Water Resources Management
in the Potomac River Basin
under Climate Uncertainty

by

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1.0 BACKGROUND

There has been considerable national and international interest in the likely effects of potential climate change as a consequence of global warming due to increasing greenhouse gas emissions. There are numerous and substantial uncertainties associated with this anticipated phenomenon, creating difficulties in simply establishing a credible range of likely physical effects (e.g., temperature, precipitation) and natural systemic responses (e.g., watershed runoff, ecosystem adaptation). More difficult still, is the forecasting of socioeconomic impacts and the efficacy (reliability, cost-effectiveness) of alternative response strategies that would be designed to avoid, ameliorate, or adapt to the potential changes.

During the past twenty years, the Interstate Commission on the Potomac River Basin (ICPRB) has extensively investigated the demands for municipal water supply in the Washington Metropolitan Area (WMA) and the operation of available raw water resources to meet those demands. For the past fifteen years, ICPRB has been responsible for predicting municipal water demands and allocating raw water resources among the major water supply utilities which supply the WMA. With this background of information and activity, ICPRB conducted the present study and produced this report. Professor John J. Boland, of the Johns Hopkins University has extensive academic and professional experience in the field of water demand forecasting. He was responsible for producing the work described in the sections discussing Climate Scenarios and Water Use Forecasts.

2.0 OBJECTIVES

This study was specifically developed to: (a) investigate the concurrent impact of potential future climate change on the management of water resources and on water demands in the WMA, and (b) compare the performance of the WMA water resources system "with" potentially changed climate to system performance under the assumption of continued average historical conditions ("without" change), for insight into the range of relative impacts determined.

3.0 APPROACH

The general approach of this study is to apply a range of changes in temperature and precipitation, resulting from documented potential future climate scenarios, to forecasts of water demand and the availability of water supply reservoir and river resources so that resulting impacts to planning and management may be assessed. In particular, the approach consists of the following elements:

3.1 Climate Change Scenarios

A selection of climate change scenarios is chosen to represent the range of potential future meteorologic conditions. One of the scenarios (historical) assumes no change in climate, and for the others, the climate change information is derived from the output of five General Circulation Models (GCMs): Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute for Space Studies (GISS-A) and (GISS-B), United Kingdom Meteorological Office (UKMO), and Max Planck Institute (MPI). All of the GCM results used in this study are from transient model runs (assuming a gradual increase in the atmospheric concentration of CO_2). Except for the GISS-B scenario, climate changes for the period 1990 to 2030 are represented by the differences between first and second decade results of the GCMs. In order to obtain a global cooling scenario, GISS-B results for the first decade (1990 to 2000) were used. The resulting GCM output data are in the form of modified average monthly temperature and precipitation values interpolated to two points in the Potomac River Basin which are representative of water demand and water resource locations. These two points are referred to as the "Basin" and "WMA" centroids throughout the study.

3.2 Water Use Forecasts

Water use is forecast to the year 2030 for the counties and independent cities served by the major water supply utilities in the WMA. The forecasts are developed using the IWR MAIN model for winter water use; summer water use is predicted separately for each of the climate scenarios based on the estimated sensitivity of water use to changes in moisture deficit. In total, three levels of water use are produced for each climate scenario. Each level of water use reflects different assumptions regarding water conservation policies and water price. These results provide insight into the potential impact of future demand management initiatives. The forecasts developed for the climate change study presented in this report differ from those presented in Mullusky, et al. (1995), which are accepted by the larger utilities in the WMA.

3.3 Water Resource Scenarios

The effects of potential climate change on water resources were produced by the development and application of watershed based water balance models from the work of Thornthwaite and Mather. The models were developed and calibrated on average monthly values from 52 years of historical data. With the temperature and precipitation results from the climate scenarios, they were used to calculate river flow for the water supply operations index gage on the Potomac River and reservoir inflow to refill the four water supply reservoirs available to the WMA.

3.4 Water Management Operations

Two water resource management models were utilized for this study. The first was a direct adaptation of the current WMA water resource daily operating rules to a monthly time step. This model proved unable to adequately represent realistic operation of the resource system. A second model was applied to "seasonal" and monthly time steps. It produced results which are consistent with the scale of the modeled water use forecasts and water resource scenarios.

3.5 Management Implications

The results of the water resources management operations element of the study, including the results of prior elements, provide a basis on which to make inferences regarding the effects of potential climate change. These include an examination of the system objective -- satisfying water supply demands with out incurring water supply source deficits -- through comparisons of "with" and "without" climate change for the year 2030. The performance measure of the system objective is the degree to which the existing water supply source system could or could not meet future demands with and without climate change. System performance was examined under a range of water conservation policies to mitigate estimated future water supply source deficits.

4.0 FINDINGS

The principal findings of the study are presented in the order that the major elements of the study were conducted.

4.1 Climate Scenarios

The GISS-A, GFDL, MPI, and UKMO climate change scenarios predict decreased soil moisture relative to average historical conditions, due to either higher summer temperatures, reduced precipitation, or both. The GISS-B scenario predicts increased soil moisture, due entirely to cooler summer temperatures which result from assumptions of increased volcano activity. The largest decrease in soil moisture is associated with the UKMO climate scenario, averaging 3-6 cm (1.14-2.28 in) higher than the corresponding historical climate assumptions.

The resulting temperatures from the climate scenarios maintain consistent relative positions at both representative locations in the basin (the 'Basin' and 'WMA' centroids). As expected, the temperatures are slightly higher at the WMA centroid. The highest summer temperatures were produced by the UKMO and MPI scenarios. Also, the highest winter temperatures at both centroids were produced by the UKMO and MPI scenarios.

The relative precipitation among the climate scenarios is also consistent at both centroids. The GISS-B and UKMO scenarios produced the highest summer precipitation, while the GFDL and GISS-A scenarios show the lowest early and late summer precipitation, respectively.

4.2 Water Use Impacts

Water use for the year 2030 was forecast at three levels of conservation for average historical climate conditions and each of the climate change scenarios. For Conservation Policy 1 (year 1990 prevailing measures), summer water use in the year 2030 increases by 100 percent under continued historical climate conditions. Under climate change scenarios, the water use increases range from between 74 percent for the GISS-B scenario to 138 percent for the UKMO scenario over year 1990 values. The order of intermediate increases is, from smallest to largest: historical, GISS-A, GFDL, and MPI scenarios. With regard to climate change impacts only, the range of variation in forecasts for the year 2030 summer water use is -13 percent to +19 percent, when compared to the calculated increase in water use under historical climate.

For Conservation Policy 2 (as Policy 1 plus public education, recycling, and advanced plumbing code), summer water use in the year 2030 increases by amounts less than those for Policy 1. Water use increases from between 40 percent and 92 percent over year 1990 values. The order of smallest to largest increase among scenarios and the range of variation in forecasts for the year 2030 summer water use are essentially the same as for Policy 1.

For Conservation Policy 3 (as for Policy 2 plus 50 percent increase in water charges), summer water use in the year 2030 is calculated to increase by amounts less than those for Policy 1 and Policy 2. Water use increases from between 27 percent and 74 percent over year 1990 values. The relative positions among the scenarios are essentially the same as for Policy 1 and Policy 2.

4.3 Water Resource Impacts

The greatest reduction of critical "season" (June through October) inflow to reservoirs for the WMA centroid (Occoquan, Patuxent, and Little Seneca) is -32 percent, relative to stationary climate, with the GISS-A scenario at each site. In decreasing order of magnitude, the other scenarios producing reductions in flow are: GFDL, UKMO, and MPI. Increased inflow of between +14.6 percent to +21.6 percent to those reservoirs is produced only by the GISS-B scenario.

The GISS-A climate scenario also produces the greatest reduction in flow at the basin centroid sites (Jennings Randolph Lake and the Potomac River at Point of Rocks), of -1 percent and -49 percent, respectively. In decreasing order of magnitude, the other scenarios producing reductions in flow are: GFDL and MPI. However, both the GISS-B and UKMO produce increases in flow, relative to stationary climate, at the basin centroid sites.

4.4 Water Management Operational Impacts

Water management operations are examined for a critical "season" defined as beginning one month prior (June) to the typically highest demands and ending one month after (October) the typically lowest flows. Beginning with June 1st is also consistent with the current policy of having the reservoirs at least 90 percent full on that date.

The water resource system of reservoirs and natural flow of the Potomac River is utilized more fully under climate change conditions affecting both demand and resource availability, in the year 2030, for the GISS-A, GFDL, and MPI scenarios, than for the historical climate scenario. Conversely, the GISS-B and UKMO scenarios require less utilization of the resources than for a continuation of historical conditions. Of the scenarios which more fully use the system, the GISS-A and GFDL scenarios result in water supply deficits during some months of the critical operating "season," even with full utilization of all sources available for water supply. The GFDL based scenario shows a deficit of 0.24 mcm/d (64.29 mgd) for the month of September, resulting in a cumulative deficit of 7.42 mcm (1,960.98 mg). The GISS-A based scenario shows a deficit of 0.63 mcm/d (165.27 mgd) for the months of July through September, resulting in a cumulative deficit of 76.00 mcm (20,080.50 mg).

5.0 CONCLUSIONS

1) Forecasts from the selected climate change scenarios (GFDL, GISS-A, GISS-B, UKMO, and MPI) produce a range of climate conditions which bracket current (normal 1960- 1990, i.e. historical) conditions. These results are shown in the resulting values for soil moisture deficit, temperature and precipitation, and are specified for two representative centroids of reservoirs and demands in the Potomac River basin.

2) Forecasts of water use to the year 2030, conducted under the selected climate change scenarios, also produce a range of results around forecasts conducted under historical climate. The WMA could experience growth in water use of between 74 percent and 138 percent greater than 1990 values, relying only on conservation measures in place for that year. The maximum increase in summer water use would be +19 percent above that forecast for historical climate conditions.

3) Under an aggressive conservation plan with price increases (Policy 3), demand in year 2030 could grow to between 27 percent and 74 percent above 1990 values. The maximum increase in summer water use would again be +19 percent above that forecast for historical climate conditions with aggressive conservation.

4) Potential water resource performance conducted under the selected climate change scenarios produces a range of results around the performance produced under historical climate. Among the reservoirs, the refill for the critical operating "season" varies from between -32 percent to +21.6 percent of that calculated for historical climate. The range of flow of the Potomac River at Point of Rocks varies from between -49 percent to +33 percent for the climate change scenarios, when compared with historical climate.

5) When managing resources to meet demands under the selected climate change scenarios, deficits are encountered in year 2030 for two scenarios. One being four percent of demand for one month, and the other running for four months with a maximum deficit of 23 percent of demand for the worst month.

6) Policy Implications

- Both water demands and the performance of presently available water supply resources would be impacted by changes in climate.

- Water demands and water supply resource performance move in opposite directions under the influence of climate change, confounding the ability of resources to meet demands.

- Under all potential climate change scenarios examined, conservation (demand management) is a potential means to reduce water use and thus contribute to the mitigation of future water supply deficits.

- Under the selected range of potential climate change scenarios, water resources managers need to be aware that resources may be more (or less) fully utilized than under a continuation of historical climate conditions.

- Under most climate scenarios examined, presently available water supply resources could satisfy water demands forecast (for this study) to occur in the year 2030.

- For those few climate change scenarios under which presently available water supply resources could not satisfy demands, the supply-demand imbalance could be made up entirely by increased conservation in water use.

- At this time, water management decisions should involve consideration of whether or not to plan for the mitigation of the most severe climate change impacts determined in this study.

- If the decision is made now to plan for the mitigation of climate change impacts, the choices of effective measures would include: the imposition of increased conservation measures, construction of new water supply resources, or a combination of the two.

Metric/U.S. Units Equivalences

U.S.		Metric
1 cfs	=	0.028 cms
1 mgd	=	0.044 cms
1 mgd	=	0.00379 mcm/d
1 mg	=	0.00379 mcm
1 bg	=	3.79 mcm
1 in	=	2.54 cm
1 ^{0}F	=	1.8 ^{0}C + 32

Metric		U.S.
1 cms	=	35.3 cfs
1 cms	=	22.8 mgd
1 mcm/d	=	264.2 mgd
1 mcm	=	264.2 mg
1 mcm	=	0.264 bg
1 cm	=	0.39 in
1 ^{0}C	=	(^{0}F - 32)/1.8

U.S.		U.S.
1 cfs	=	0.65 mgd
1 mgd	=	1.55 cfs
1 mg	=	0.001 bg
1 bg	=	1,000 mg

cfs	cubic feet per second
mgd	million gallons per day
mg	million gallons
bg	billion gallons
^{0}F	degrees Fahrenheit
cms	cubic meters per second
cm	centimeter
in	inch
^{0}C	degrees Centigrade
mcm/d	million cubic meters per day

1: INTRODUCTION

There has been considerable national and international interest in the likely effects of potential climate change as a consequence of global warming due to increasing greenhouse gas emissions. There are numerous and substantial uncertainties associated with this anticipated phenomenon, creating difficulties in simply establishing a credible range of likely physical effects (e.g., temperature, precipitation) and natural systemic responses (e.g., watershed runoff, ecosystem adaptation). More difficult still is the forecasting of socioeconomic impacts and the efficacy (reliability, cost-effectiveness) of alternative response strategies that would be designed to avoid, ameliorate, or adapt to the potential changes.

Water resources related impacts (availability, use, and management) are among the most important potential consequences of climate change. Other water-related impacts include sea level rise and increased marginalization of irrigation in semi-arid regions. The UN Intergovernmental Panel on Climate Change (Carter, et al. 1992) states that the objective of climate change assessment is to provide policy makers with estimates of the effects on human activities. "The role of assessments is to assist in the development of alternative strategies for managing human activities under changeable climate conditions."

1.1 Objective

This study was specifically developed to investigate the concurrent impact of potential future climate change on water demands and the management of water resources to meet those demands for the Washington Metropolitan Area (WMA). The assessment of potential climate change impacts was accomplished by comparing the results of the analysis "with" climate change and the results "without" climate change. Also, the relative impacts among the climate change scenarios were assessed.

1.2 Approach

The study was conducted in five elements as stated and presented in Figure 1.1 below.

1. Choose representative General Circulation Models (GCMs) and determine appropriate future temperature and precipitation scenarios.

2. Develop water use forecasts based on population increase and the selected future climate scenarios.

3. Determine hydrologic impacts on the water supply sources for the Washington Metropolitan Area (WMA).

4. Analyze the WMA system performance with future climate scenarios simultaneously affecting future water use and water supply source hydrology.

5. Determine implications of potential climate change on the present and future management of WMA water supply sources.

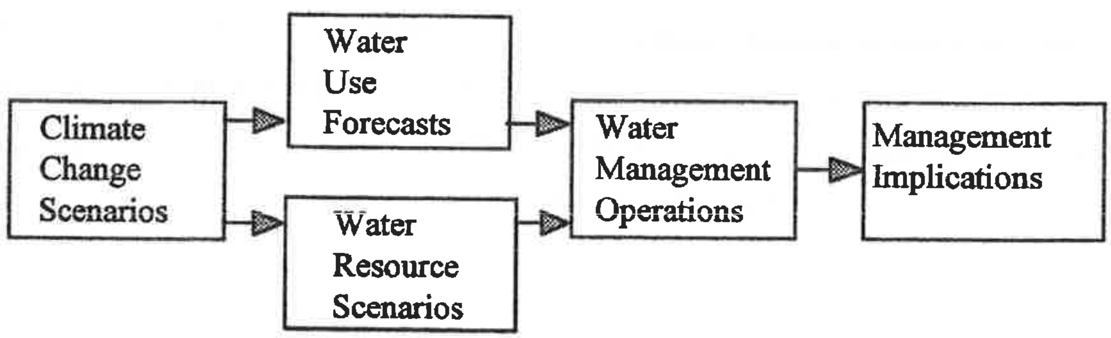


Figure 1.1 Major elements of the study

The study began with the development of temperature and precipitation data for six climate scenarios--one based on historical weather data and five developed from climate change models. Water demand forecasts and water resource responses were developed for each scenario. The resulting demands and resources were combined in water management operations in order to assess their the concurrent impact on system response. These impacts led to the inference of potential changes to water management policy, now and/or in the future for the WMA. The differences between management "with" and "without" climate change would form the basis for evaluating cost-effective changes in management strategies (Stakhiv, 1993).

1.3 Components of the Study

1.3.1 Climate Change Scenarios

This study considers a number of climate change scenarios and their effects on water demands and resources in order to demonstrate the potential range of uncertainty of future climate on the management of those water resources for the WMA. The climate scenarios were chosen to represent the range of potential future outcomes. One of the scenarios (historical) is based on mean climate for the period 1960 to 1990, assumed to continue through the study horizon (year 2030); for the others, the climate change information was derived from the output of five transient General Circulation Models (GCMs). These scenarios provide the basis for a comparative assessment of water resources management under both "with" and "without" climate change conditions as well as a comparison of climate change information derived from some of the more recent models and modeling assumptions. The climate data used in this study are in the form of modified average monthly temperature and precipitation values at two points (centroids) in the Potomac River basin which are representative of water demand and water resource locations.

1.3.2 Water Use Forecasts

Water use was forecast to the year 2030 for the counties and independent cities served by the major water supply utilities in the Washington, D.C. Metropolitan Area (WMA). The forecasts were developed using the IWR MAIN model for a continuation of historical climate conditions and using the meteorological data developed under each of the selected climate change scenarios. Three forecasts were produced on assumptions of three levels of water conservation measures, in order to provide a range of potential demand management effectiveness. It should be noted that the forecasts produced for the climate change study presented in this report differ from those presented in Mullusky, et al. (1995), which are accepted by the larger utilities in the WMA.

1.3.3 Water Resource Scenarios

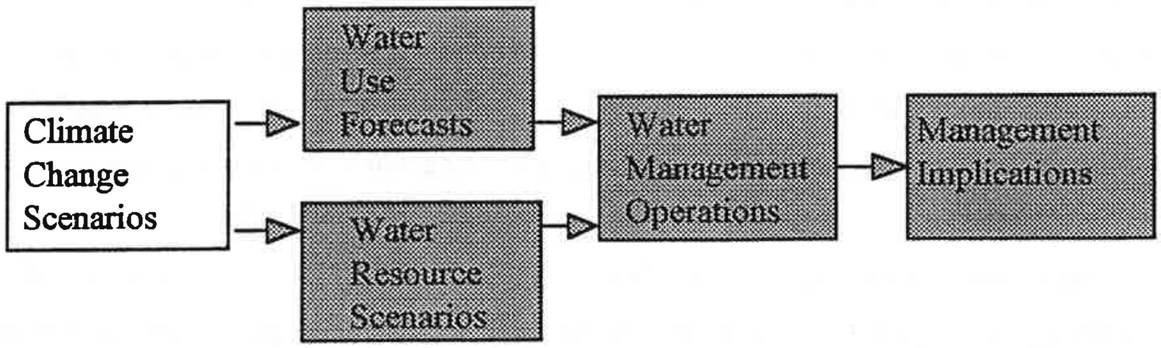
The effects of potential climate change on the water resources for the WMA were produced by the development and application of water balance models based on the work of Thornthwaite and Mather (1955). The models were developed and calibrated on average values derived from more than fifty years of historical data. They convert the climate change scenario temperature and precipitation data to a monthly time series of river flow and reservoir inflow for each of the water supply sources of the WMA, for each of the climate scenarios.

1.3.4 Water Management Operations

A water management operations model based on the current WMA water resources daily operating rules, adapted to operating on a monthly time step, was unable to represent the operation of the system — especially under drought conditions. Therefore second model, based on broad current operating policies applied to "seasonal" and monthly time steps, produces results which are consistent with the scale of the prior water use forecasts and water resource scenarios.

1.3.5 Potential Effects of Climate Uncertainty

The operation of water resources for the WMA was examined under the system objective of being able to supply all demands for water without reducing reservoir storage below 40 percent of capacity. The principle measure of performance of the system is the degree to which those resource constraints are violated with water demands forecast for the year 2030, under each of the selected climate scenarios and water conservation policies. Based on the resultsof the performance analysis, the need and timing for changes in water resource capacity augmentation and demand management can be determined.



