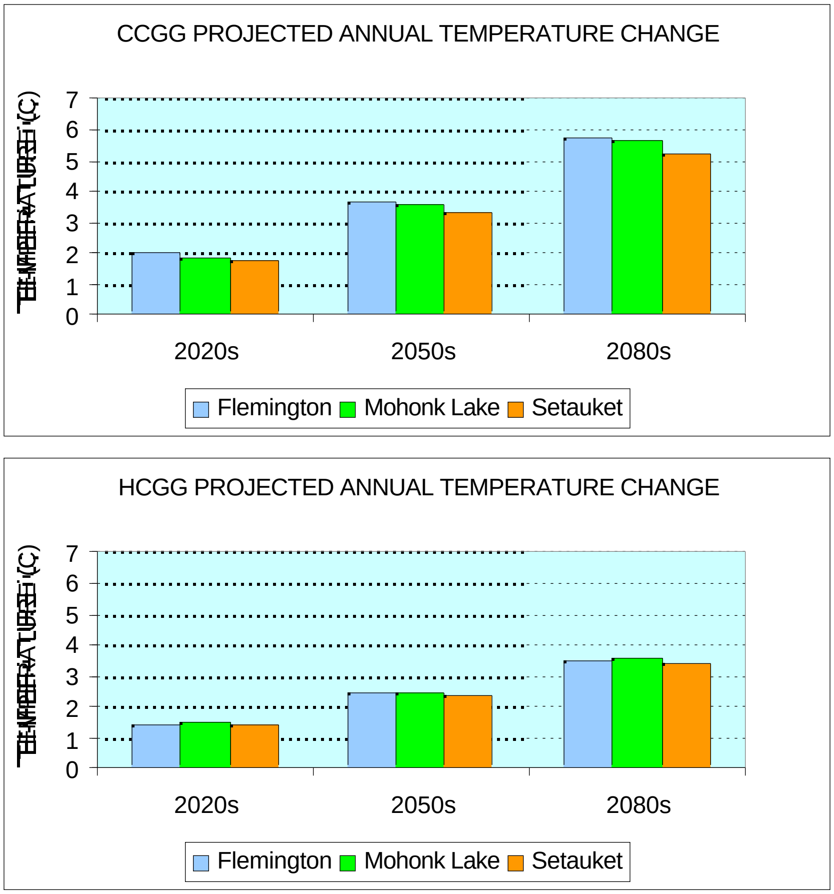

Figure IIE-6: CCGG and HCGG Projected Annual Temperature Change

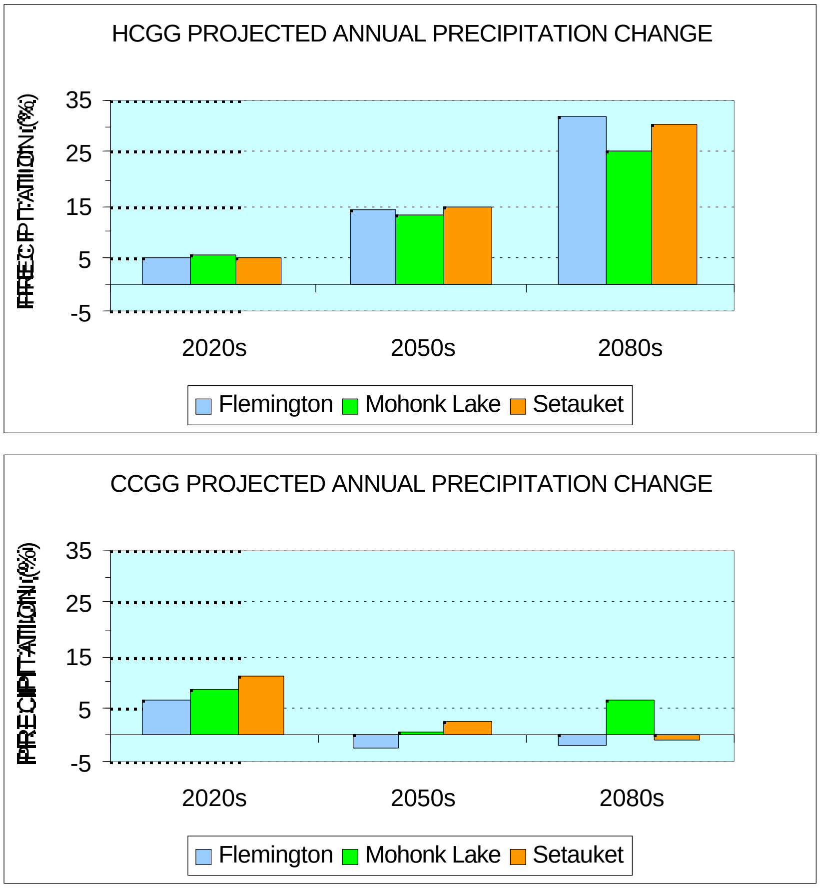

Figure IIE-7: CCGG and HCGG Projected Annual Precipitation Change

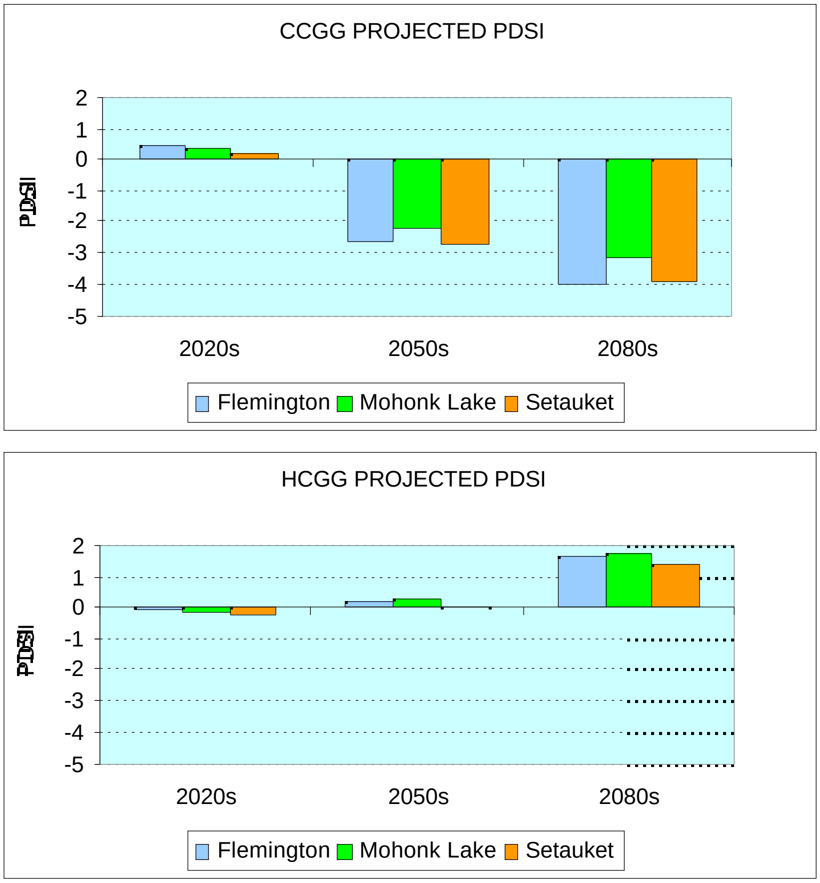

Figure IIE-8: CCGG and HCGG Projected PDSI

Adaptation (General).Adaptation measures for climate change in water resources are discussed in Chapter 14, “Water Resources Management,” of IPCC 1966b; an excellent survey of evaluation methods is in Carter et al., 1994. Major (1998; see also Stakhiv and Schilling, 1998 and Carter *et al.*, 1994) provides a list of adaptive measures in water resources, including:

> Interconnection of systems to provide additional backup for changing regional conditions.
>
> Incremental construction where possible and economically feasible (e.g., a number of small systems rather than one large one) to allow for adaptation to changing circumstances.
>
> Choice of robust designs, in which the chosen design will be fairly good under a wide range of outcomes, rather than optimal under one outcome.
>
> Postponement of irreversible (or very costly to reverse) decisions.

Use of a range of formal decision techniques, including scenario analysis, sensitivity analysis, Monte Carlo methods, and others.

Designing for extreme conditions. Using historical or synthesized flows, the water resource planner can suggest approaches that deal with extreme events (floods and droughts) rather than simply maximizing the expected value of net benefits.

Reallocation of storage. After projects are constructed, and circumstances change, storage can be reallocated to improve project performance under changed climatic conditions. In a dryer climate, for example, storage can be shifted from flood control to water supply.

Reallocation of supply through the development of water markets.

Development of non-structural measures such as warning systems. Flood and storm warning systems (inland and coastal) can be used to adjust to the risks and uncertainties of flooding.