2: CLIMATE SCENARIOS

2.1 Introduction

It seems clear that future climate will be different from present conditions. Climate has changed in the past, and can be expected to change in the future. The question is not whether climate will change, but in what direction, how much, and how rapidly. With respect to these latter queries, there are varying degrees of uncertainty.

It is now widely accepted that certain human activities, primarily the combustion of fossil fuels since the start of the Industrial Revolution, will cause a net warming of the earth, over and above what would have occurred in the absence of human intervention. Based on predictions of general circulation models (GCMs), most climatologists believe that this warming will be very rapid by comparison to other periods of warming in the history of human life. If this is true, we can expect significant demographic and economic dislocations over the next 100 years. Among these is the possibility of more severe water shortages in urban areas as a consequence of warmer, drier summers.

On the other hand, it is not clear that climate change will necessarily occur in this way. For any specific location, average summer precipitation may increase rather than decrease. Future volcanism and/or changes in global circulation patterns may produce cooler summers in the medium-term future, with either increased or decreased precipitation. All of these possibilities have implications for water management, but they do not necessarily lead to water shortages.

It is true that the GCMs all predict net global warming. As the models are refined and consensus grows regarding key assumptions, the various predicted rates of warming become more similar. Each prediction of global warming, however, is a spatial average over many individual cells covering the surface of the earth. The specific results for any particular cell vary widely from place to place, and from model to model. Because of the type of data used to calibrate and bound these models, and the general lack of local detail, predictions for individual cells are not regarded as reliable. They are statements of what could happen, rather than useful forecasts of what is likely to happen.

In presenting guidelines for studies of this kind, IPCC (1994) discussed three approaches to projecting future climate, employing synthetic, analog, and GCM-based scenarios. This study is a hybrid of the first and third approaches. It employs results of five different GCM runs for five of the six scenarios, but there is no attempt to identify the "best" or most representative GCM. Rather, the various sets of output data are chosen so as to illustrate a reasonable range of possible outcomes. These outcomes are chosen for the sole purpose of delineating response of the water resource system to uncertain future climate, in the spirit of the IPCC definition of synthetic scenarios. The identities and characteristics of the GCMs used in this study may affect the plausibility of the range of climate outcomes considered, but otherwise the technical details of these models have limited relevance to the analysis that follows. For this reason, relatively little discussion of the GCM runs is included in this report.

Those GCM results available early in the study (1994, approximately) were reviewed and cell-level predictions were extracted from a number of them. These predictions were chosen to illustrate a range of possible outcomes: warm dry weather, warm wet weather, and cool wet weather.

The final GCM results provided five future weather scenarios; current average "normal" weather (as defined by the National Weather Service) was used to construct a sixth, historical climate scenario. As noted above, none of these scenarios is intended as a prediction of future climate. Taken together, however, they depict a reasonable range of climate variability and permit an assessment of the sensitivity of various water management alternatives to uncertain future climate.

2.2 Construction of Climate Scenarios

Data on possible future climate were obtained from the outputs of five GCMs. These are:

Geophysical Fluid Dynamics Laboratory, new version (GFDL)
Goddard Institute for Space Studies, version A (GISS-A)
Goddard Institute for Space Studies, version B (GISS-B)
United Kingdom Meteorological Office, Hadley Centre (UKMO)
Max Planck Institute, Germany (MPI)

Complete output data sets were obtained for all of these models through the National Center for Atmospheric Research (NCAR).

All of the GCM results cited in this report are from transient model runs. In these cases, atmospheric CO_2 is assumed to increase gradually over time (according to a predetermined schedule) until it reaches twice the base line figure (usually 300 to 330 ppm). Results are calculated for each month and year. Because of drift and jumping-off errors, it is customary to discuss the outputs of these models in terms of first decade (base period), second decade (approximately 2020), and third decade (approximately 2050) averages. In this study, with the exception of the GISS-B scenario (discussed below), changes for the period 1990 to 2030 are represented by the difference between second and first decade results.

It should be noted that the two sets of GISS results derive from different assumptions applied to the same model. Both incorporate the same gradual increase in atmospheric concentration of greenhouse gases (measured as equivalent CO_2 concentration) and provide monthly values of temperature, precipitation, etc., for each decade after the base year. The GISS-A results provide monthly data for 1960 to 2060 with no major volcanic activity following El Chichon; GISS-B provides monthly data for 1960 to 2030 with an El Chichon-like volcanic event in the 1990s and a Southern Hemisphere Mt. Agung-like eruption in the 2010s.[1] In order to obtain a cooling scenario, however, annual GISS-B results for the 1990 to 2000 period were used.

All GCMs produce results for individual cells, but the sizes and locations of the cells vary from model to model. Generally, cell dimensions range from several degrees of longitude or latitude to as much as ten degrees (for the GISS model). By comparison, the Potomac River basin is roughly 4°30' in the east-west dimension, and 2°15' in the north-south direction. Data were sought for two points:

The centroid of the Potomac River drainage basin (39°15' N, 78°45' W) and
The centroid of the Washington Metropolitan Area (WMA) (39°00' N, 77°00' W).

A two-dimensional linear interpolation was used to translate model results to these two points.

The climate scenarios used in this study consist of alternate weather predictions for the year 2030. They are based on "normal" weather for 1990, defined as the 1961 to 1990 averages for temperature and precipitation.[2] The historical period (1961 to 1990) used by the National Weather Service to develop Normal statistics, and referred to as the historical climate scenario. Normal weather was calculated for the centroids of the drainage area, and for each of the counties and independent cities of the WMA. Linear interpolations among weather stations were used.

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1 El Chichon erupted in 1982 in Mexico; Mt. Agung erupted in 1963 in Indonesia.

2 1951-1980 averages were also examined and found to be significantly different from the 1961-1990 figures. However, the later period was used in this study.

The temperature predictions for five climate change scenarios are in the form of 2030 to 1990 temperature differences. Adding these differences to the year 1990 normal weather gave the year 2030 prediction. For three of the models (GFDL, UKMO, and MPI) precipitation changes were stated as 2030/1990 ratios. In the case of the two sets of GISS results, precipitation data were available only as 2030-1990 differences. The various differences and ratios were applied to 1990 normal precipitation to obtain year 2030 predictions. These five climate change scenarios are in addition to an "historical" climate scenario which assumes that 1990 normal weather continues unchanged to 2030.

The final list of climate scenarios is as follows:

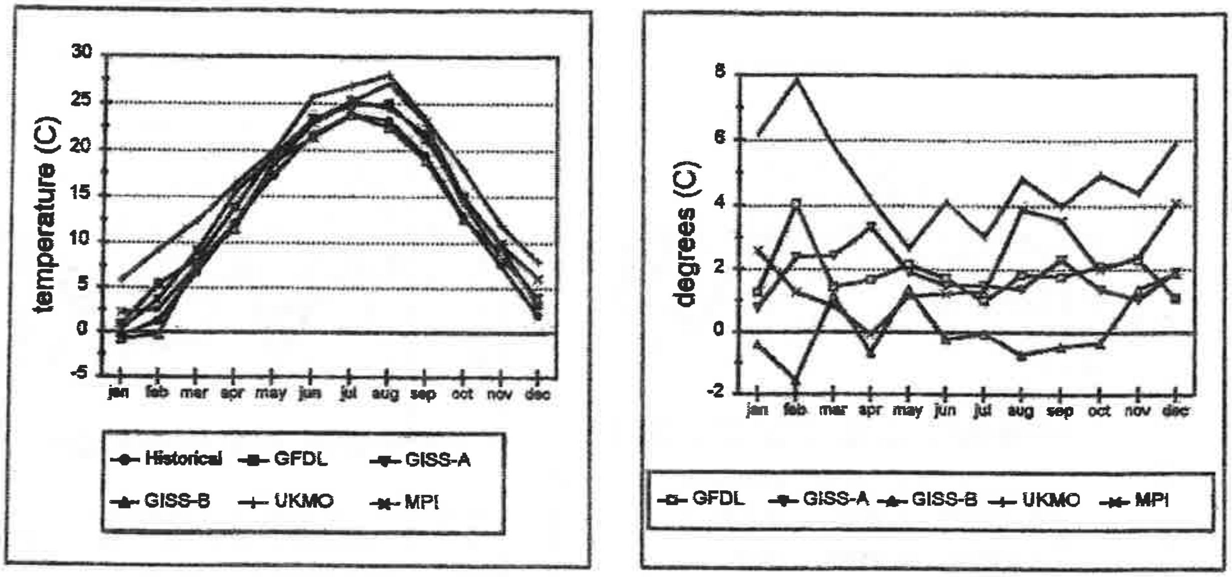
Historical -- Year 2030 climate defined by 1961 to 1990 average ("normal") weather
GFDL -- second decade results
GISS-A -- second decade results
GISS-B -- results for 2000
UKMO -- second decade results
MPI -- second decade results

2.3 Final Climate Scenarios

The record of historical weather gives the first future climate scenario. The GCM results include predictions of temperature and precipitation by calendar month. When calculated for the centroid of the Washington Metropolitan Area (WMA), applied to base year weather data as described above, the five GCMs form the basis for five alternate predictions of weather for the urban area. When calculated for the centroid of the Potomac River basin, applied to base year weather data as described above, the five GCMs form the basis for five alternate predictions of weather for the up stream water supply resources. The monthly meteorological data for the historical and each of the GCM scenarios at the two centroids are presented in Table 2.1. Figures 2.1-a,b and 2.2-a,b show the mean monthly temperatures associated with each of these scenarios at the Basin and WMA centroids, respectively. Figures 2.3-a,b and 2.4-a,b show the monthly precipitation for the six scenarios at the two centroids.

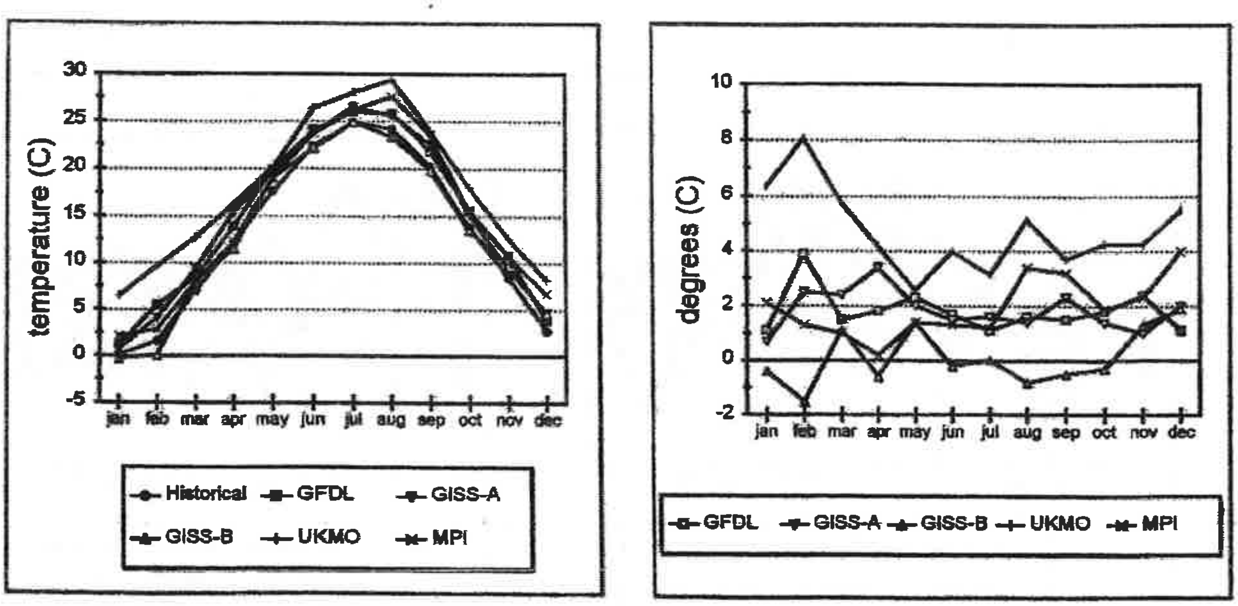
Table 2.1 Mean monthly temperature (^{0}C) and precipitation (mm) for year 2030 — Basin and WMA centroids

Basin Centroid		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Historical	T (C)	-0.4	1.3	6.7	12.2	17.3	21.7	23.9	23.2	19.4	13.0	7.5	2.0
	P (mm)	60.5	58.4	74.2	74.9	89.9	83.8	89.7	82.0	80.5	75.2	70.4	63.8
GISS-A	T (C)	0.4	3.7	9.1	15.5	19.3	23.2	25.4	24.6	21.8	14.4	8.6	3.9
	P (mm)	39.1	64.1	71.0	48.9	103.1	92.3	96.6	80.5	72.0	49.9	68.2	61.8
GISS-B	T (C)	-0.8	-0.2	7.8	11.5	18.7	21.4	23.8	22.5	19.0	12.7	8.9	3.9
	P (mm)	67.3	61.6	68.5	66.7	109.5	101.7	104.8	103.6	77.3	66.9	81.7	73.8
GFDL	T (C)	0.9	5.4	8.1	13.8	19.5	23.4	24.9	25.1	21.2	15.1	9.8	3.1
	P (mm)	65.3	66.5	82.8	60.7	95.3	66.0	68.1	82.0	78.7	77.2	85.1	59.2
MPI	T (C)	2.2	2.6	7.5	12.1	18.5	22.9	25.2	27.1	23.0	15.0	9.9	6.1
	P (mm)	60.5	61.9	67.1	54.9	94.7	76.8	85.1	57.8	81.7	85.3	82.3	68.3
UKMO	T (C)	5.8	9.2	12.4	16.3	20.0	25.8	26.9	28.1	23.4	17.9	11.9	7.9
	P (mm)	75.0	85.7	82.2	92.0	105.2	117.2	97.6	83.7	69.1	79.6	41.4	61.7
WMA Centroid													
Historical	T (C)	0.1	1.6	7.0	12.1	17.6	22.4	24.9	24.2	20.3	13.8	8.4	2.7
	P (mm)	75.6	73.5	86.0	85.0	109.5	93.1	103.3	107.7	92.4	85.3	88.0	85.6
GISS-A	T (C)	0.8	4.1	9.4	15.5	19.6	23.9	26.5	25.6	22.6	15.2	9.4	4.7
	P (mm)	54.3	79.3	82.9	59.1	122.7	101.7	110.4	106.2	84.0	60.1	86.0	83.8
GISS-B	T (C)	-0.3	0.1	8.1	11.5	19.0	22.2	24.9	23.4	19.8	13.5	9.7	4.6
	P (mm)	82.5	76.8	80.4	76.9	129.1	111.1	118.6	129.3	89.3	77.2	99.4	95.8
GFDL	T (C)	1.2	5.5	8.5	13.9	19.9	24.1	26.0	25.8	21.8	15.6	10.8	3.8
	P (mm)	81.7	80.8	92.0	68.9	109.5	67.9	79.6	108.8	91.4	89.6	102.1	81.3
MPI	T (C)	2.2	2.9	8.0	12.3	19.0	23.7	26.1	27.6	23.5	15.7	10.7	6.7
	P (mm)	72.6	75.7	88.5	67.2	121.6	86.6	100.2	83.0	96.0	101.5	100.3	91.6
UKMO	T (C)	6.4	9.7	12.8	16.3	20.2	26.4	28.1	29.3	24.0	18.1	12.7	8.2
	P (mm)	93.0	108.0	87.7	107.1	108.4	121.9	105.4	125.0	104.4	92.1	52.8	77.0



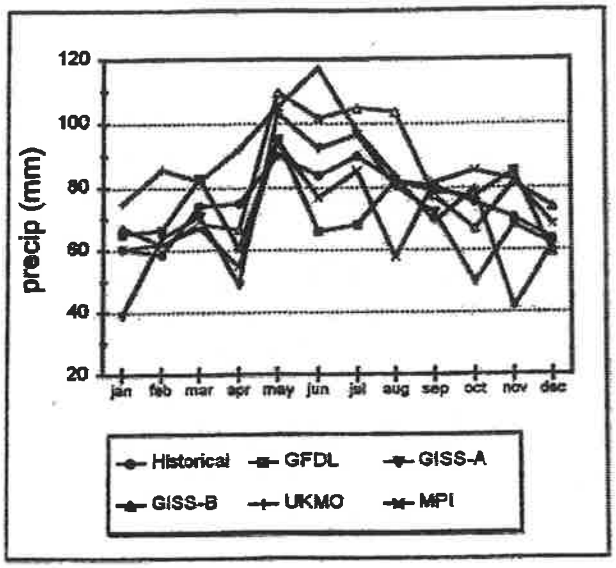
a b

Figure 2.1-a,b Mean monthly temperature for year 2030 at Basin centroid: (a) °C, (b) °C deviation from historical scenario

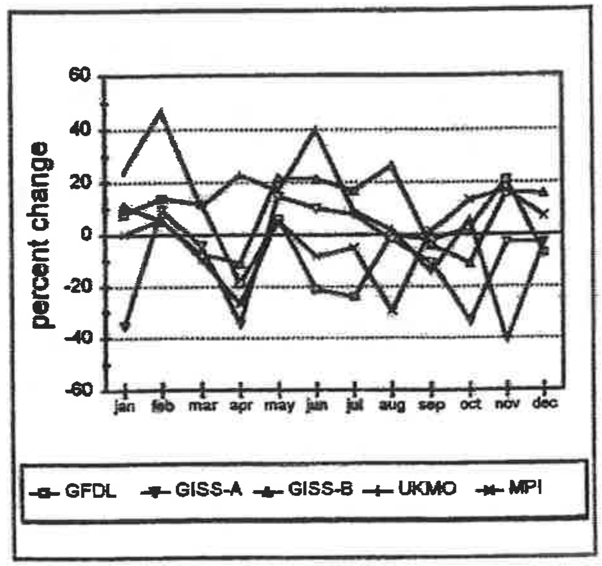


a b

Figure 2.2-a,b Mean monthly temperature for year 2030 at WMA centroid: (a) °C, (b) °C deviation from historical scenario

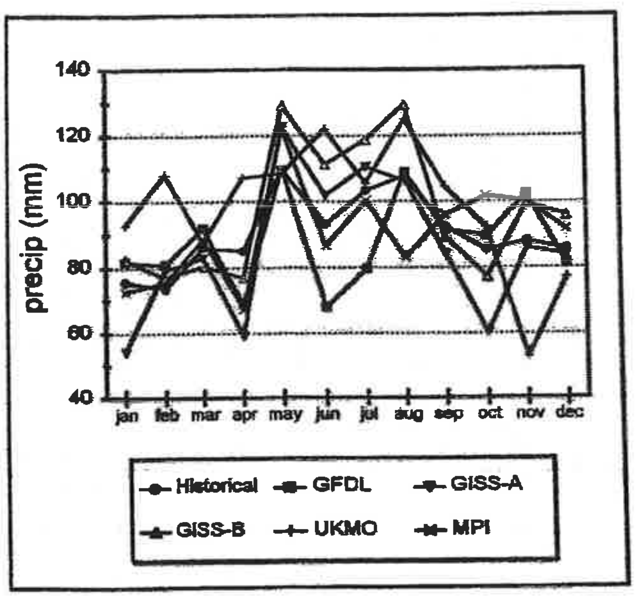


a

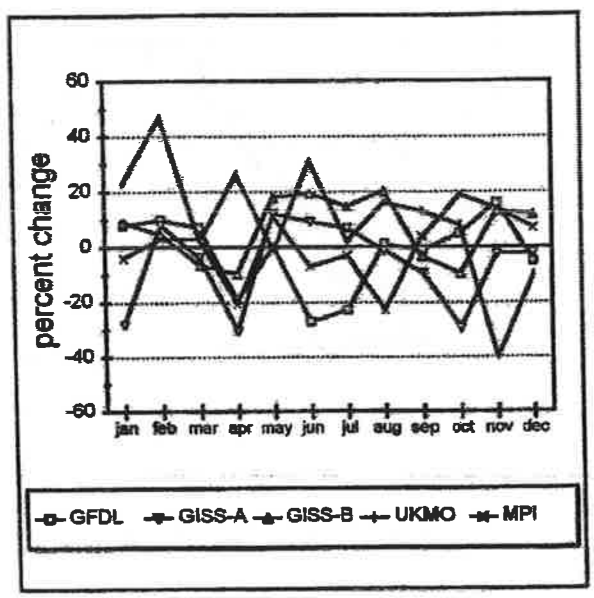


b

Figure 2.3-a,b Mean monthly precipitation for year 2030 at Basin centroid: (a) mm, (b) percent deviation from historical scenario



a



b

Figure 2.4-a,b Mean monthly precipitation for year 2030 at WMA centroid: (a) mm, (b) percent deviation from historical scenario

It was found that rather than clearly represent any consistent scenarios, the models fluctuated seasonally among these climatic states. As a result, the set of scenarios employed covers a wide range of climatic variation, but no single GCM covers one specific weather scenario, such as hot and dry, throughout the year.

In general, the GCM scenarios compare to historical conditions as follows:

GFDL:	marginally warmer, drier spring and summer, winter near historical
GISS-A:	marginally warmer, wetter summer, drier autumn and winter
GISS-B:	coolest scenario, yet only marginally below historical, wettest summer and autumn with a drier than historical spring
UKMO:	warmest scenario, most notably warm in the winter months, with wide variation in precipitation--largely much wetter with a very dry November and December
MPI:	marginally warmer year with a warm winter, though cooler than UKMO dry spring and summer, wetter autumn and winter.

Further changes were needed to transform the climate scenarios into useful data. As noted above, GCM data from several cells were spatially interpolated to yield weather predictions for the centroid of the Washington Metropolitan Area. Each interpolated weather datum was extrapolated to give a weather prediction for each county and independent city in the WMA. Existing "normal" (1961 to 1990 average) weather data for weather stations within the WMA were used to develop normal weather estimates for the centroid of each political jurisdiction; these were compared to the WMA centroid normal weather; temperature differences and precipitation ratios were then used to extrapolate climate scenario predictions to the political jurisdiction centroids.

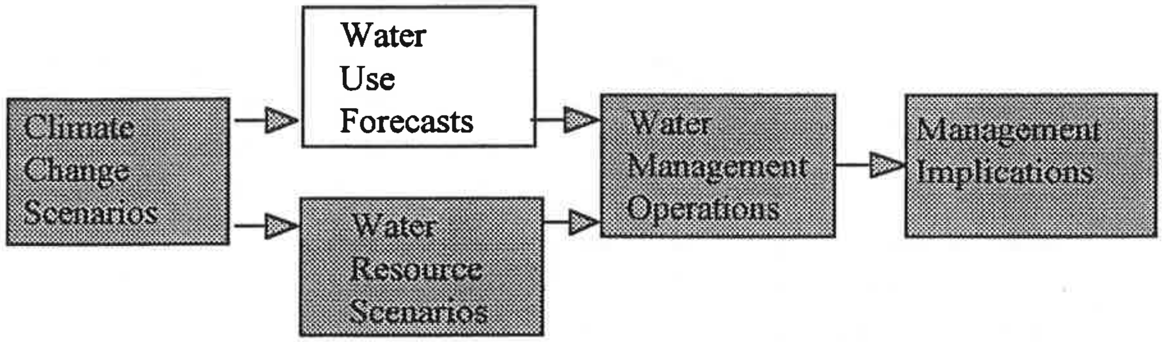
Finally, for each scenario, weather data for the June-August period were combined according to the method of Thornthwaite and Mather (1957) to give a three-month summer moisture deficit. Moisture deficit is generally defined as the difference between the potential evapotranspiration of rye grass turf (the amount of water needed to support maximum growth) and the actual effective precipitation (the fraction of precipitation that is retained in the root zone). The three month period (June through August) and the use of the moisture deficit parameter reflect the requirements of the Howe-Linaweaver water use model (see Section 3.1 and Appendix B).

Table 2.2 displays the soil moisture assumptions for the various counties and independent cities of the WMA. For each climate scenario, three values of moisture deficit are relevant: that corresponding to actual 1990 weather, the 1990 normal figure (1961 to 1990 mean), and the year 2030 prediction. Actual weather refers to a moisture deficit calculation based on observed 1990 temperature and precipitation. All weather data vary from place to place. Only the 2030 predictions vary from climate scenario to climate scenario.

It can be seen that the GISS-A, GFDL, MPI and UKMO climate scenarios predict increased moisture deficit, due to higher summer temperatures, reduced precipitation, or both. The GISS-B scenario predicts reduced moisture deficits which are due entirely to cooler summer temperatures (because of the volcanism assumptions). The largest moisture deficits are associated with the UKMO climate scenario, averaging 3 to 6 cm (1.14 to 2.28 in) higher than the corresponding historical climate assumptions.

Table 2.2 Summer season moisture deficit, by climate scenario and location (cm/3 months)

Location	1990		Year 2030, by Climate Scenario					
	Actual	Normal	Historical	GFDL	GISS-A	GISS-B	UKMO	MPI
District of Columbia	20.5	24.3	24.3	28.8	26.7	21.0	30.0	29.2
Calvert Co., MD	14.6	24.2	24.2	28.1	26.6	20.1	29.4	28.6
Charles Co., MD	16.8	23.4	23.4	27.3	25.6	19.8	28.7	27.9
Frederick Co., MD	23.4	21.5	21.5	26.9	24.4	19.6	24.5	26.3
Montgomery Co., MD	19.8	23.5	23.5	27.0	25.1	20.1	27.8	27.5
Prince George's Co., MD	16.7	23.8	23.8	27.7	25.7	20.0	28.8	28.0
Alexandria City, VA	17.7	24.8	24.8	29.3	27.6	21.4	30.6	29.8
Arlington Co., VA	17.7	24.8	24.8	29.3	27.6	21.4	30.6	29.8
Fairfax Co., VA	18.7	24.0	24.0	28.4	26.7	21.0	29.7	28.8
Loudoun Co., VA	23.3	24.2	24.2	28.3	26.5	20.7	29.6	28.7
Prince William Co., VA	22.4	27.4	27.4	29.4	25.8	20.8	30.4	29.5
Stafford Co., VA	26.3	26.2	26.2	35.1	28.6	22.5	31.9	30.9



3: WATER USE FORECASTS

3.1 Choice of Method

Forecasting the level of any future activity, such as water use, can be divided into two tasks: (1) explanation and (2) prediction. Explanation of water use usually takes the form of a model which relates the past observed level of water use to various explanatory variables. Replacing past values of the explanatory variables with those expected in the future produces a prediction of future water use. This prediction is conditioned on several levels of assumptions including the accuracy of the water use model, the applicability of that model to the future, and the accuracy of postulated future values for explanatory variables.

In choosing a forecasting approach, therefore, a number of decisions are required. The first concerns the possibility of disaggregating water use for explanation and prediction purposes. For example, the major sectors of water use are usually designated as residential, commercial/institutional, industrial, and public. These sectors can be expected to follow different trends over time, and water use in each sector generally responds to a unique set of explanatory variables. Accordingly, it may be helpful to explain (model) and predict each sector separately. Further disaggregation is possible so as to reflect differences among housing types (e.g., single family residences vs. multi-family buildings) or among industrial categories. In general, increased disaggregation improves the explanatory power of models and leads to more accurate forecasts.

Another issue involves the form and degree of complexity of the water use models in each sector. These may range from simple unit use coefficients (such as the per capita method once used almost universally) to multivariate econometric demand models. To be useful in the present application, water use models must at least relate water use to weather variables; in this way the sensitivity of water use to climate change use can be predicted. Where feasible, econometric demand models are usually preferred to statistical models and unit use coefficients. An extensive review of water use models reported in the literature prior to 1984 appears in Boland, et al. (1984). A more recent assessment, focusing particularly on studies in the UK, can be found in Herrington (1996).

The most detailed and disaggregate forecasting system in general use in the U.S. is the IWR MAIN forecasting system supported by the U.S. Army Corps of Engineers, Institute for Water Resources. This is available as an integrated computer-based system containing a range of forecasting models, explanatory variable projection procedures, and data management facilities. It also incorporates consideration of water conservation measures, where needed. Version 5.1 of IWR MAIN (the most recent version available at the time the data were collected) was used in this study.

IWR MAIN 5.1 is characterized by a high level of disaggregation and considerable diversity with respect to water use modeling. Table 3.1 outlines the organization of the IWR MAIN water use models (Davis, et al., 1988).

Table 3.1 Organization of IWR MAIN 5.1

Sector	Water Use Category	Water Use Model
Residential	Metered/sewered Flat rate/sewered Flat rate/unsewered Master-metered apartment	Econometric demand model Multivariate requirements Multivariate requirements Multivariate requirements
Commercial/ Institutional	Up to 50 categories, including 23 predefined categories based on groups of 4-digit SIC codes	Unit use coefficients, or per employee coefficients
Industrial	Up to 200 categories, including 198 predefined 3-digit and 4-digit SIC codes	Unit use coefficients, or per employee coefficients
Public/ Unaccounted-for	Up to 30 categories, including distribution losses and free service	Unit use coefficients, or per capita coefficients

The principal explanatory variables utilized in the water use models are listed in Table 3.2. In addition, there are three alternative procedures for generating future values of explanatory variables and the ability to incorporate as many as eighteen water conservation measures, affecting any or all sectors of water use.

Table 3.2 Principal explanatory variables for IWR MAIN

Demographic data	Population, household size
Housing data	Number of units, housing type housing value, housing density
Economic data	Water/waste water tariff
Employment data	Employment by SIC code: commercial, institutional, industrial
Other data	Conservation measures, moisture deficit, unaccounted-for fraction

IWR MAIN has been used by water utilities, consultants, and various government agencies for more than 25 years. Extensive revisions begun in 1982 have permitted much expanded use. Major applications of IWR MAIN in recent years include Phoenix (AZ), Metropolitan Water District of Southern California, State of New Mexico, New York State, Springfield (IL), Southwest Florida Water Management District, San Diego (CA), and Southern Nevada (Planning and Management Consultants, Ltd., 1995).

The residential water use models incorporated into IWR MAIN 5.1 were originally developed by Howe and Linaweaver (1967) and subsequently revised by Howe (1982). The expressions derived for metered and sewered single family residences are econometric demand models, incorporating price and housing value (a surrogate for income). The summer water use model for the eastern U.S. contains moisture deficit, a variable which expresses the water requirement for lawn and garden irrigation (see Appendix A). Moisture deficit is calculated from temperature and precipitation data. As described in Section 2.3, climate change scenarios can be translated into alternative predictions of moisture deficit.

The relationship between weather and climate, explained in IWR MAIN in terms of moisture deficit, can be described in other ways. Some investigators have employed maximum temperature, average summer temperature, cooling degree days, and various measures of precipitation for this purpose. Early work by Linaweaver (1965), however, demonstrated that actual water use for seasonal outdoor purposes closely follows the type of moisture deficit measure used by Howe and Linaweaver in their later work (1967). Since that time, most studies of residential water use in humid regions have used the same explanatory variable with considerable success (other approaches are more common in semi-arid regions, such as the Southwest U.S.). All versions of IWR MAIN through 5.1 incorporate the Howe-Linaweaver specification of moisture deficit.

The IWR MAIN system, when used to its full potential, can require a substantial data collection effort. However, there are a number of advantages for this method, when compared to other forecasting approaches.

- IWR MAIN's level of disaggregation (four major sectors and up to 284 individual categories) provides insight into patterns and trends of water use.

- Forecasts can be spatially disaggregate allowing separate water use forecasts for specific study areas such as cities, counties, water utilities, or load zones. This disaggregation permits accounting for different pricing policies and differential growth trends within each region and can assist in identifying the locations of future increases in water use. In the present application, this attribute facilitates the development of forecasts at the county and independent city level.

- IWR MAIN estimates future water use as a function of many of the likely determinants of water use: characteristics of housing units, detailed structure of employment, tariffs, irrigated residential acreage, and weather.

- Residential water use forecasts are seasonally disaggregate. More specifically, the forecasts are presented as summer daily water use, winter daily water use, and average daily water use. This provides an improved ability to estimate peak period water use and thus establish the adequacy of water supply.

- IWR MAIN forecasts account for the long-term impacts of as many as 18 different water conservation measures that have been implemented in the past or may be implemented in the future. This feature is indispensable where future water use may be restricted by various conservation measures.

For these reasons, IWR MAIN was adopted for this study. Version 5.1 of the model was applied separately to each county and independent city within the metropolitan area.

3.2 Data Collection — Base Year

IWR MAIN requires base year values for all explanatory variables. This serves several purposes:

- When the base year values include actual weather conditions, the resulting water use estimate can be compared to actual water use and the results of the comparison used to improve the calibration of the model.

- When the base year values include normal, rather than actual weather conditions, the resulting water use estimate provides a basis for comparison with forecasts of normal weather water use in future years.

- Some of the base year values are used internally to generate future year estimates of explanatory variables.

The required data and methods for collection and processing are described in the IWR-MAIN User's Manual (Davis, et al., 1988). Data requirements consist of base year values for the variables of the type listed in Table 3.2, including both actual and normal values for moisture deficit, and specifications of any active water conservation measures. Data sources include the U.S. Bureau of the Census, County Business Patterns, water and wastewater utilities, local and regional planning agencies, and the U.S. Weather Service.

For this application, the base water use year was defined as calendar 1990. Separate IWR MAIN forecasts were required for each of ten counties, one independent city, and the District of Columbia. Accordingly, base year data were prepared for each of these twelve jurisdictions. This level of spatial disaggregation approximates the service areas of the various water agencies serving the WMA, so that each data set can include tariff and water conservation data specific to the major agency in that political jurisdiction. Also, the collection of demographic, housing, and economic data from U.S. Census reports was simplified.

Following the collection, processing, and entry of the data, IWR MAIN was used to obtain provisional estimates of base year water use for each of the twelve jurisdictions. This estimate provided the basis for the verification and calibration steps to follow.

3.3 Verification and Calibration

Prior to use for forecasting, water use models must provide an acceptable explanation of past (base year) water use within the region. Accordingly, provisional base year estimates utilizing actual weather data were compared to recorded water use for 1990, as obtained from the water supply agencies. Where discrepancies were found, both estimated and reported data were investigated to determine, if possible, the source of the error. Data from the District of Columbia can be used to illustrate this process.

Actual 1990 water use data were obtained from various sources within the D.C. water utility. Data are available on total water delivered to the distribution system as well as billed water use. Limited information on water use by user category was obtained but could not be used because of discrepancies in the definitions of certain categories.

The first verification results indicate that residential water use is biased upward because of the presence of a significant number of high value residential units. Accordingly, housing value was capped at $300,000 per unit (1990 value) -- all higher value units were entered as $300,000. This change produced a base year estimate of 0.538 million cubic meters/day (142.1 mgd), as shown on Table 3.3. Summer season water use was estimated at 0.634 million cubic meters/day (167.5 mgd), while winter season use was 0.442 million cubic meters/day (116.8 mgd).

Table 3.3 IWR MAIN estimate of actual 1990 water use: District of Columbia (millions of cubic meters/day)

Sector	Summer	Winter	Annual
Residential	0.383	0.190	0.286
Commercial/institutional	0.172	0.172	0.172
Industrial	0.003	0.003	0.003
Publuc/unaccounted-for*	0.078	0.078	0.078
Total	0.634	0.442	0.538

* Unaccounted fraction is 14.3% of annual average use

Comparison of the IWR MAIN estimate to reported actual water use, summarized in Table 3.4, shows that it overestimated actual use by 1.9 percent. Summer use was overestimated by 11.4 percent; winter use was underestimated by 9.4 percent. This seasonal discrepancy may suggest some error in the IWR MAIN estimates; however, in this case, it more likely reveals a bias in the water use data reported by the District. Monthly production data were not available, so seasonal estimates were developed from annual production data and monthly metered use totals. The latter necessarily incorporate a lag, due to meter reading intervals, which tends to understate summer use and overstate winter use. Taking these factors into consideration, the result was considered an adequate basis for performing the necessary forecasts.

Table 3.4 IWR MAIN 1990 verification for District of Columbia (millions of cubic meters/day)

Season	Water delivered to distribution system	IWR MAIN estimate*
Summer (April to September)	0.569	0.634
Winter (October to March)	0.488	0.442
Annual	0.528	0.538

* Unaccounted fraction is 14.3% of annual average use

Similar procedures were followed in the other eleven jurisdictions. In some cases, certain assumptions (such as number of housing units per acre in various residential categories) were revised based on better information. In other cases (as described for the District of Columbia) probable biases in the reported water use information were noted. Information on water conservation measures was also revised for some counties. When the correspondence between estimated and actual water use was judged to be reasonably close, the calibration process ended.

It is worth noting that the IWR MAIN data inputs do not include any water use information. Instead, water use is estimated entirely from demographic, housing, economic, and other data. Nevertheless, even before calibration, the adjusted data sets produced estimates of water use generally within about five percent of actual. This error is comparable to the magnitude of errors commonly noted in measurements of actual sectoral water use due to meter misregistration, incorrect classification of customers, etc.

3.4 Water Conservation Policies

To determine the sensitivity of future water use to various policy interventions, three alternative water conservation policies were defined and summarized in Table 3.5. The conservation measures included in these policies are described in the IWR MAIN 5.1 User's Manual (Davis, et al., 1988).

Table 3.5 Water Conservation Policies

Conservation Policy	Water conservation measures
1	Measures existing in 1990 within jurisdiction, complete implementation of Moderate Plumbing Code
2	Measures included in Policy 1, above, plus: public education, Industrial reuse/recycle, commercial reuse/recycle, advanced plumbing code
3	Measures included in Policy 2, above, plus: 50% real increase in all water/wastewater tariffs

With the exception of price changes (Policy 3), the effectiveness of each water conservation measure is determined by IWR MAIN as follows:

$$E_{msdt} = R_{msd} C_{mst} Q_{std} \qquad (1)$$

Where:

E_{msdt} = effectiveness of measure m on water use d in sector s at time t

R_{msd} = fraction reduction of water use d in sector s, for conservation measure m

C_{mst} = coverage of measure m for sector s at time t

Q_{std} = unrestricted level of water use d in sector s at time t

Where interactions occur among several measures in effect at the same time, the following calculation is made:

$$E_{123} = E_1 + (a_{12} E_2) + (a_{13} a_{23} E_3) \qquad (2)$$

Where:

E_{123} = combined effectiveness of measures 1, 2, and 3

E_i = effectiveness of measure i, when implemented alone

a_{ij} = interaction coefficient for measure i when added to measure j

All coefficients are default values taken from IWR MAIN coefficient libraries (see Davis, et al., 1988).

In the case of tariff changes (Policy 3), IWR MAIN uses price directly in the calculation of metered and sewered single family residential water use. The remaining residential categories, where residents do not face a marginal price for water, are not expected to be price-sensitive. Unit use coefficients in the commercial/institutional and industrial sectors are adjusted for the difference in forecast year price; default elasticities for the two sectors are -0.80 and -0.65, respectively.

All of the conservation measures considered here affect year-round use. The measures are specified in the IWR MAIN data files and winter water use estimates prepared as described above. The modified calculation of summer water use (described in Appendix A) roughly preserves the effect of the non-price water conservation measures, even though no specific calculations are made for summer impacts. Price effects, however, are probably understated in the summer season, since there is no way to consider the higher summer price elasticity. Summer water use estimates, therefore, may be biased upward for Conservation Policy 3.

3.5 Forecast Results

Following successful verification and calibration, actual weather measures of moisture deficit for the twelve study areas were replaced with normal weather data. The base year estimates prepared for normal weather show higher levels of summer water use, because normal moisture deficit is approximately 18 percent higher than the deficit actually experienced in 1990 (see Table 2.1). Economic projections developed by the Metropolitan Washington Council of Governments and the National Planning Association were used to predict year 2030 levels of population, housing units, household income, and employment for each area.

IWR MAIN was then used to prepare water use forecasts for each of the twelve jurisdictions for 2030. The first round of forecasts assumed no increase in the use of water conservation measures, except for continuing compliance with 1980 legislation mandating 13 liters/flush toilets and 9.5 liters/minute shower nozzles (Conservation Policy 1 -- see Table 3.5).