Demand management measures. These measures, such as implementing pricing schemes, requiring low-flow toilets or formulating drought contingency plans, can be used to control demand and thus provide in effect a measure of additional capacity in existing supplies.

Shoreline planning schemes to provide adaptability to rising sea levels.

Physical project changes to account for sea-level changes (e.g. raising outflow levels).

Preservation of ecosystems. As an adjustment to uncertainty, areas can be reserved to protect against the uncertain effects of climate change on ecosystems.

Many of these are relevant to, and some have been used for, the New York City System. The assessment of the suitability of these and other adjustments should be undertaken in the context not only of their benefits with respect to climate change impacts, but also in terms of their effects on general system efficiency.

Adaptation (Specific). In the MEC region's water supply systems, some adaptations to this climate change, both small and large, can be made within individual systems, which makes them simpler in institutional terms. As noted earlier, a well-known instance is the raising of an outlet pipe for City Tunnel #3 at Roosevelt Island in New York City above its original design level, explicitly in response to potential sea level rise.

A larger example of a within-system adaptation that might be undertaken in response to climate change impacts is the possible expansion of New York City's Chelsea pump station on the east bank of the Hudson River south of Poughkeepsie. This is described in more detail in Section IV, below, Integration Across Sectors.

Many adaptations to climate change in the region's water systems relate to new institutional, operational and infrastructure relationships among systems that are now connected, but need to be more closely integrated, and among systems that are not now connected. Some of these changes may be worthwhile from the standpoint of climate change adaptation, and some from the standpoint of climate change and operating efficiency even absent climate change. Something of the geographic range of potential changes can be seen by considering Figure IIE-9, which shows the counties that were part of the Mayor's Task Force; in addition to these, there are also systems in New Jersey, and systems along the Delaware River (see Figure IIE-10).

FIGURE IIE-9 : **Mayor's Intergovernmental Task Force on New York City Water Supply Needs, Counties Participating**