A separate forecast was prepared for each climate scenario (see Table 2.1) and for each study area. While the results for the District of Columbia seemed plausible, most suburban counties showed little or no difference between summer and winter water use. Investigation of this anomaly revealed problems with the suitability of one of the water use models used by IWR MAIN. The problem is described and details of the alternative forecasting method that was used for summer water use are provided in Appendix A.

Using the revised procedure, water use forecasts were prepared for the year 2030, for each county or city, and for each climate scenario. To illustrate the level of detail, winter water use estimates for 1990 and 2030 are shown in Table 3.6; this estimate assumes Conservation Policy 1. Because they are for winter water use, the same estimates apply to all climate scenarios. Note that the ratio of 2030 water use to 1990 water use varies from 1.36 to 29.06, depending on the jurisdiction. When county/city results are summed to give a forecast for the entire Washington Metropolitan Area (WMA), the 2030/1990 ratio is, coincidentally, exactly 2.00. Because of the method used to estimate summer water use (Appendix A), 2030 summer water use (and therefore also annual water use) for the historical climate scenario and Conservation Policy 1 will also be exactly 2.00 times 1990 water use (see Table 3.7).

Table 3.6 Winter water use estimates by jurisdiction, Conservation Policy 1

Jurisdiction	Winter water use mcm/d)		
	1990	2030	Ratio
DC	0.40	0.55	1.36
Calvert	0.01	0.18	29.06
Charles	0.02	0.06	2.35
Frederick	0.04	0.11	3.09
Montgomery	0.39	0.85	2.18
Prince George's	0.32	0.43	1.38
MD	0.78	1.64	2.11
Alexandria	0.07	0.13	1.85
Arlington	0.13	0.20	1.55
Fairfax	0.47	1.08	2.30
Loudoun	0.03	0.07	2.51
Prince William	0.07	0.22	2.97
Stafford	0.01	0.03	2.64
VA	0.79	1.74	2.21
WMA	1.96	3.93	2.00

Based on the winter water use forecast, summer water use estimates were obtained for each jurisdiction and for each climate scenario. Again, water use was summed over the twelve jurisdictions to obtain the WMA total. Next, summer and winter results were further decomposed to yield forecasts of monthly water use for 2030. This was accomplished by calculating month/season ratios for each calendar month based on a year 2020 forecast for the larger utilities in the WMA (Mullusky, et al., 1995, p. N-1). Applying each month's ratio to the IWR MAIN seasonal forecast gave a forecast of monthly water use. It should be specifically noted that the forecasts developed for the climate change study presented in this report differ from those presented in Mullusky, et al. (1995) which have been adopted by the larger utilities in the WMA.

Estimated and forecast water use for Conservation Policy 1 are displayed in Table 3.7. This table shows increases in summer water use (for the six month period April to September) that range from 74 percent (GISS-B) to 138 percent (UKMO) of base year values. The range of variation in forecasts of year 2030 summer water use is -13 percent (GISS-B) to +19 percent (UKMO), when compared to historical climate. Table 3.7 also shows forecast average annual water use at 85 percent to 122 percent of base year water use. The range of variation is -8 percent (GISS-B) to +11 percent (UKMO), compared to the historical climate result. Detailed comparisons of conditions representing "with" and "without" climate change may be made by examination of Table 3.7.

Table 3.7 Estimated and forecast water use: Washington Metropolitan Area, Conservation Policy 1 (million cubic meters/day)

	1990	Year 2030, by Climate Scenario					
	Normal	Historical	GFDL	GISS-A	GISS-B	UKMO	MPI
Winter	1.96	3.93	3.93	3.93	3.93	3.93	3.93
Summer	2.74	5.48	6.32	5.91	4.76	6.52	6.39
Annual	2.35	4.70	5.12	4.92	4.34	5.23	5.16
Jan	1.96	3.92	3.92	3.92	3.92	3.92	3.92
Feb	1.90	3.79	3.79	3.79	3.79	3.79	3.79
Mar	1.91	3.82	3.82	3.82	3.82	3.82	3.82
Apr	2.41	4.82	5.56	5.20	4.19	5.74	5.62
May	2.57	5.16	5.95	5.56	4.48	6.14	6.01
Jun	2.89	5.79	6.67	6.24	5.03	6.89	6.74
Jul	2.99	6.00	6.91	6.47	5.21	7.14	6.99
Aug	2.82	5.66	6.52	6.11	4.92	6.74	6.60
Sep	2.72	5.46	6.29	5.89	4.74	6.50	6.36
Oct	2.09	4.18	4.18	4.18	4.18	4.18	4.18
Nov	2.00	4.00	4.00	4.00	4.00	4.00	4.00
Dec	1.93	3.85	3.85	3.85	3.85	3.85	3.85

The same forecasts were made for Conservation Policy 2, and are shown in Table 3.8. Growth in water use is substantially less than for Conservation Policy 1, as a result of the more aggressive water conservation program. Summer water use ranges from 40 percent (GISS-B) to 92 percent (UKMO) of 1990 levels; average annual water use is from 49 percent (GISS-B) to 79 percent (UKMO) of the base year. Although the level of water use is lower, the percentage variation from one climate scenario to another is basically the same as for Conservation Policy 1.

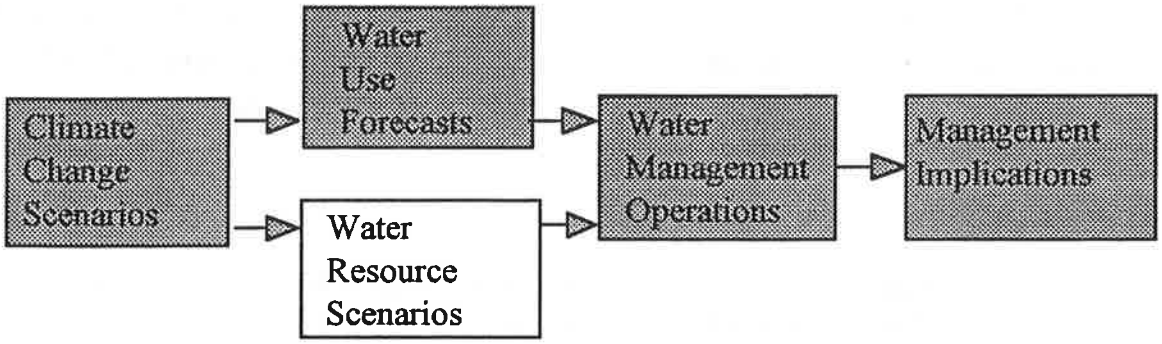
Table 3.8 Estimated and forecast water use: Washington Metropolitan Area, Conservation Policy 2 (million cubic meters/day)

	1990	Year 2030, by Climate Scenario					
	Normal	Historical	GFDL	GISS-A	GISS-B	UKMO	MPI
Winter	1.96	3.17	3.17	3.17	3.17	3.17	3.17
Summer	2.74	4.41	5.08	4.74	3.83	5.25	5.13
Annual	2.35	3.79	4.12	3.95	3.50	4.21	4.15
Jan	1.96	3.16	3.16	3.16	3.16	3.16	3.16
Feb	1.90	3.06	3.06	3.06	3.06	3.06	3.06
Mar	1.91	3.08	3.08	3.08	3.08	3.08	3.08
Apr	2.41	3.88	4.47	4.17	3.37	4.62	4.51
May	2.57	4.15	4.78	4.47	3.60	4.94	4.83
Jun	2.89	4.65	5.36	5.01	4.04	5.54	5.42
Jul	2.99	4.82	5.56	5.19	4.19	5.74	5.62
Aug	2.82	4.55	5.24	4.90	3.95	5.42	5.30
Sep	2.72	4.39	5.05	4.72	3.81	5.23	5.11
Oct	2.09	3.37	3.37	3.37	3.37	3.37	3.37
Nov	2.00	3.22	3.22	3.22	3.22	3.22	3.22
Dec	1.93	3.10	3.10	3.10	3.10	3.10	3.10

The forecasts were repeated for Conservation Policy 3, which adds a price increase to the aggressive water conservation program. The range of increases in summer water use (see Table 3.9), as compared to the base year, is 27 percent (GISS-B) to 74 percent (UKMO). Average annual water use is predicted to increase between 35 percent (GISS-B) and 62 percent (UKMO). As for Conservation Policy 2, the variation among scenarios is similar to that shown for Policy 1, for both summer use and average annual use.

Table 3.9 Estimated and forecast water use: Washington Metropolitan Area, Conservation Policy 3 (million cubic meters/day)

	1990	Year 2030, by Climate Scenario					
	Normal	Historical	GFDL	GISS-A	GISS-B	UKMO	MPI
Winter	1.96	2.86	3.10	3.10	3.10	3.10	3.10
Summer	2.74	3.98	4.59	4.30	3.46	4.75	4.64
Annual	2.35	3.42	3.72	3.58	3.16	3.80	3.75
Jan	1.96	2.85	2.85	2.85	2.85	2.85	2.85
Feb	1.90	2.76	2.76	2.76	2.76	2.76	2.76
Mar	1.91	2.78	2.78	2.78	2.78	2.78	2.78
Apr	2.41	3.50	4.04	3.78	3.05	4.18	4.09
May	2.57	3.74	4.32	4.05	3.26	4.47	4.37
Jun	2.89	4.20	4.85	4.54	3.66	5.01	4.90
Jul	2.99	4.35	5.03	4.71	3.79	5.20	5.08
Aug	2.82	4.11	4.74	4.44	3.58	4.90	4.80
Sep	2.72	3.96	4.57	4.28	3.45	4.73	4.62
Oct	2.09	3.04	3.04	3.04	3.04	3.04	3.04
Nov	2.00	2.91	2.91	2.91	2.91	2.91	2.91
Dec	1.93	2.80	2.80	2.80	2.80	2.80	2.80



4: WATER RESOURCE SCENARIOS

4.1 Introduction

To assess the effect of changing meteorologic conditions on the water supply sources available to the Washington Metropolitan Area (WMA), the climatic data derived from the selected GCM model runs were translated into water supply source availability scenarios through the application of water balance models for the watershed of each major water supply source in the WMA system.

While several water balance models were considered for use, a model based on the work of Thornthwaite and Mather (1955) was selected for this study. The model uses two of the parameters which are products of the GCM analysis (precipitation and temperature) to generate watershed runoff as annual hydrographs of average monthly values. The Thornthwaite-Mather water balance model has been used in several other climate change analysis studies, e.g., Delaware River Basin (McCabe and Ayers, 1989).

The water balance model was calibrated for five water supply sources serving the WMA; the Potomac River flow at Point of Rocks and the inflow to each of the following reservoirs: Jennings Randolph, Little Seneca, Occoquan and Patuxent. The calibrated model was then used to generate Potomac River flow at Point of Rocks and reservoir inflow data corresponding to each of the climate change scenarios under consideration. The projected hydrologic data were used as input for the third phase of the study, operational impacts, as discussed in Section 5 of this report.

4.2 Watershed Water Balance Model

An algorithm is needed to transform the precipitation and temperature data derived for the climate scenarios to climate-influenced runoff as it affects the raw water supply sources of the WMA. After review of the several modeling techniques, the Thornthwaite-Mather model was selected for this study. As well as offering a well established and accepted technique, the model had the added advantages of input and output formats compatible with this analysis. The model's principal inputs are temperature and precipitation, readily developed from the GCM analysis; and the model was developed for use on a monthly time scale, as adopted for this study. Further, the principle output, runoff, is the required parameter for input to the next phase of this study, the operational impact analysis.

4.2.1 Runoff Model Data Requirements and Computational Framework

The adaptation of the monthly accounting model to a specific watershed requires precipitation and temperature data on a monthly time scale. The model also requires an estimate of soil moisture holding capacity and percent of available moisture retained in the watershed from one month to the next. Locational data are required for development of heat index numbers, used in deriving evapotranspiration rates. The input requirements and model output are represented in the following sequence:

Input: temperature and precipitation (Section 4.2.1.1)
location (Section 4.2.1.2)
soil moisture capacity and retention (Section 4.2.1.3)

Output: monthly average runoff (Section 4.2.2)

As originally developed, the model relied on a number of look-up tables presented in Thornthwaite and Mather (1957). Where possible, those tables were converted to formulae for ease of computation. For this study, the Thornthwaite-Mather water balance model was developed as a computational spreadsheet.

4.2.1.1 Temperature and Precipitation

To develop the required input data, precipitation and temperature information was interpolated to locations which represent the climate for the several sources of raw water which serve the municipal and industrial needs of the WMA. The monthly meteorological data for the two centroids are presented in Table 2.1, and displayed graphically in Figure 2.1-a,b to Figure 2.4-a,b. The locations of the five raw water supply sources, as well as locations of the centroids of both the Potomac River basin and the metropolitan area, are shown in Figure 4.1.

As shown in Figure 4.1, the five water supply sources are geographically dispersed. A point approximating the centroid of the Potomac River basin was chosen as being representative of the climate which determines the inflow to Jennings Randolph Reservoir in the North Branch sub-basin and the flow in the Potomac River at Point of Rocks, upstream of the Potomac River intakes for the WMA. A point approximating the centroid of the WMA was chosen as being representative of the climate which determines the inflow to the off-Potomac reservoirs serving the suburban water utilities.

4.2.1.2 Locational Information

Locational information is required as input to the Thornthwaite-Mather model in determining a heat index to be used in calculating evapotranspiration rates. Specifically, latitude is used to determine the number of hours of sunlight per month for each location.

The five water supply locations, while dispersed relative to the basin, span a latitudinal range of less than one degree. The northernmost station is Jennings Randolph Reservoir at latitude 39°22', while the southernmost location is the Occoquan Reservoir at 38°41'. From look-up tables presented in the original model (Thornthwaite and Mather, 1957), the mean monthly duration of sunlight, expressed in units of twelve hours, varies by less than 0.2 over this range. Additionally, model runs prove to be fairly insensitive to this variable and a mid-range value corresponding to 39°00' was used in all applications.

	*Basin Centroid	*WMA Centroid
Latitude	39°15'	39°00'
Longitude	78°45'	77°00'

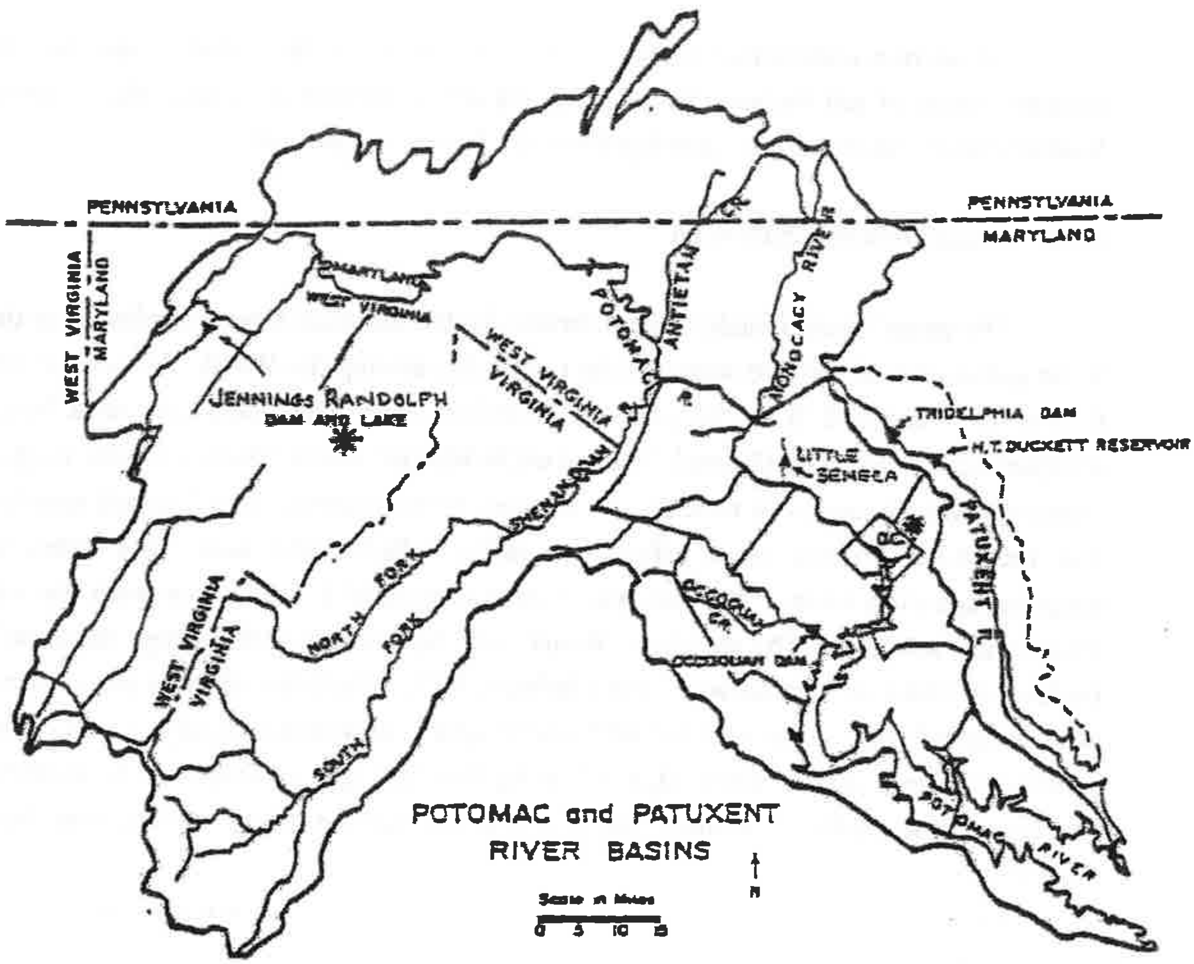


Figure 4.1 Water supply sources and location Centroids

4.2.1.3 Soil Moisture Capacity and Retention

The estimated soil moisture holding capacity determines the relationship between the modeled soil moisture and accumulated potential water loss each month. The accumulated potential water loss is the sum of the previous monthly amounts, within a calendar year, by which potential evapotranspiration exceeds precipitation. The watershed retention factor simply influences the rate of response of the watershed, varying from high peak flow and rapid hydrograph recession to lower peak flow with attentuated recession and higher base flow.

These two parameters represent the least known of the initial conditions. A range of tabulated values of soil moisture holding capacity and watershed retention, after Thornthwaite and Mather (1957), were used to develop the water balance equations.

4.2.2 Runoff Model Calibration

The water balance model was calibrated for the historical flow data relevant to the Potomac River and to each of the five water supply reservoirs serving the WMA. Monthly average runoff data sets, determined from 52 years of historical daily data, were used as a benchmark for comparison to the uncalibrated Thornthwaite-Mather water balance model output. Model sensitivity was examined in relation to a number of parameters, including soil moisture capacity and retention, location as it affects the latitude factor (the heat index determinant), and evapotranspiration rates. The first parameters examined in calibration were the soil moisture capacity and retention. The initial conditions were representative mid-range values selected from the look-up tables of Thornthwaite and Mather (1957). Variation of these parameters affects the peak value and rates of rise and fall of the hydrograph of average monthly flows. During model calibration these values were adjusted to fit the hydrograph properties to average historical conditions. The results of detailed analysis of parameter sensitivity are displayed in the Figures 4.2 and 4.3.

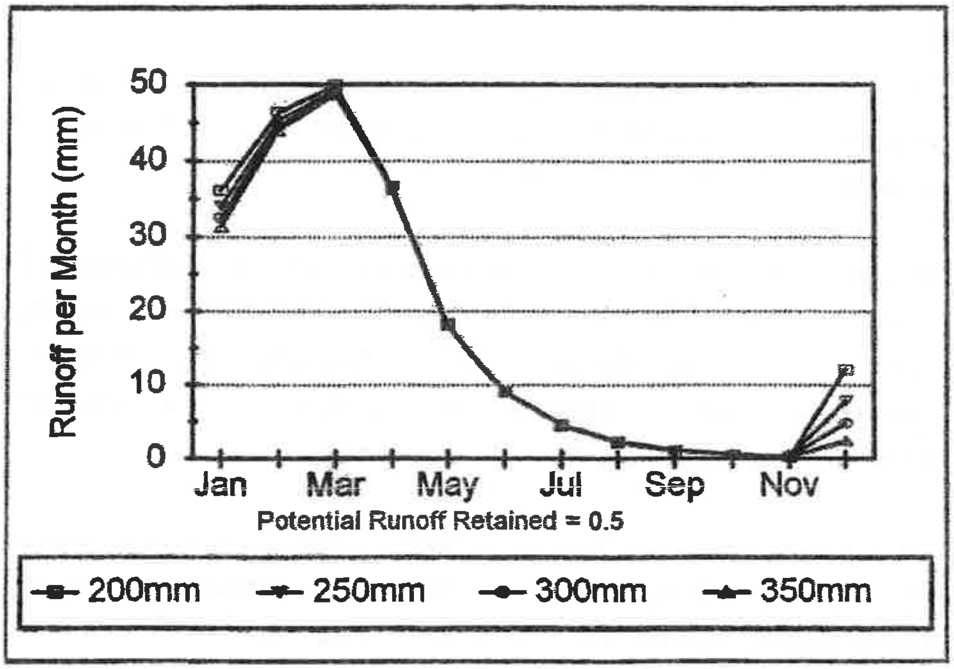


Figure 4.2 Model response to variation in soil moisture capacity (mm)

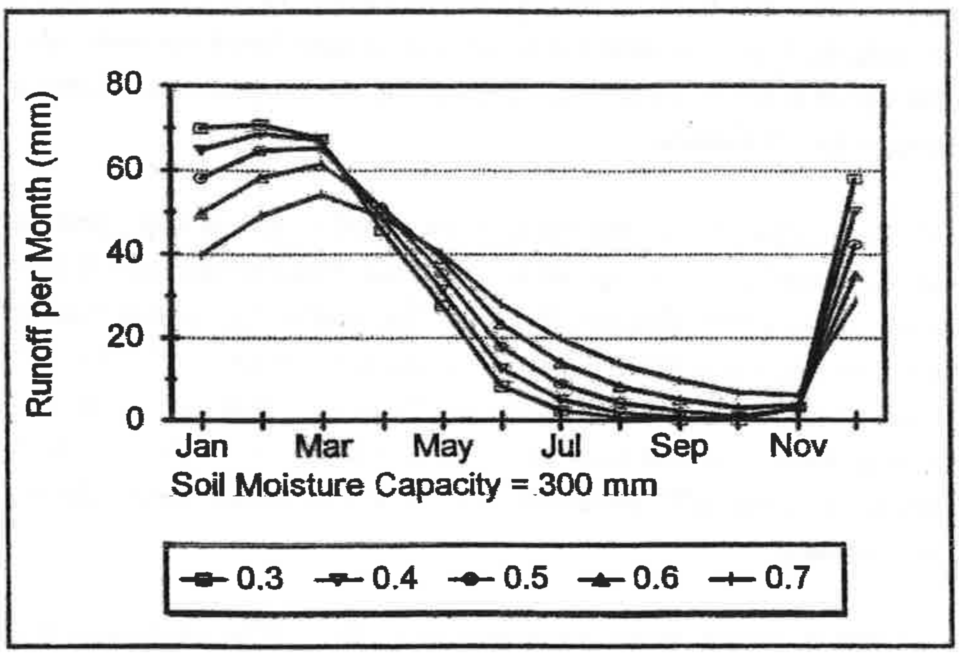


Figure 4.3 Model response to variation in soil moisture retention factors

The data show that variation of the retention factor has a significant impact on the shape of the hydrograph. As the retention factor increases, the curve is dampened. The lower the retention factor, the quicker the response of runoff to precipitation.

By comparison, variation of soil moisture capacity has a trivial effect on hydrograph shape. The rates of soil moisture depletion and recharge, as well as the average monthly values of runoff, were largely unchanged. The only impact occurs in November, when the soil moisture is refilled. Hence, soil moisture capacity was dismissed as a significant factor in calibration and a mid-range value of 300 mm was maintained for all but one location.

Two other factors considered in calibration were latitude factor and evapotranspiration. Latitude factor is a variable tied to the site location and represents the hours of sunlight available during a given month. This value is used in developing a heat index at each site. Because initial model assumptions include a mid-range location for the basin in setting this parameter, an abbreviated sensitivity analysis was conducted. A fairly large change in the latitude, well beyond the range of values for extreme locations within the basin, was found to have only a minor impact on model results. While factor values for basin extremes vary by less than 0.6 (in units of 12 hours of sunlight), factor variation 2.0 to 2.5 times greater than the present values resulted in final runoff changes of less than ten percent. Hence, the mid-range values chosen as initial conditions were retained for all models.

Evapotranspiration is addressed in the model in several steps, primarily in the forms of potential and actual evapotranspiration. Potential evapotranspiration (PET) is calculated as a function of temperature, location, and an annual heat index. Actual evapotranspiration (AET) is calculated as a function of PET, precipitation, and soil moisture. PET and AET are identical during months when the soil moisture capacity is full. During the summer and early autumn months when there is a soil moisture deficit, AET drops below PET as a percentage of the precipitation is diverted to fill the deficit of the previous month and thereby made unavailable for evapotranspiration.

As PET decreases, precipitation previously diverted to soil moisture is available for runoff. As in the case of soil moisture retention, decreasing PET has a dampening effect on the annual monthly hydrograph, decreasing the rate of recession during summer months. When there is a soil moisture deficit, this deficit amount becomes a factor in the computation of AET. Variation in AET therefore primarily impacts runoff in summer months and early autumn when there is a deficit condition. Altering the formula for calculating AET thus also impacts primarily the receding leg of the runoff hydrograph, as was the case with PET adjustment, but has an additional though slight impact on winter months due to a weakening of influence on summer and autumn runoff.

On an annual basis similar effects could be obtained in variations of PET, AET and soil moisture retention. Because PET and AET rates were calculated as a function of actual temperature and locational data, while soil moisture coefficients were obtained only as average values from look-up tables, ET adjustment proceded by adjustment of soil moisture cpacity.

The five graphs which follow, Figures 4.4 to 4.8, display the historical average flows for each location, as well as initial uncalibrated output, and model output calibrated through the variation of soil moisture parameters. Calibration of the water balance model for each water supply resource was achieved primarily through variation of the soil moisture retention factor. In each case, the best fit was determined as the set of parameter values which produce the least sum of squared errors between the reference (historical) data set and the runoff derived as model output.

Where the 'calibrated' model output still differed significantly from the historical record, a final round of calibration was used to bring modeled runoff into alignment with the historical record. A correction factor equal to the ratio of historical to modeled runoff was derived for each location.

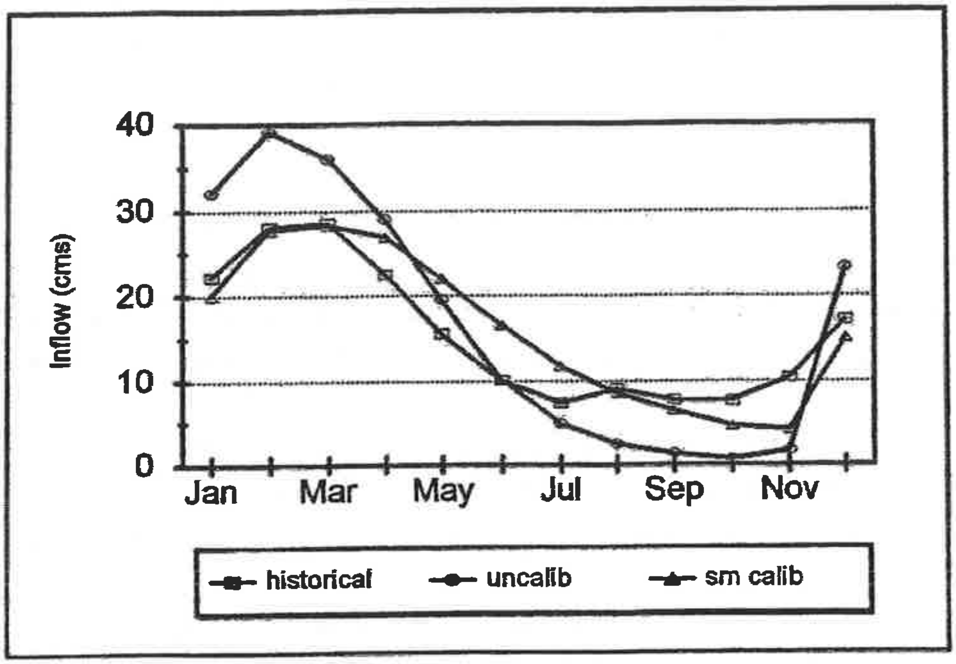


Figure 4.4 Occoquan Reservoir inflow (cms)

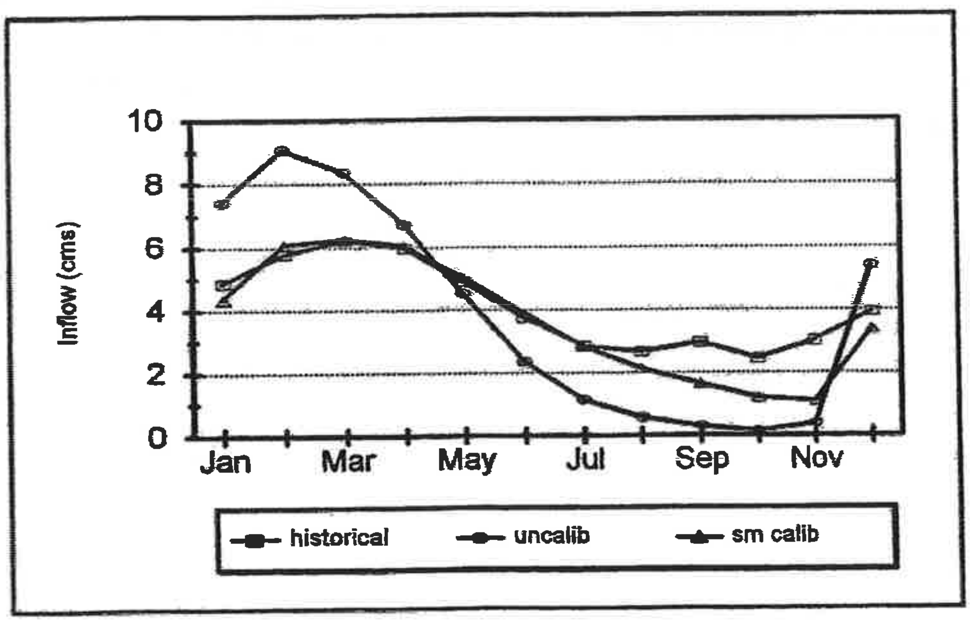


Figure 4.5 Patuxent Reservoir inflow (cms)

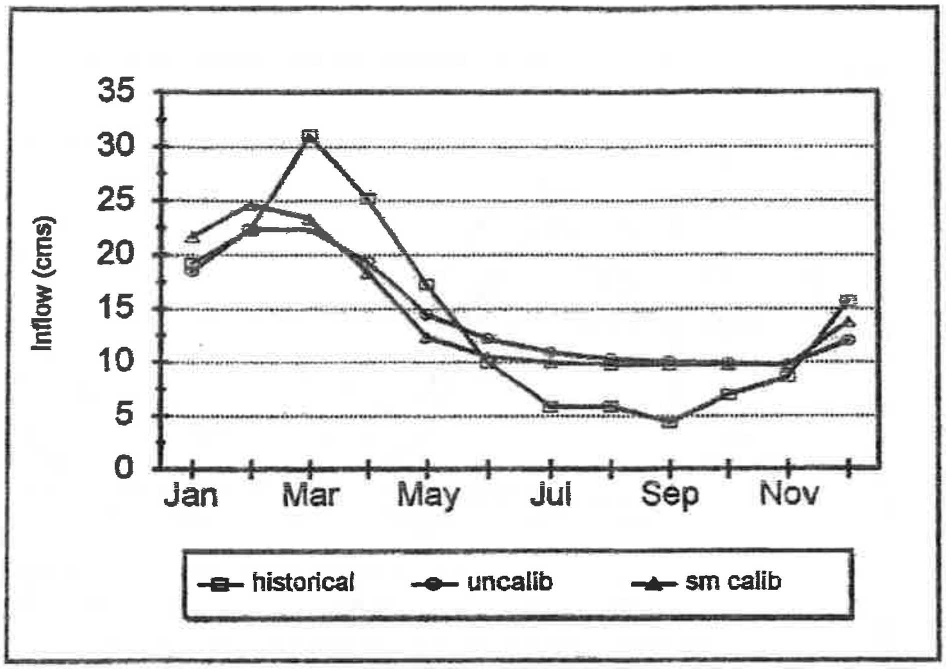


Figure 4.6 Jennings Randolph Reservoir inflow (cms)

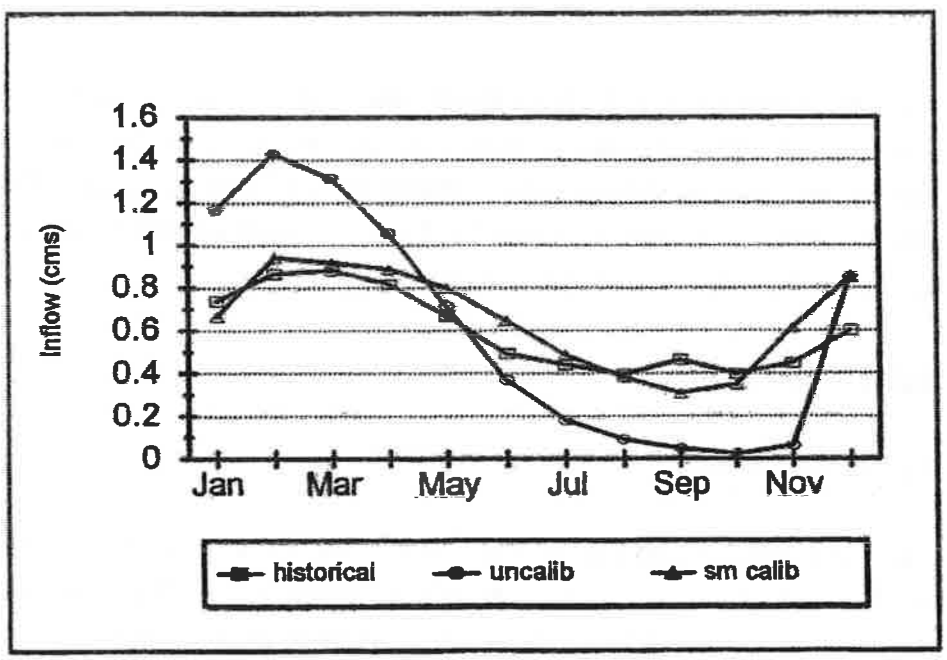


Figure 4.7 Little Seneca Reservoir inflow (cms)

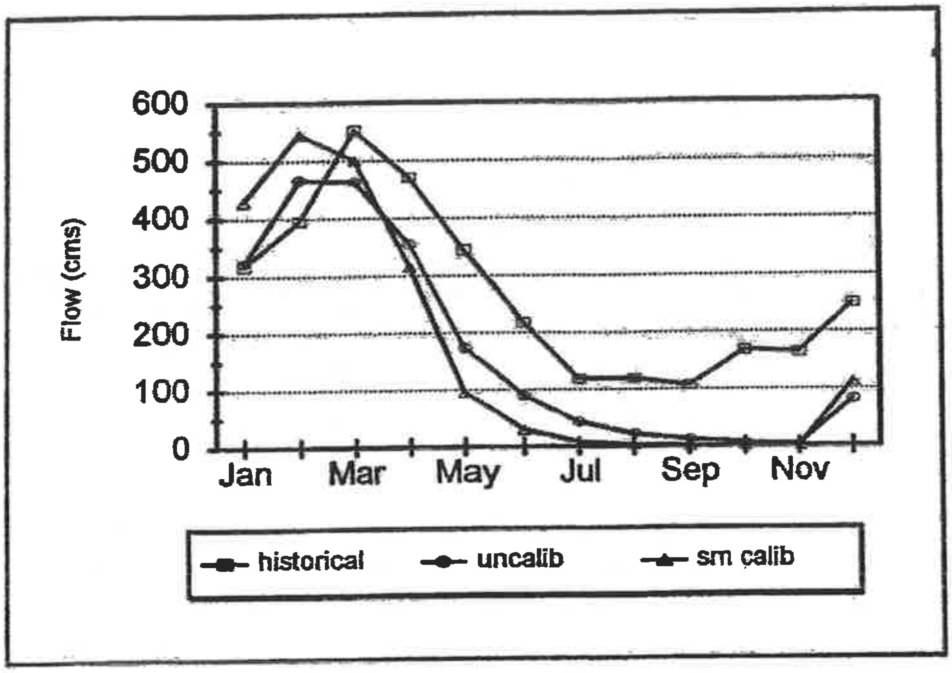


Figure 4.8 Potomac River at Point of Rocks flow (cms)

The reservoir inflow and Potomac River flow models were used next to generate input data to the water management operations model discussed in the following chapter. The input data required by the operations model include the annual series of average monthly flow for each water supply source. These data were produced by the appropriate geographic centroid water balance model for each of the climate change scenarios.

4.3 Water Supply Source Availability under Climate Uncertainty

4.3.1 Hydrologic Impacts

The hydrologic response for each water supply source was modeled under climate conditions for each of the scenarios. Models for the inflow to Occoquan, Patuxent, and Little Seneca reservoirs employed WMA centroid data while models Jennings Randolph Reservoir and the Potomac River flow at Point of Rocks used Basin centroid inputs.

In general, the hydrologic models for the WMA centroid water supply sources show similarly shaped inflow hydrographs. Likewise, the hydrologic model results for the Basin centroid supplies show results which are similar to each other. Summer flows in the WMA models are more constant than those of the Basin models in which summer declines are followed by earlier rises in the autumn.

The WMA models display a clear range of response to the varying climate scenarios. Warmer scenarios all result in reduced runoff. The percentage of reduction varies throughout the year, reflecting model conditions that vary seasonally as discussed in Section 1. Cooler scenarios yield increased runoff, as would be expected.

The Basin centroid models, Jennings Randolph Reservoir and the Potomac River at Point of Rocks respond to changing climate scenarios more rapidly than the WMA models. This more rapid response is expected from the paekedness of the historical monthly hydrographs. The rapid response characteristic accentuates the runoff generated under the wetter climate scenarios, such as GISS-B, (typified by a wet winter). The warm, wet winter conditions result in a large, immediate jump in runoff.

Examining runoff model results as a whole, a range of variation of +25 to -49 percent of historical climate conditions can be observed. In general, however, the summer months exhibit reductions in runoff under warmer scenarios and increases in summer flows under cooler and/or wetter conditions. The results for the summer period (June through October) are summarized in Table 4.1 for the climate change scenarios as percent deviation from historical conditions, and are plotted in Figures 4.9 to 4.18 (expressed in cms and as percent deviation from historical).