NEW YORK CITY AND DELAWARE BASIN WATER SUPPLY SYSTEMS

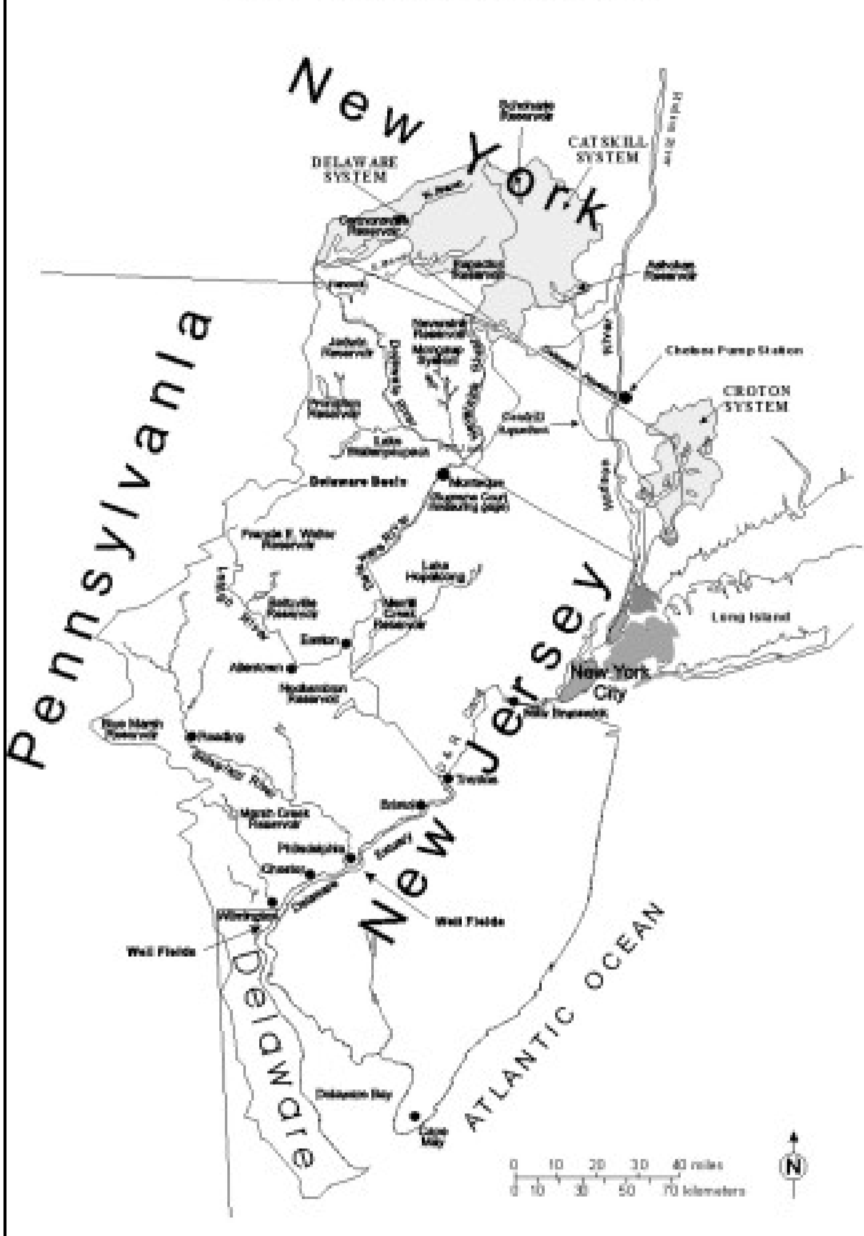

FIGURE IIE-10

Climate change impacts may require a still more integrated operation of the New York City reservoirs on the Delaware and other Delaware Basin systems (Hansler and Major, 1999). To the west of the City, the Delaware River and the New York City system are already linked operationally through a strong institution, the Delaware River Basin Commission (see, for example, Delaware River Basin Commission, 1983). The main surface water systems of interest in the Delaware Basin downstream of the New York City reservoirs include the F. E. Walter

Reservoir in the Lehigh Basin west of the Delaware, operated by the U.S. Army Corps of Engineers; the Merrill Creek Reservoir in New Jersey, operated by a consortium of electric utilities; the Philadelphia intake pipe at Torresdale, which provides an average 200 mgd to Philadelphia; and the intake of the Delaware and Raritan Canal at Bull Island, operated by the New Jersey Water Supply Authority, which draws 100 mgd for areas in central and northern New Jersey.

The ecological systems of the Delaware River and the estuary are directly impacted by releases from the Delaware River reservoirs of the New York City System and other reservoirs in the Delaware Basin. For example, lower basin well fields near Camden, New Jersey and New Castle, Delaware draw water from the Potomac/Raritan/Magothy aquifer, which is sensitive to salinity in the estuary as affected by releases to the river. In addition, recreation and fishing demands in the Delaware can be competitive for reservoir storage with water supply demands, and during drough and not weather, this competition is at its keenest.

Infrastructure changes appropriate to climate change may include the rehabilitation of the Delaware Canal in Pennsylvania, modification of dams, and interconnections among Delaware systems. Institutional implications of such changes may include water banking, reservoir and canal cost-sharing, intake modification cost-sharing, and interconnection cost-sharing.

Also to the west of New York City, other useful links among systems may include water sharing between the New York City system and northern New Jersey. During the 1981 drought, a pipe to transfer 20 mgd was laid across the George Washington Bridge (Delaware River Basin Commission, 1981), and the maintenance of such a link is certainly feasible (Figure IIE-11 (to be added)).

On the eastern side of the New York City System, infrastructure and institutional change may be needed to link the New York City System with Long Island groundwater systems (Figure IIE-11). Given sea level rise and the differing hydro-geologic characteristics of the systems, there may be scope both for a water exchange and for some net water supply to Long Island. If sea level rise results in salt-water intrusion into the Long Island aquifers, a serious problem of water supply would occur, because Nassau and Suffolk counties on Long Island currently depend completely on groundwater supply.

One solution, which would require substantial institutional and infrastructure investments, would be to supply some of the Island’s water through the New York City system. To do this, there will have to be immediate attention to a design issue in City Tunnel #3. City Tunnel #3, when completed, will reach to eastern Queens, and so could be used as a conduit for water destined for Long Island users. The third stage will go from Kensico Reservoir to the interconnecting chamber of Stage 1 just south of Hillview Reservoir, and the fourth stage will go from the northern terminus of Stage 1 directly to Queens. However, as currently planned, the third and fourth stages are designed to meet New York City needs alone. They would have to be reconfigured in terms of physical design and operating rules in order to permit supply to Long Island at some future time. Such infrastructure changes will have to be accompanied by the development of institutional relationships that are still embryonic.

To the north of the City system, operational integration of several reservoirs in the Adirondacks in the case of extreme droughts might be contemplated, although the location of these reservoirs in the Adirondack Park, protected as wilderness in the New York State Constitution, would doubtless make integration institutionally complex.