Table 4.1 Sub-basin runoff as percent deviation from historical

Water Supply	Climate Scenario				
Sub-basin	GFDL	GISS-A	GISS-B	UKMO	MPI
Occoquan Res.	-22.0	-32.0	21.6	-7.0	-5.0
Patuxent Res.	-21.0	-32.0	18.4	-12.0	-5.0
Jennings Res.	-0.8	-1.0	1.0	1.6	-0.2
Little Seneca Res.	-21.0	-32.0	14.6	-13.0	-6.0
Point of R. Flow	-24.0	-49.0	25.0	33.0	-15.0

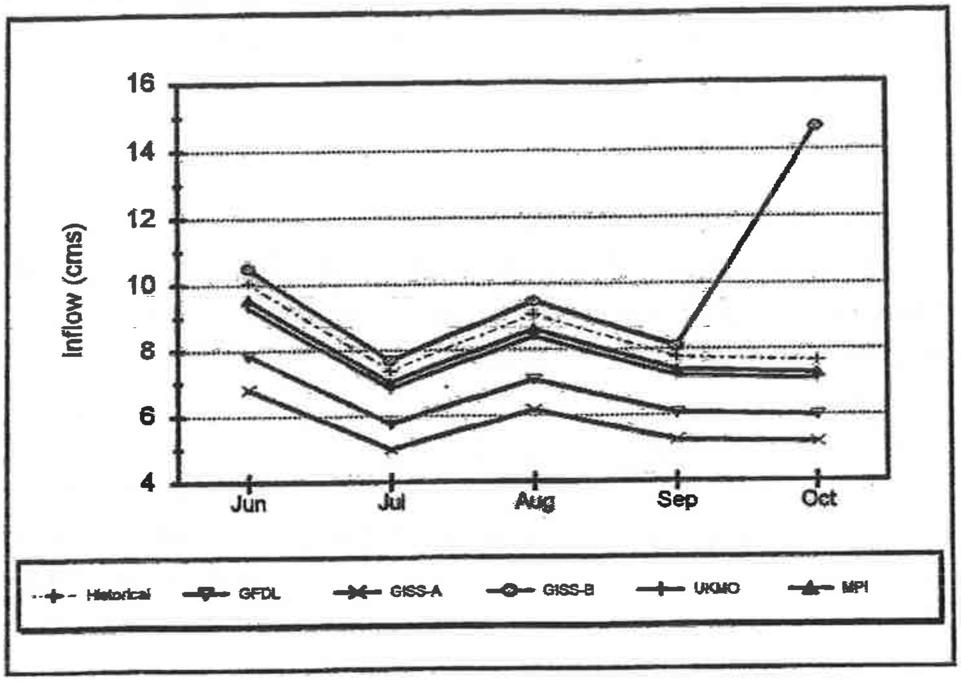


Figure 4.9 Occoquan Reservoir summer inflow (cms)

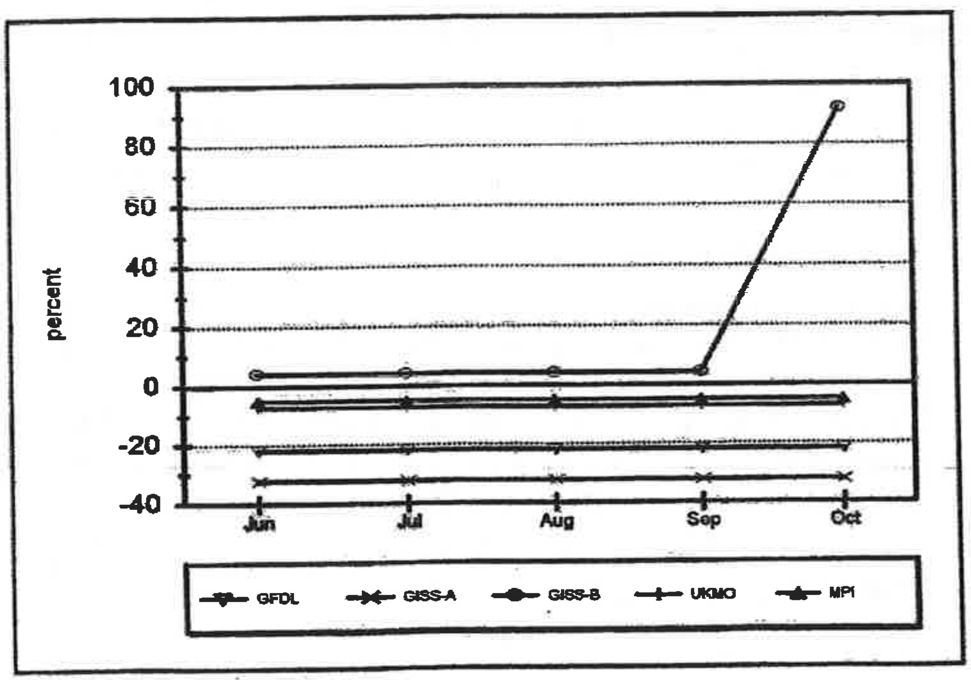


Figure 4.10 Occoquan Reservoir summer inflow deviation from historical (percent)

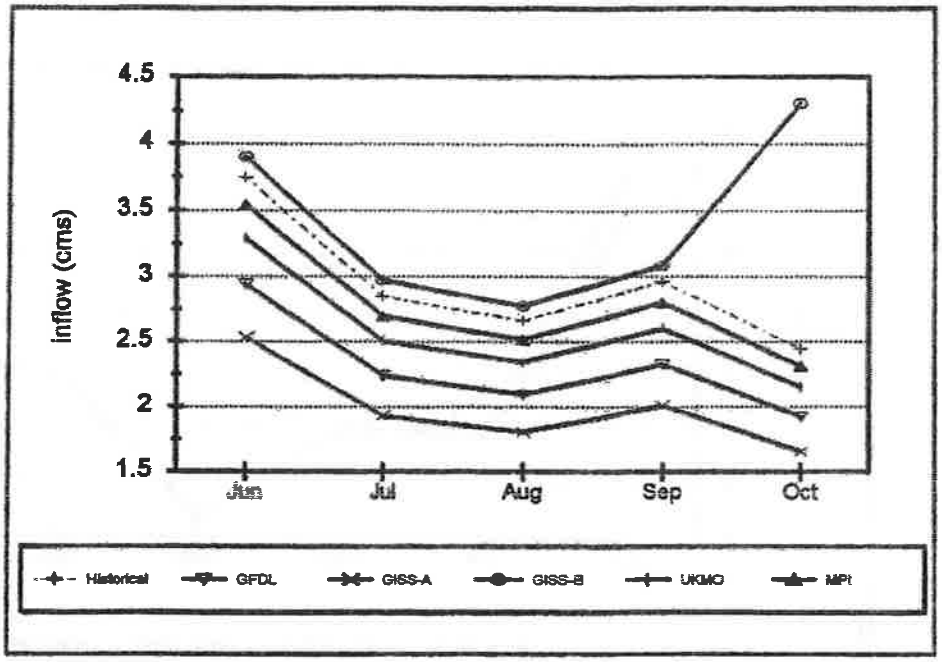


Figure 4.11 Patuxent Reservoir summer inflow (cms)

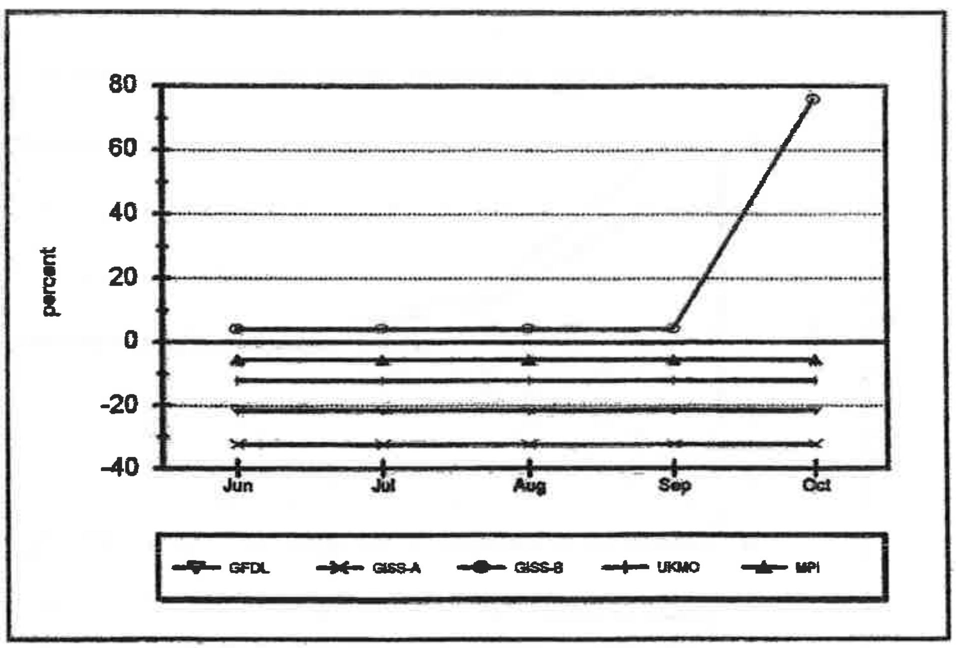


Figure 4.12 Patuxent Reservoir summer inflow deviation from historical (percent)

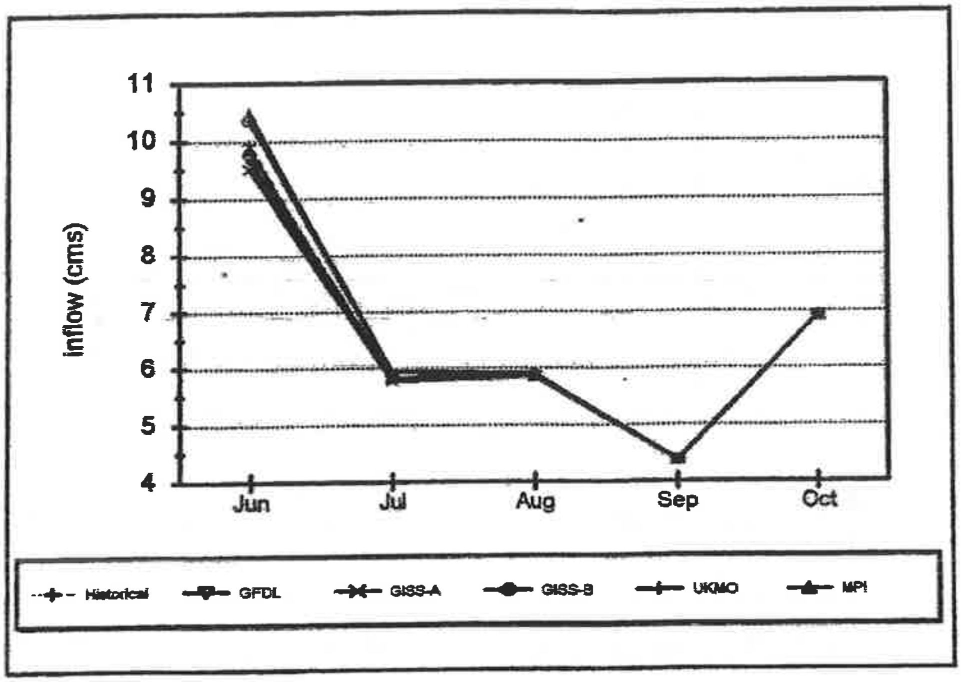


Figure 4.13 Jennings Randolph Reservoir summer inflow (cms)

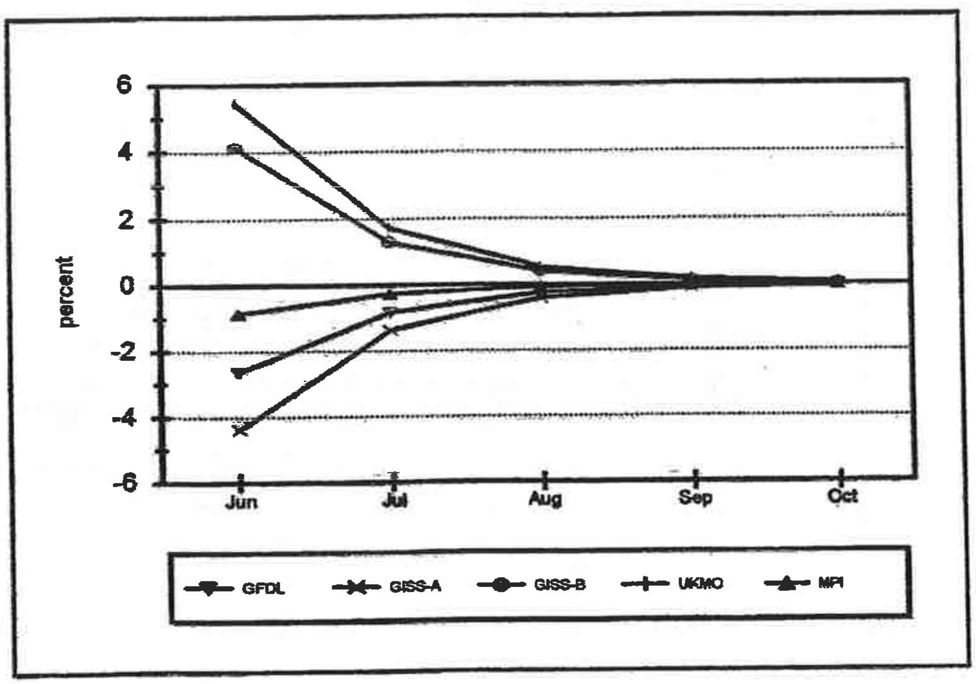


Figure 4.14 Jennings Randolph Reservoir summer inflow deviation from historical

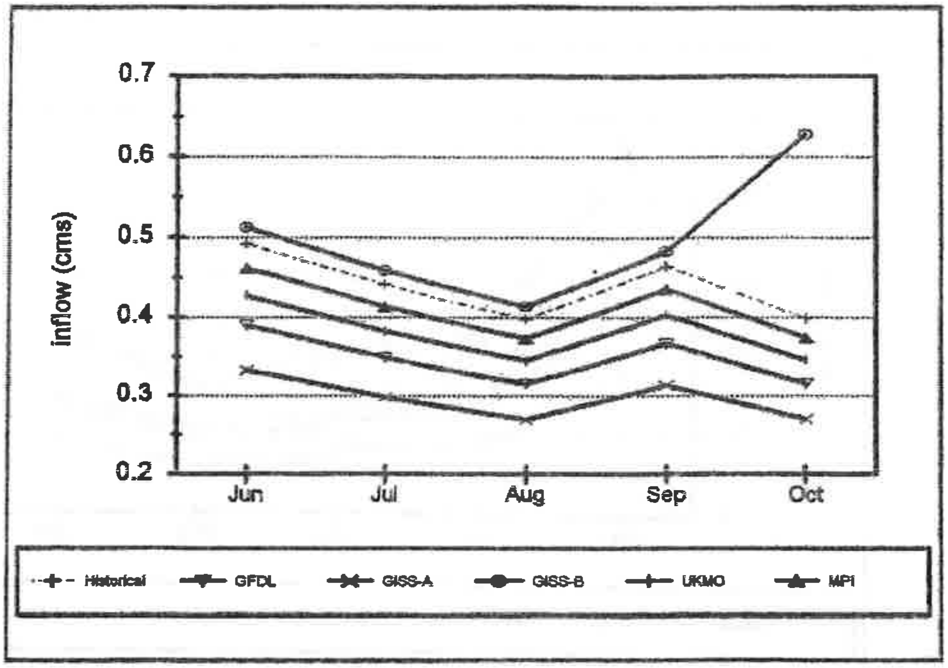


Figure 4.15 Little Seneca Reservoir summer inflow (cms)

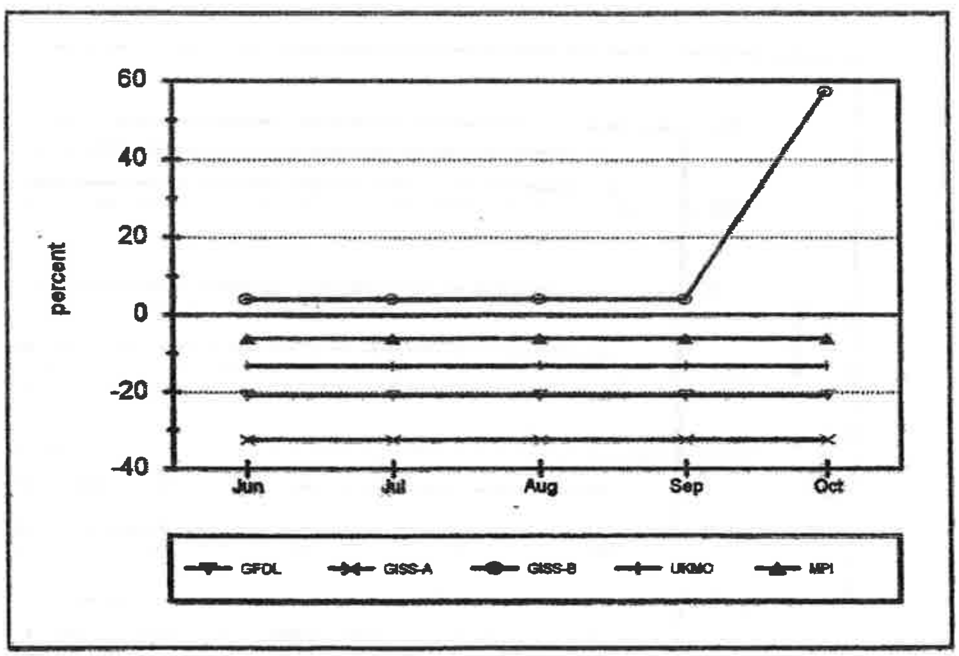


Figure 4.16 Little Seneca Reservoir summer inflow deviation from historical (percent)

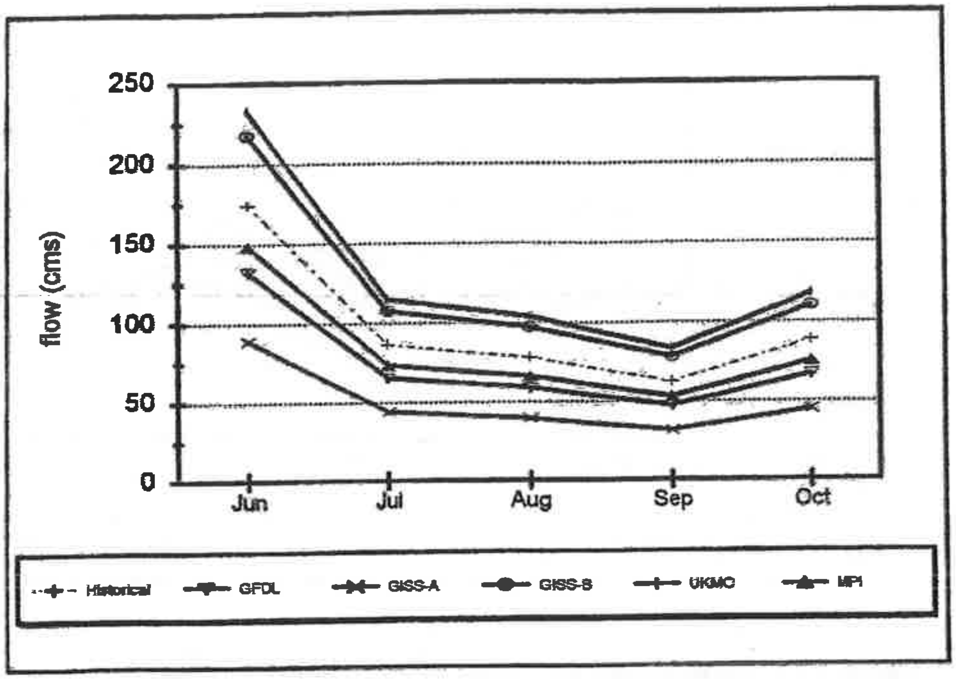


Figure 4.17 Potomac River at Point of Rocks summer flow (cms)

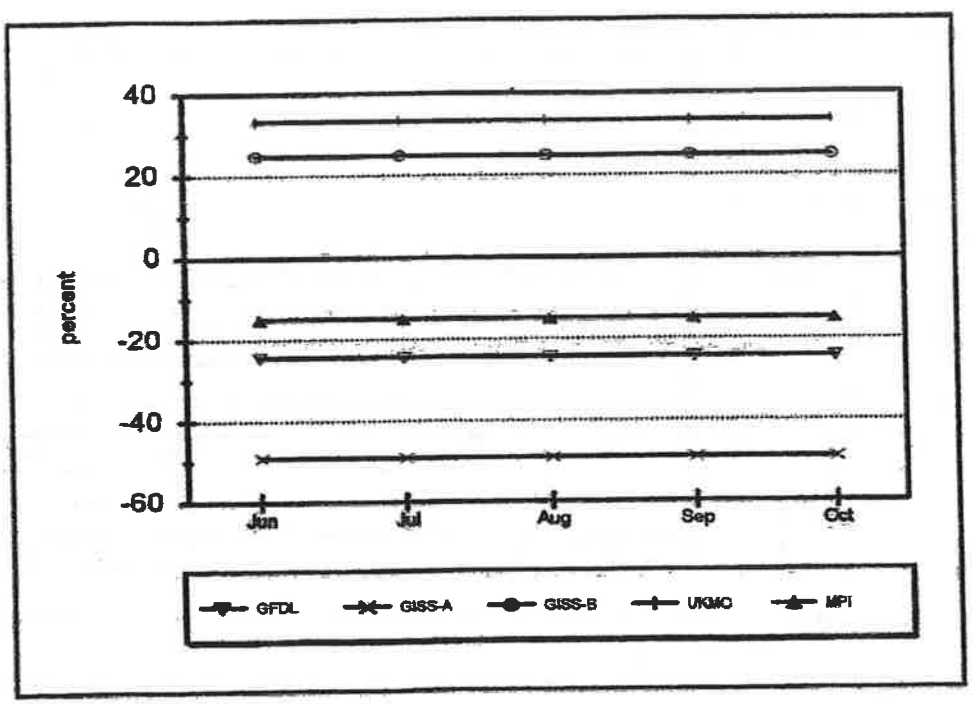


Figure 4.18 Potomac River summer flow deviation from historical (percent)

4.3.2 Hydrologic Model Performance and Limitations

Because the data produced at each step of this study became input to a subsequent step, the uncertainty of each phase of modeling needed to be assessed. In this phase of the analysis, specifically in comparing the various scenario results or runoff, it became clear that there were a number of places where the limits of the modeling approaches were met or exceeded. Thus, before turning to the discussion of the impact of climate uncertainty on the management of water resources, the limitations and overall performance of the hydrologic model employed in this phase of the project are discussed.

Two specifications in particular of the Thornthwaite-Mather approach to hydrologic modeling limit confidence in the results obtained to this point. The first of these pertains to the time scale and the second to the mechanics of the model.

In the Thornthwaite-Mather model, both input temperature and rainfall conditions as well as runoff projections are expressed as monthly averages; accordingly, for model calibration, long term average monthly values were used. Hence, the model can only be used to make projections on similar statistics, that is, to project long term average values, rather than trends or extremes.

The difference between long term average monthly values and monthly averages in a given year can be significant. For example, the variation in flow, as percent deviation from long term average (Normal), for the five sub-basins in the year 1966 is illustrated in Figure 4.19. That year was the drought year of record in the Potomac, as evidenced by the extremely low summer and autumn flows at Point of Rocks and and low inflows to Jennings Randolph Reservoir. While it was not the lowest flow year in these locations (due to local summer storms), it was among the lowest due to a very dry autumn and winter. In both locations, seasonal flows differed by as much as 80 to 90 percent from the long term average flow.

Thus, use of average monthly conditions in a planning process can pose significant disadvantages. When data are to be used to make decisions on the capacity or timing of future resource needs, the information may be inadequate to provide anything more than a relative comparison among scenarios, especially if the application of water management procedures depends on hydrologic signals at a sub-monthly time scale.

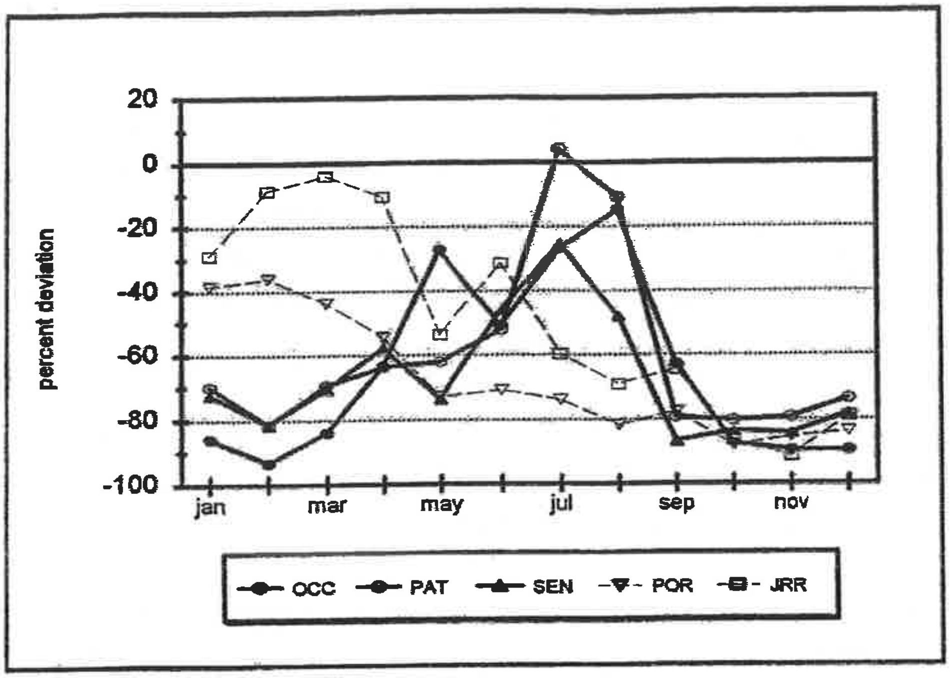


Figure 4.19 Flow deviation: low flow from historical average

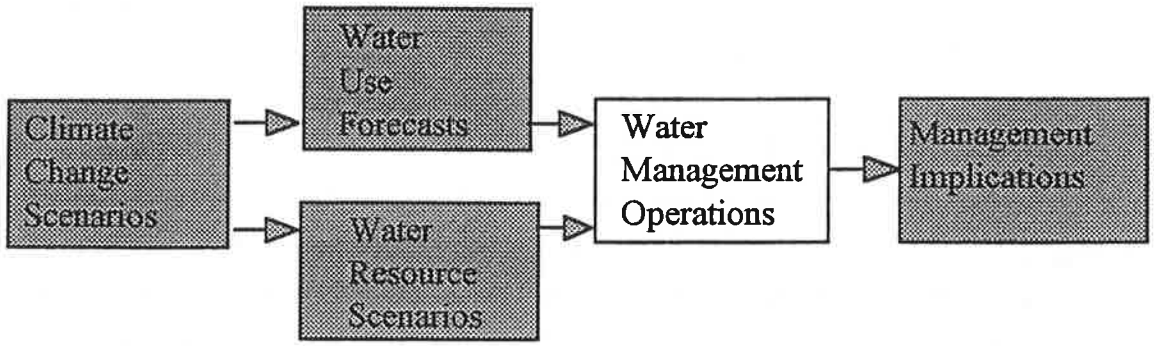
In the case of water supply planning and management, extreme conditions, variability and reliability are crucial. Just as long-term averages eliminate extreme annual conditions from consideration, the use of a monthly time step smoothes daily and weekly extremes. Historically on the Potomac River, variability in streamflow has been significant. For example, the greatest variation in supply occurred in February of 1966 when streamflow jumped from a value near 1.89 mcm/d (500 mgd) to over 378.50 mcm/d (100,000 mgd) (three orders of magnitude) within a two week period, and remained high through the balance of the month. Comparing this type of variability to long term monthly averages illustrates the loss of important characteristics inherent in the use of monthly time-steps. In a similar manner, though to a much lesser degree, municipal demand for water also fluctuates over time.

The loss of information associated with any averaging over time has implications on both the depletion and refill of the supply system. In terms of supply depletion, the loss of variability in inflow due to averaging can lead to an underestimate of capacity needs. Extreme low flows, which dictate peak supply requirements, are lost to consideration. On the other hand, averaging out peak flows assumes more time for their capture (to recharge the supply system) and thus overestimates total available supply at the same time as underestimating maximum needs. The peak flows in the river flow to the estuary, unused for municipal supply, while peak demands have to be met.

The refill aspect of monthly time-step smoothing leads to the second inherent limitation of the model. The Thornthwaite-Mather model is based on a simplified soil moisture accounting system, using estimated soil moisture capacity and retention factors. During months when precipitation exceeds evapotranspiration, excess flow fills soil moisture to capacity. In months when evapotranspiration exceeds rainfall, the soil moisture is depleted at a rate determined by the retention factor. Soil moisture deficit accumulates during periods of depletion. Precipitation that occurs when the soil moisture deficit is greater than zero first refills the accumulated deficit before becoming available as runoff.

During the summer months when soil moisture was depleted, all runoff models achieved a constant rate of recession. At these times, the model calculated no direct runoff because the soil moisture deficit was positive. Considering this assumption, while at the same time keeping in mind the extreme variability of flows in the historical record, it is obvious that perfect capture is a misleading assumption. Again, this simplifying assumption led to the overestimation of long term supply during these periods.

Thus, while the hydrologic modeling approach supported a comparative analysis and sound long-term average projections, the limitations of the approach need to be kept in mind as the results become input for the analysis of water management operations.



5: WATER MANAGEMENT OPERATIONS

5.1 Introduction

An important study objective is to determine the extent to which decisions regarding future planning and water management operations may need to be made specifically as a result of potential future climate conditions which may be different from those of recent decades. These decisions may be different from those made for present conditions. To determine if it is appropriate that the operation of water resources be changed now or in the future due to the potential effects of climate change, it is important to examine how water resources are presently managed. Current management can be considered to be the "without" climate change condition, which is referred to as the historical climate scenario conditions presented in this study. In addition to possible changes in future operations, the planning for future resources and demand management considerations may be affected under conditions “with" potential climate change.

Water management operations for the WMA are based on the primary objective of coordinated use of all resources in order to maximize the possibility of satisfying the demands for water of the three major suppliers, without relying on restrictions. Both demands for water and resources available to meet those demands display short and long-term cycles. Rates of demand and resource availability are relevant to operations on an hourly, daily, weekly, seasonal and annual basis in the WMA. Although many water resource management operations are conducted on shorter time intervals, a monthly time step was adopted for this study. A month is a compromise among the availability of climate data from the GCM runs, the water use forecast time step, modeled runoff response to climate change stimuli, and current management operations time scales. The water demand and runoff values used as input to the management operations model reflect average monthly conditions for the historical and each of the climate change scenarios.

The development of water demand data is discussed in Section 3. The raw water resources are principally dependent upon the natural flow of the Potomac River and reservoir inflows discussed in Section 4. This section describes the operation of the water supply system for the WMA under current operating rules, assuming historical climate conditions; and provides the context for the presentation of how altered climate may affect the planning for future resources.

Water is supplied to the WMA by the three major water supply utilities: Fairfax County Water Authority (FCWA), Washington Aqueduct Division (WAD) of the U.S. Army Corps of Engineers, and Washington Suburban Sanitary Commission (WSSC). The Interstate Commission on the Potomac River Basin (ICPRB) is responsible for providing coordinated resource management to the utilities when the *natural* flow of the river, together with the maximum safe withdrawal from the local reservoirs, is predicted to be insufficient to meet unrestricted off-stream demands plus an environmental in stream flow requirement. Under these conditions, the flow in the Potomac River is augmented by releases from Jennings Randolph and Little Seneca reservoirs; and the objective of meeting all *unrestricted* demands and the in stream flow requirement, with coordinated resource allocation, continues.

Each of the three utilities has two sources of raw water supply with associated water treatment works. Each has an intake on the mainstem of the Potomac River near the District of Columbia (WAD, which serves Washington, D.C. and parts of northern Virginia, has two river intakes but no access to off-Potomac reservoirs). The suburban utilities (FCWA and WSSC) each own off-Potomac direct supply reservoir sources. The intakes, reservoirs and treatment facilities are shown schematically in Figure 5.1.

The operational procedures are specified in the Drought Operations Manual which is part of the Water Supply Coordination Agreement (1982) among the water utilities and ICPRB. Those procedures require that withdrawals from the off-Potomac direct supply reservoirs be limited to rates which allow them to meet predetermined refill targets. The rest of the demand is to be met from the Potomac River, with low flow augmentation releases from upstream water supply storage as necessary. Each of the utilities has constraints on its treatment and distribution systems which determine the maximum extent to which each of the sources may individually satisfy demands.

With current operating policies, existing resources would be completely exhausted under hydrologic conditions of the worst drought of record when forecasted demands reach levels expected in approximately the year 2030, Mullusky, et al. (1996). These policies assume no diminution of storage capacity due to sedimentation, and that all reservoirs are emptied without resort to restrictions. However, as a recent refinement to those policies, new resources will be needed prior to the year 2030, as severe restrictions would in all likelihood be imposed long before reservoir storage is fully exhausted.

Two operational algorithms were examined: (1) daily operations as currently used in annual drought preparedness exercises, and which would guide the region in the event of an actual drought or water shortage from another cause, and (2) current operating policies adapted to monthly and "seasonal" time scales which are more appropriate for the present application.

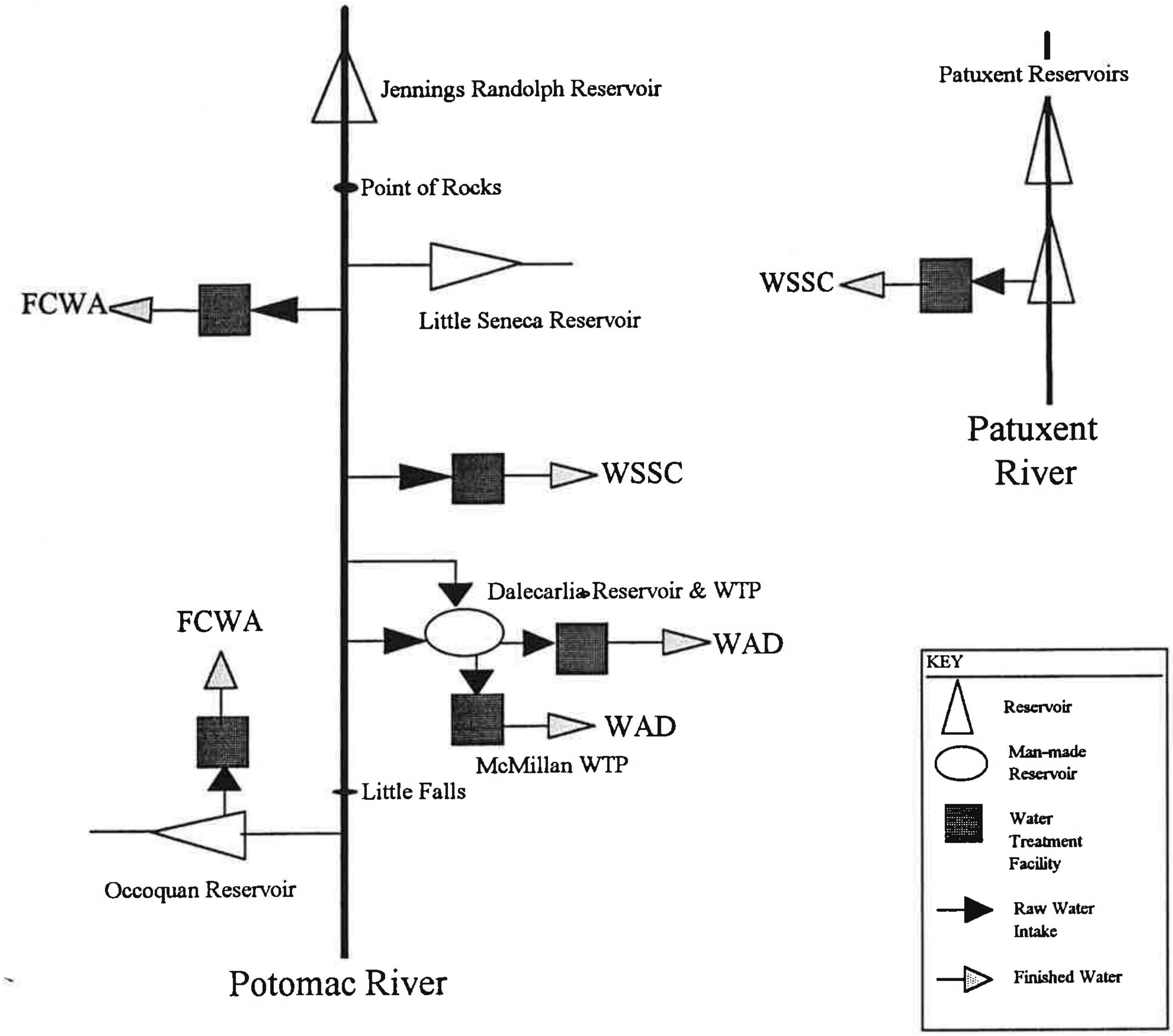


Figure 5.1 WMA resource and treatment facilities

5.2 Daily Water Management Operations Algorithm

There is a long history of concern and planning for meeting the anticipated future demands for municipal water supply in the WMA. A comprehensive study was conducted by the U.S. Army Corps of Engineers (1963) which identified 16 large new water supply/multi-purpose reservoirs in the Potomac River basin to meet foreseeable demand. The proposed reservoirs met significant difficulty with public acceptance and appropriation of construction funds. Following the severe drought of the 1960s in the northeastern portion of the U.S., the Corps of Engineers (1977) conducted a water supply study of that area which identified a number of alternatives for the WMA to meet its anticipated future water shortage. As an outgrowth of the Northeastern United States Water Supply Study, the Corps of Engineers (1983) conducted a detailed evaluation of alternative methods of alleviating anticipated future deficits. The current mode of coordination of use among water resources for the WMA began with the work of Palmer et al. (1982).

The first of the two water management algorithms used for this study is based on a suite of daily programs and spreadsheets currently used by the ICPRB Section for Cooperative Operations on the Potomac, but modified only slightly to operate on a monthly time step. The procedure is summarized in the following steps:

a. monitor river flows, compare with action thresholds of flow and current demands,
b. forecast municipal and suburban demands for the operating period,
c. add in stream environmental requirements to determine total demands,
d. utilize river flow in excess of environmental requirements to meet as much municipal demand as possible,
e. meet remaining suburban utility demands with reliable yield of off-Potomac reservoirs, and
f. meet remaining WAD and suburban demand deficit by releases from up stream low flow augmentation storage.

The operational methods underlying the individual components of the water resources management model are discussed more fully in the following sections.

5.2.1 Local Resource Allocation to Meet Utility Demands

The first steps in water management operations for the WMA involve determining the current state of local resources and allocating available water to the expected demands of each of the water utilities.

Potomac river flows were developed for each climate change scenario as described in Section 4. The WAD demand is met from the Potomac River via its gravity intake at Great Falls and an intake at Little Falls, which requires pumping. Each intake is capable of supplying the total WAD demand; however, it is preferred to meet as much demand as possible at the Great Falls intake. Withdrawals below 1.32 cms (30 mgd) at Great Falls are not feasible. The treatment capacity at each of the two WAD plants is capable of meeting the demand of the entire WAD service area.

Additionally, a current environmental instream flow requirement of 13.2 cms (300 mgd) must pass the WAD Potomac River intake at Great Falls, and an environmental flow of 4.4 cms (100 mgd) must pass the downstream WAD intake at Little Falls, in order to support aquatic habitat down stream to the head of tide. This requirement is specified in the Potomac River Low Flow Allocation Agreement (1978) and the recommendations of the Maryland Department of Natural Resources Potomac River Environmental Flow-by Study (1981).

Reservoir inflows for this study were determined using the Thornthwaite-Mather water balance model described in Section 4. The maximum reliable withdrawal from each of the *direct supply* reservoirs is available to meet demands of the respective suburban utility distribution area. The reliable withdrawal rate is calculated such that the reservoirs refill to 90 percent of capacity with 95 percent probability by the following June 1st. Reservoir withdrawals and remaining storages are tracked in the operations model. Inflow to the reservoirs in excess of the available unused storage capacity is spilled. Similarly, the inflow to the *flow augmentation* reservoirs is determined, as well as storage, spill, and discharge.

The operational algorithm first draws on Potomac River flow (in excess of environmental requirements) and minimum operating requirements at the Occoquan and Patuxent treatment plants to meet as much municipal demand as possible. All the demand from WAD must be met from Potomac River. Any remaining demands of the suburban utilities are first met by residual unallocated flow in the river, next by withdrawals from the Occoquan and Patuxent reservoirs, up to their safe yield, and finally by flow augmentation releases from upstream reservoirs in the Potomac River basin.

5.2.2 Potomac River Flow Augmentation Storage Releases

If the flow in the Potomac River is insufficient to meet the instream flow requirements and utility demand, flow augmentation releases are made from river regulating storage in upstream reservoirs (Jennings Randolph and Little Seneca).