Institutional changes have been significant in the development of the New York City water supply system. Perhaps the most notable example since World War II is the creation of the Delaware River Basin Commission. More recently, the intergovernmental group formed as a result of the work of the New York City Mayor's Intergovernmental Task Force on New York City Water Supply, the Southeastern New York Intergovernmental Water Supply Advisory Council has played a useful role in maintaining relationships, fostering cooperation, and studying key problems. In the United States as a whole, important new developments in water institutions include the increasing use of markets and privatization. These methods have not been as common in the relatively water-rich east as in the west, but they may become more common as climate change and demand pressures increase uncertainty. With respect to markets, for example, the Metropolitan Water District of Southern California (MWD) has announced its willingness to buy additional supplies of water on the free market; the MWD already operates water banks with groundwater operations in Kern County and Ventura County, California (Metropolitan Water District of Southern California, 1999). The Delaware River Basin Commission has undertaken one example of this type of institutional innovation, purchasing water supply storage in the U.S. Army Corps of Engineer’s F.E. Walter flood control reservoir in the Lehigh Valley. There has been some privatization of pubic water supply operations (although not generally of ownership) in the MEC area, for example the operation of the Jersey City system by the United Water Company. These types of institutional changes, while not directly related to climate change, can be expected to increase institutional flexibility in adapting to climate change in the future.

Many adaptations can be made that do not require great detail for planning purposes. However this is not true for every change in the system, especially for some operating system changes. An example of the complexity of detailed operational changes from climate change is provided by fish habitat maintenance in the Esopus. (See Rosenzweig et al., 1999, water sector pp. 10-11.) Esopus Creek, which is the water link between the Schoharie and the Ashokan Reservoirs via the Shandaken tunnel, is a multi-purpose stream. It is used, among other purposes, for float tubing (which may be quite important as measured by user-days/years), kayaking and canoeing. However, one of the most important of the Creek’s uses is for trout fishing; it is a celebrated Northeastern trout fishery. It supports the natural reproduction and growth of rainbow trout (*Salmo gairdenerii*); brown trout (*Salmo trutta*); and brook trout (*Salvelinius fontinalis*), the breeding populations of which may occur principally in small tributaries.

The greatest dangers to the trout are low levels of dissolved oxygen; slow stream velocity; low depth of flow; high water temperature; and high levels of turbidity. The spawning and growth of trout eggs are enhanced by the proper bed load and material. In fact, the female trout often uses the bed material to cover and protect her eggs. However, if the stream flow and stream-depth are low, fine sediments build up and settle in the stream bed. This condition inhibits the supply of dissolved oxygen from the atmosphere to the developing embryos and is exacerbated if turbidity levels in the stream are high. The net result is the formation of anoxic conditions that suffocate the embryos.

If the Esopus Creek's stream flow and stream depth are reduced in a warmer climate with low precipitation, additional water would have to be supplied to the Ashokan reservoir through the Shandaken tunnel to support the trout fishery. However, since the turbidity levels increase when flow enters it from the tunnel, the trout fishery of the Esopus Creek may be jeopardized. This scenario illustrates the complexity of adaptations to climate change at the operational level, and of the need for detailed studies of operating rules in such cases.

III. Interpretation – Challenges and Opportunities

The challenge of adaptation in the New York City Water Supply System and adjacent systems is to undertake the preparatory work for the required institutional and infrastructure changes.   This should be begun and completed within the next decade, in order to stay ahead of possible climate impacts. The work should include more detailed studies of adaptation opportunities, assessment of benefits and costs, and optimal scheduling. All of this should be done to the level at which agencies can undertake detailed implementation studies as required. Further, periodic monitoring and analysis of possible climate-related changes in precipitation, temperature, and sea level rise should be undertaken by the agencies.

IV. Integration across Sectors

The water sector relates to many of the other impact sectors, including health, institutions, and sea level rise.   In particular, it relates to sea level intrusion, both through effects wetlands (for a survey of wetlands in the New York City watersheds, see Tiner, 1997), aquifers, and water intakes located on rivers. An example of the last is the Chelsea Pumping Station. The pumping station is located on the east bank of the Hudson at Chelsea, south of Poughkeepsie, and has a present capacity of 100 mgd. The pump station is located just to the east of the railway tracks on the east side of the Hudson. River water is taken via an intake into the pump station, and after treatment is forced into the nearby Shaft 6 of the Delaware Aqueduct, where it mixes with water from the Delaware system. Studies have been made to increase its capacity, and further studies of the Hudson River system are underway for New York City, also by Malcolm Pirnie. Detailed diagrams of the current station and possible expansion options are provided in (Malcolm Pirnie, 1986). Increased sea level rise, bringing increased salinity, could affect the operation of the station. This would exacerbate a fundamental conflict, which is that the station is needed most in drought, which is precisely the time when the salt front moves upstream. Adaptations to this could include moving the intake upstream and changing the seasonal use of the station. For this purpose, careful assessments would have to be done of sea level rise and the salinity front. Here, regular monitoring from this point forward should be undertaken.