Jennings Randolph Reservoir is a multi-purpose project, operated by the Corps of Engineers for water supply, water quality improvement, and flood control. Water quality storage is used to maximize water quality in approximately 230 miles of the North Branch and the mainstem Potomac River, including the environmental flow-by requirement at Little Falls. The water quality release requirements are described in the U.S. Army Corps of Engineers Master Manual for Reservoir Regulation, North Branch Potomac River Basin (1986).

Releases from Jennings Randolph Reservoir to satisfy water supply needs are made in addition to the amount of water quality releases. Inflows to the reservoir are allocated to water supply and water quality storage accounts according to the Master Manual. The monthly operations spreadsheet accounts for inflows, releases, spills and changes in water supply storage.

Little Seneca Reservoir, nearer to Washington, D.C., is normally used to make up within day differences between demand from the river and available flow as augmented by Jennings Randolph Reservoir releases, which would have been made several days previously. Due to the modified daily time step of the operations model developed for this study, Little Seneca Reservoir storage was used simply as additional storage. Jennings Randolph and Little Seneca were combined in a single storage facility referred to as River Augmentation Storage (RAST). Releases were made from RAST to make up deficits in any of the flow requirements discussed previously. RAST releases were subject to combined rates and capacities of the two contributing reservoirs. Combined releases were decomposed into releases from Jennings Randolph and Little Seneca at rates proportional to their inflows.

5.3 Daily Model Performance and Limitations

The modified daily management model was run initially with demand data for 2030 under the historical climate scenario. The run with historical climate was intended to test the model operations and produce a baseline estimate of water resource usage for comparison with the range of climate change scenarios. None of the runs significantly stress the current supply system.

This result was unexpected; however, it can be explained by the somewhat unrealistic starting condition of the state of reservoir storage. It was assumed that all reservoirs would be full at the beginning of the water supply season, as has been the case historically. However, in all likelihood, with the anticipated growth in future demand they would contain a volume of storage more representative of the minimum acceptable amount (presently 90 percent of capacity).

5.4 Monthly and "Seasonal" Application of Major Operating Policies

The use of a modified daily management model having failed to produce credible results, a monthly and summer "seasonal" application of major water resource operating policies was carried out with regard to the following considerations.

5.4.1 Temporal Resolution

The critical conditions of water supply (highest demand and lowest river flow and reservoir inflow) do not exactly coincide for the WMA. Therefore, this operational analysis for climate change effects is conducted for a period which includes both critical conditions. The "season" June through October is chosen for analysis of water resources operations because it provides a margin of one month prior to the month of typically highest demand (July) and one month after the month of typically lowest river flow (September). The beginning of this period coincides with the operational target date on which current operating policies require the reservoirs to be at least 90 percent full to begin the water supply season.

5.4.2 Reservoir Utilization

The WMA water supply system reservoirs have gross and net water supply volumes as shown in Table 5.1. Net storage is in addition to storage set aside for sediment accumulation and dead storage, which is not accessible for withdrawal. Also shown are values representing 90 percent of net storage as the operational target for refill by June 1st, and 50 percent of net storage. This operations analysis assumes that all reservoirs are 90 percent full on June 1st, and are used on a consistent (or average) daily basis during the chosen critical operating "season," June through October. At the end of the period, the reservoirs are assumed to still contain 40 percent of net water supply storage. This is a somewhat arbitrary figure which assumes that around November, reservoir inflows exceed withdrawals and flow in the Potomac rebounds significantly from low summer values. Also, the analysis initially assumes no application of water use restrictions during the June through October period. It is assumed that restrictions would likely be imposed when reservoir resources decline to below approximately 40 percent. Thus, there is approximately 50 percent of net water supply storage, in addition to inflows, available for the period June through October under these assumptions.

Table 5.1 Washington Metropolitan Area reservoir capacities

Reservoir	Gross		Net		90% of Net		50% of Net	
	mcm	bg	mcm	bg	mcm	bg	mcm	bg
Jennings Randolph	50.79	13.40	50.79	13.40	45.71	12.06	25.39	6.70
Occoquan	31.84	8.40	31.08	8.20	16.60	7.38	15.54	4.10
Patuxent	41.69	11.00	39.80	10.50	35.82	9.45	19.90	5.25
Little Seneca	15.92	4.20	14.67	3.87	13.19	3.48	7.35	1.94
Total	140.24	37.00	136.34	35.97	111.32	32.37	68.18	17.99

5.4.3 "Seasonal" Operations

The available water supply storage for the June through October "season" would be 68.07 mcm (17,985 mg). Spread over the 153 days of the "season," this would provide a supply of 0.44 mcm/d (117.5 mgd). To this yield of 50 percent of net storage on June 1st can be added the inflow to each reservoir under historical and climate change scenarios. All of the inflow is assumed available for water supply purposes, without regard to small quantities required for minimum releases from the dams. Spills are assumed to be negligible, as the reservoirs are filled to only 90 percent of capacity on June 1st, and in a critical year, withdrawals would likely exceed inflows. The initial storage and "seasonal" inflow represent the maximum available yield from the reservoirs. These quantities are shown in Table 5.2. The available flow in the Potomac River for each climate scenario is shown in Table 5.3 for each "seasonal" month.

Table 5.2 June through October "Seasonal" available water supply from reservoirs

GCM	Initial Storage		Occoquan		Patuxent		Little Seneca		Jennings R.		Total from Reservoirs	
Scenario	mcm/d	mgd	mcm/d	mgd	mcm/d	mgd	mcm/d	mgd	mcm/d	mgd	mcm/d	mgd
Historic	0.44	117.5	0.72	191.1	0.25	66.9	0.04	10.0	0.57	150.4	2.03	535.9
GFDL	0.44	117.5	0.56	149.2	0.20	52.6	0.03	7.9	0.56	148.9	1.80	476.0
GISS-A	0.44	117.5	0.49	129.4	0.17	45.3	0.03	6.8	0.56	147.9	1.69	446.8
GISS-B	0.44	117.5	0.87	229.9	0.29	77.7	0.04	11.4	0.58	152.8	2.23	589.3
UKMO	0.44	117.5	0.67	177.1	0.22	58.8	0.03	8.7	0.58	153.5	1.95	515.5
MPI	0.44	117.5	0.69	181.6	0.24	63.3	0.04	9.4	0.57	149.9	1.97	521.6

Table 5.3 Flow of Potomac River at Point of Rocks for "seasonal" months

GCM	Jun		Jul		Aug		Sep		Oct	
Scenario	mcm/d	mgd	mcm/d	mgd	mcm/d	mgd	mcm/d	mgd	mcm/d	mgd
Historical	15.07	3983	7.45	1968	6.71	1774	5.38	1422	7.64	2019
GFDL	11.39	3010	5.63	1488	5.08	1341	4.07	1075	5.78	1526
GISS-A	7.68	2028	3.79	1002	3.42	903	2.74	724	3.89	1028
GISS-B	18.80	4967	9.29	2455	8.37	2213	6.71	1773	9.53	2518
UKMO	20.09	5307	9.93	2623	8.95	2364	7.17	1894	10.18	2690
MPI	12.81	3385	6.33	1673	5.71	1508	4.57	1208	6.49	1716

The analysis proceeded by comparing the "seasonal" (June through October) water demands under each of the Conservation Policies with the reservoir storage (50 percent of capacity plus "seasonal" inflows) and available natural flow of the Potomac River in order to determine the number of months in which flow in the river would be insufficient to meet demands and what deficits might occur.

5.4.4 Results

The results for each of the Conservation Policies are presented in Tables 5.4 to 5.6. In addition to the number of months within the critical "season" that the combined resources of the reservoirs and Potomac River cannot meet the projected demand, the average daily deficit during those months, and the accumulated volume of that deficit are shown. These conditions result from the analysis of the combined impact of potential climate change on both water resource availability and water demand.

Although, under Conservation Policy 1 (prevailing year 1990 measures), four of the five climate change scenarios require more withdrawals from the Potomac River than a continuation of historical conditions only the GFDL and GISS-A scenarios show conditions which potentially could not be met in the year 2030 with currently available resources. Under conditions of the GFDL scenario, a deficit will occur in one month, resulting in an unmet demand of 0.24 mcm/d (64.3 mgd) which is equivalent to 7.42 mcm (1,961.0 mg) of storage. Under the GISS-A scenario, deficits will occur in four months, resulting in an average unmet demand of 0.63 mcm/d (165.3 mgd) for that period, which is equivalent to 76.00 mcm (20,080.5 mg) of storage (see Figure 5.4).

Under Conservation Policy 2 (as Policy 1 plus public education, reuse/recycling, and advanced plumbing code), only the GISS-A scenario in the year 2030 would result in a water supply source deficit. The deficit would occur in one month only, and would amount to 0.21 mcm/d (55.4 mgd). The accumulated volume of the deficit would be 6.29 mcm (1662.0 mg) (see Figure 5.5).

Under Conservation Policy 3 (as Policy 2 plus a 50 percent increase in water and wastewater tariffs), there would be no deficits in any months in the year 2030 (see Figure 5.6).

Table 5.4 System performance (June through October) under Conservation Policy 1

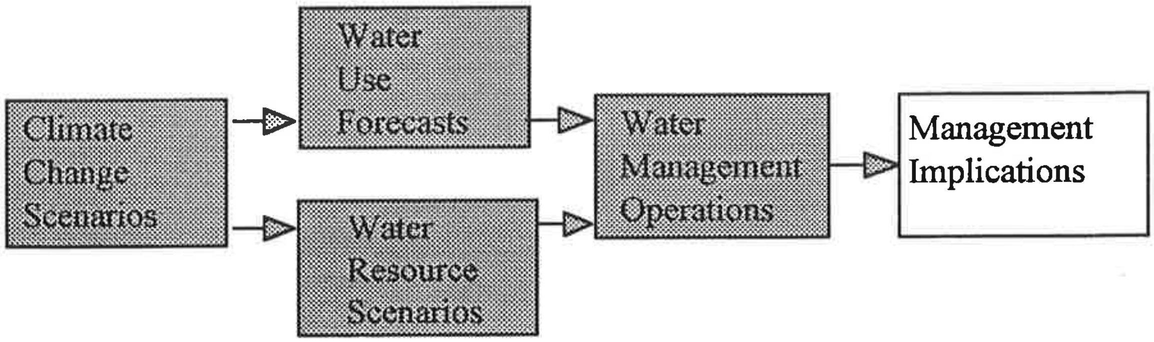
GCM Scenario	Conservation Policy 1 Demands mcm/d	Conservation Policy 1 Demands mgd	Months Deficit Jun-Oct	Daily Deficit mcm/d	Daily Deficit mgd	Accumulated Deficit (volume) mcm	Accumulated Deficit (volume) mg
Historical	5.42	1431.4	0				
GFDL	6.11	1615.3	1	0.24	64.3	7.42	1961.0
GISS-A	5.78	1526.6	4	0.63	165.3	76.00	20080.5
GISS-B	4.82	1272.4	0				
UKMO	6.29	1661.8	0				
MPI	6.17	1631.2	0				

Table 5.5 System performance (June through October) under Conservation Policy 2

GCM Scenario	Conservation Policy 2 Demands mcm/d	Conservation Policy 2 Demands mgd	Months Deficit Jun-Oct	Daily Deficit mcm/d	Daily Deficit mgd	Accumulated Deficit (volume) mcm	Accumulated Deficit (volume) mg
Historical	4.36	1151.9	0				
GFDL	4.92	1299.9	0				
GISS-A	4.64	1225.9	1	0.21	55.4	6.29	1662.0
GISS-B	3.87	1022.5	0				
UKMO	5.06	1336.9	0				
MPI	4.98	1315.7	0				

Table 5.6 System performance (June through October) under Conservation Policy 3

GCM Scenario	Conservation Policy 2 Demands mcm/d	Conservation Policy 2 Demands mgd	Months Deficit Jun-Oct	Daily Deficit mcm/d	Daily Deficit mgd	Accumulated Deficit (volume) mcm	Accumulated Deficit (volume) mg
Historical	3.93	1038.3	0				
GFDL	4.45	1175.7	0				
GISS-A	4.20	1109.6	0				
GISS-B	3.50	924.7	0				
UKMO	4.58	1210.0	0				
MPI	4.49	1186.3	0				



6: MANAGEMENT IMPLICATIONS

6.1 Introduction

The input data developed for this study, and most of the modeling analyses, relied on a monthly time step. This temporal resolution is a compromise between the longer (winter/summer) time step preferred for long-term demand forecasting, and the shorter daily time scale actually used for water management operations for the WMA. The daily operations model of the Interstate Commission on the Potomac River Basin performed poorly because the water balance model was calibrated to historical average monthly values which over-estimate supply in many years. This condition resulted in an unrealistic basis on which to test potential climate change inputs for management implications. However, more meaningful results were determined by broadly applying current operating policies to monthly and "seasonal" time scales. The results show the combined analysis of potential climate change concurrently impacting water supply resources and water use. The operational objective of WMA water resources system management is to examine the degree to which the existing system could meet demand forecast to the year 2030 under conditions with and without climate change.

6.2 Response to Climate Change

Although significant effort was put into adapting the ICPRB daily operations management tools for use in monthly climate change analysis, the results did not show realistic system responses. That line of analysis was abandoned for a somewhat broader application of current operating policies which produces results that are credibly consistent with the rest of the study.

The operational analysis compared initial reservoir contents, and modeled reservoir inflow and Potomac River flow, with water use forecast to year 2030 for the historical and each of the five climate change scenarios for the critical "season." Only the GISS-B scenario resulted in conditions with less impact on resources than the historical forecast scenario. However, under Conservation Policy 1 (prevailing year 1990 measures), two climate change scenarios result in water supply deficits. These occurred even with full utilization of all river flow available for water supply. The GFDL scenario shows a deficit of 0.24 mcm/d (64.3 mgd) for the month of September, resulting in a cumulative deficit of 7.42 mcm (1,961.0 mg). The GISS-A scenario shows a deficit of 0.63 mcm/d (165.3 mgd) for the months of July through September, resulting in a cumulative deficit of 76.00 mcm (20,080.5 mg). These deficit results indicate that there are potential climate change scenarios which would require management actions that would be different from those required if historical climate conditions continued into the future.

The GFDL scenario water supply deficit of 0.24 mcm/d (64.3 mgd) is only approximately four percent of total water use forecast for GFDL conditions in September of the year 2030 under Conservation Policy 1. There would be no supply deficits for the GFDL scenario with water use forecasts calculated under conditions of Conservation Policy 2 or Policy 3.

The GISS-A scenario water supply deficit of 0.63 mcm/d (165.3 mgd) is approximately eleven percent of total water use forecast for GISS-A conditions averaged for the period July through October of year 2030. The largest monthly deficit, 1.35 mcm/d (355.8 mgd) occurs in September of the year 2030, and amounts to 23 percent of total demand calculated under Conservation Policy 1 for that month. There would be a deficit of approximately only three percent with reduced water use forecasts calculated under conditions of Conservation Policy 2, and no deficit with even lower water use forecasts under Conservation Policy 3.

Thus, from the examination of simultaneous impacts of a range of climate scenarios on water demand and the supplies to meet those demands, the following implications can be observed for the management of water supply sources in the Potomac River basin:

- Both water demands and the performance of presently available water supply resources would be impacted by changes in climate.

- Water demands and water supply resource performance move in opposite directions under the influence of climate change, confounding the ability of resources to meet demands.

- Under all potential climate change scenarios examined, conservation (demand management) is a potential means to reduce water use and thus contribute to the mitigation of future water supply deficits.

- Under the selected range of potential climate change scenarios, water resources managers need to be aware that resources may be more (or less) fully utilized than under a continuation of historical climate conditions.

- Under most climate scenarios examined, presently available water supply resources could satisfy water demands forecast (for this study) to occur in the year 2030.

- For those few climate change scenarios under which presently available water supply resources could not satisfy demands, the supply-demand imbalance could be made up entirely by increased conservation in water use.

- At this time, water management decisions should involve consideration of whether or not to plan for the mitigation of the most severe climate change impacts determined in this study.

- If the decision is made now to plan for the mitigation of climate change impacts, the choices of effective measures would include: the imposition of increased conservation measures, construction of new water supply resources, or a combination of the two.

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APPENDIX A:

Summer Water Use Forecasts for Year 2030

Summer Water Use Forecasts for Year 2030

In attempting to use IWR MAIN to forecast summer water use for year 2030, an apparent anomaly was noted for some counties. In these cases, summer water use was equal, or nearly equal to winter water use for the same year, and invariant across climate scenarios. The source of this problem can be seen by considering the expressions used (in the eastern US) to estimate water use for metered and sewered single family residences, the largest single waer use category in WMA suburban areas.

Winter Usage

$$(Q_w)_{ms} = (234 + 1.451\ V/F_a - 45.9\ P_a - 2.59\ I_a)\ N_r \qquad \text{(A-1)}$$

Summer Use

$$(Q_s)_{ms} = (385.0 + 2.876\ V/F_a - 285.8\ P_s - 4.35\ I_s + 157.77\ B\ MD)\ N_r \qquad \text{(A-2)}$$

$$(Q_s')_{ms} = MAX\{(Q_w)_{ms}\ ,\ (Q_s)_{ms}\} \qquad \text{(A-3)}$$

Average Annual Use

$$(Q_a)_{ms} = [(Q_w)_{ms} + (Q_s')_{ms}]/2 \qquad \text{(A-4)}$$

Where:

Q	= water use for a particular category, gpd
V	= average home value in a range of values (1980 $1,000)
F_a	= assessment factor, if applicable; 1.0 otherwise
P_a	= effective annual price of water and sewer (1980 $/1,000 gals)
I_a	= effective annual bill difference variable (1980 $/billing period)
P_s	= effective summer marginal price of water and sewer (1980 $/1,000 gals)
I_s	= effective summer bill difference variable (1980 $/billing period)
B	= irrigable land per dwelling unit (acres/unit) = $0.803\ H_d$-1.26
H_d	= housing density (units/acre)
MD	= summer season moisture deficit (inches/season) = E - 0.6 R
E	= summer season potential evapotranspiration (inches/season)
R	= summer season precipitation (inches/season)
N_r	= number of residences in value range

The explanatory variables should all be familiar with the possible exception of I, the bill difference variable. This economic variable, added to the specification by Howe (1982), reflects the effect of block-type tariff structures and fixed charges on water use. It is defined as the difference between the actual cost of water to the typical user for a billing period, and the cost that would apply if all water were billed at the marginal price. The variable is believed to capture the income effect of tariff design.

The summer water use forecasting problem arises because of the linear specification used for the summer season (equation A-2). Housing value is assumed to increase in real terms over time (based on growth models contained within IWR MAIN), so that the value of equation A-1 is larger on a per- unit basis in 2030 even though the water tariff does not change. However, when negatively signed variables such as the price of water (P) and the bill difference variable (I) are large in absolute terms, as they are in most of the suburban counties, the heavy weight given to these variables in equation A-2 can produce a summer water use estimate that is less than winter water use (equation A-1). This is in spite of the effect of increasing housing value on both equations. The constraint imposed by equation A-3 leads to a result of uniform year-round use.

In order to avoid this problem, an alternative method for estimating summer water use is developed. This method relies on IWR MAIN to produce estimates of both winter and summer water use for 1990. IWR MAIN also produces a forecast of 2030 winter water use. Summer water use for the year 2030 is estimated by the following expression:

$$Q_{s,2030} = Q_{w,2030} \, (Q_{s,1990}/Q_{w,1990}) \, (MD_{2030}/MD_{1990})^{0.904} \qquad \text{(A-5)}$$

Where:

Q_s = total summer water use, gpd

Q_w = total winter water use, gpd

The exponent, 0.904, is estimated from the data set originally used by Howe and Linaweaver (1967), and later by Howe (1982) to generate equations A-1 and A-2. This approach avoids the problem described above and produces year 2030 forecasts which at least reflect the differences in the climate scenarios. Whether this exponent derived from data more than 30 years old is appropriate for water use patterns more than 30 years in the future cannot be determined. If it is in error, the result will be incorrectly forecast summer/winter ratios. The principal results of this study, which are the variation among climate scenarios and the effect on water use of demand management practices, are not unduly sensitive to this assumption.