A study of the Chelsea Pump Station system (Malcolm Pirnie, 1986) indicated that an additional 100 mgd of withdrawal would cost $28 million, and an additional 200 mgd of withdrawal would cost $86 million; the corresponding costs with filtration would be $223.5 million and $327.9 million. These costs, when updated by the ENR 20-city construction cost index from the 1986 average to the 1998 construction cost average would amount to $38.6, $118.7, $308.4, and $452.5 million respectively. Increased withdrawals would also affect the salt front (and thus potentially the Poughkeepsie water supply intake), especially in conditions of climate change and sea level rise. Changes in the pump station intake and seasonal operating rules might be required as a result. The updated costs given here are thus simply illustrative; the actual costs would take into account impacts of climate change and other factors relating to an ongoing New York City study of the Hudson River.

V. Information and Research Needs

Research needs include detailed assessments of the adaptation possibilities that have been identified, with engineering, economic and environmental details relevant to assessing the benefits and costs of adaptations and their optimal scheduling over time. In examining the ability of these mature water supply infrastructure systems to be dynamically adapted to new conditions of climate change, the first step is a comprehensive identification of infrastructure and institutional adaptations that are available both within each system and between and among systems. Many of the most promising adaptations become feasible if the New York City and Delaware River Basin water supply systems, as well as some additional neighboring systems such as those on Long Island, are jointly operated in a more completely integrated way. Potential adaptations include water banking, drought and other joint operating system revisions, physical system interconnections and emergency pumping. The effectiveness of potential adaptations to climate change should be comparatively evaluated with current hydrologic and demand conditions and a range of future scenarios based on GCM results and demand forecasts. The costs of adaptations and appropriate timing for them should be evaluated and the potential overall success of system adaptation to climate change assessed. A new and revised forecasting study for the New York City system that takes climate change into account would be helpful. The research needs summarized here should provide early, vitally needed and well-founded results and recommendations.

VI. Policy Recommendations

The water supply system of New York City, and those of neighboring areas, face new sources of uncertainty from climate change, especially as it is manifested through temperature, precipitation, and sea level changes. Because of the uncertainty associated with climate change itself and the level of its manifestations, as well as the dearth of detailed studies of the relationships of these changes to specific demands and supply sources, it is difficult at this stage to make effective forecasts. However, what is known is that there are substantial opportunities for increasing the resilience of the area's water supply systems, and these should be carefully examined and related to increasingly good forecasts of climate change effects. A useful next step would be for SENYIWSAC to undertake a committee study of possible adaptations, at first with the existing membership, and then in conjunction with experts from the Delaware Basin and New Jersey. (Beyond that, it may be appropriate for the National Academy of Sciences to undertake a study of adaptation to climate change for these key urban water systems.) The discussions should cover the information and research needs, and the challenges and opportunities described in this report. The principal elements for examination should include:

The likely effects in direction and amount of climate change on each element of demand and supply in the region's systems.

Feasible infrastructure adaptations to climate change that can be undertaken to exploit currently unused joint operation opportunities in these interregional systems, taking into account current and future hydrologic and demand conditions.

Feasible institutional adaptations to climate change that can be undertaken to exploit currently unused joint operation opportunities in these interregional systems, taking into account current and future hydrologic and demand conditions?

The benefits, costs and optimal timing of each available adaptation.

Development of a strategy of adaptation, including infrastructure and institutional changes, staged over time, and intended to be cost-effective in coping with the variability of climate change (in addition to natural variability).

Barring very substantial surprises, the region's water supply systems should be able to cope with climate uncertainty over the very near term, but an effective planning process needs to be put in place soon in order to consider the adaptations that may be required in the future, especially because the implementation of institutional and infrastructure measures is likely to require long-term institutional commitments. The long time scales and planning horizons, engineering and environmental challenges and political complexity of these issues argue strongly for moving ahead now with planning.

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