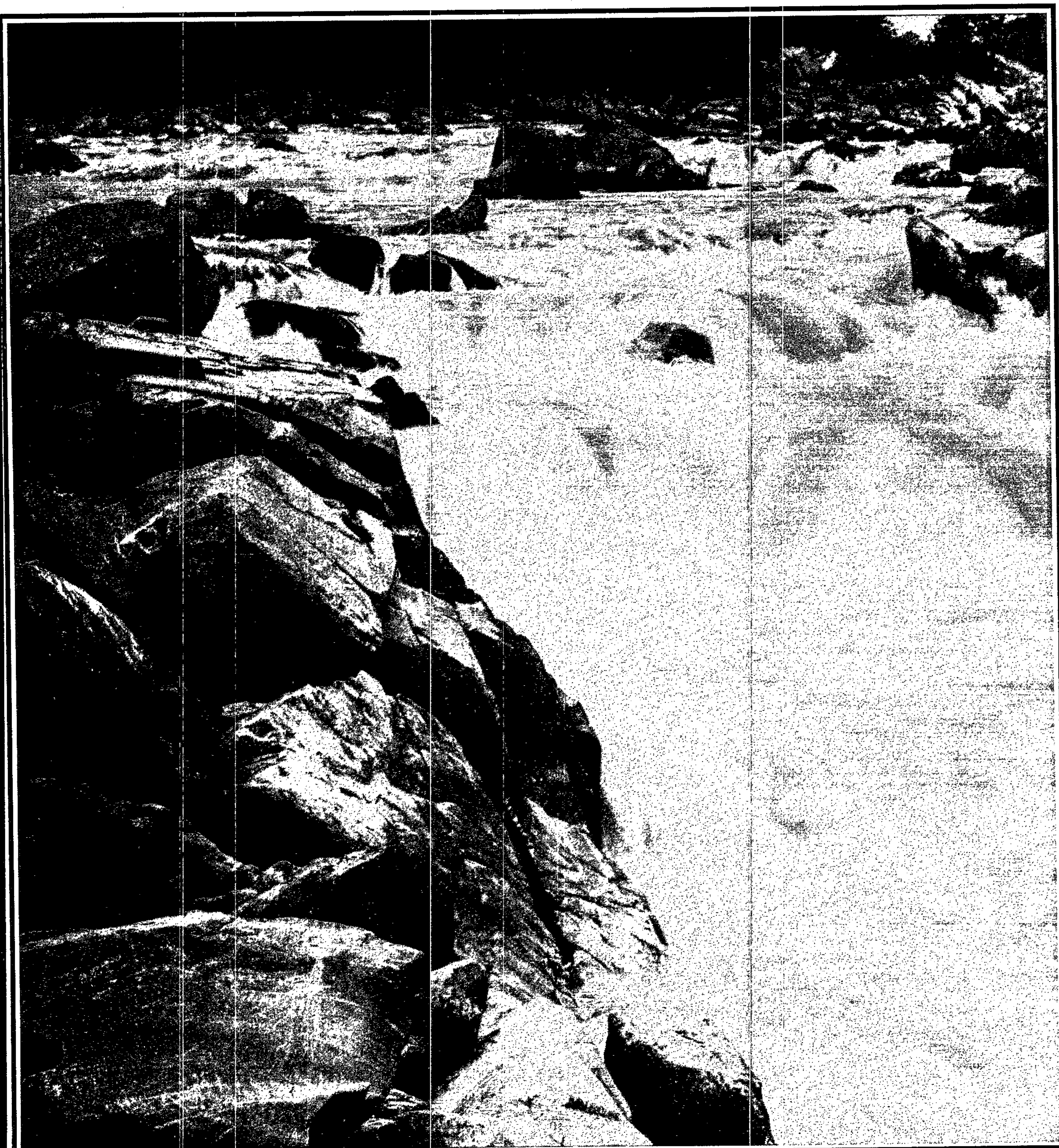
United States
Environmental Protection
Agency

Policy, Planning,
And Evaluation
(2122)

EPA 230-R-95-003
May 1995

EPA

Climate Change And The Boston Area Water Supply



Climate Change and Boston Area Water Supply

By Paul Kirshen
and
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May 1995

A Report Prepared For:

The United States Environmental Protection Agency
Office of Policy, Planning and Evaluation
Climate Change Division

EPA 230-R-95-003

ACKNOWLEDGEMENTS

Neil Leary of the U.S. Environmental Protection Agency (EPA) and his colleagues at the EPA are thanked for their extensive review comments. The authors also would like to thank Joel Smith, formerly of the EPA, for his support on this effort. In addition, they would like to thank Stephen Estes-Smargiassi, Daniel Nvule, and Joseph Smith of the Massachusetts Water Resources Authority (MWRA) for their many efforts. The help of Eric Anderson of the US National Weather Service in obtaining and implementing the rainfall/runoff model is highly appreciated. Dennis Joseph of the National Center for Atmospheric Research (NCAR) promptly and efficiently supplied meteorological and GCM data. Peter Eagleson and Dara Entekhabi (both of the Massachusetts Institute of Technology) provided useful discussions and references in regard to Ep and Et calculations. Harry Schwarz, David Major, and Thomas Stevens were also very helpful. The authors also appreciate the comments of the reviewers. The authors would also like to thank the following for their contributions; Bettina Burbank, Kathleen O'Connor, Louis Diminico, Sharon Diminico, and Andrew Taylor. This work was performed under contract for the U.S. Environmental Protection Agency, contract number 68-W2-0018. ICF, Inc., the primary contractor with the EPA for this project, provided administrative and other support.

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PREFACE

Rising atmospheric concentrations of greenhouse gases threaten to warm the earth and alter the global climate system. Global climate change poses wide ranging risks to the environment, human welfare, and human health. To advance our knowledge of the risks, the Climate Change Division of the United States Environmental Protection Agency has conducted and supported a number of studies to examine different categories of climate change effects. *Climate Change and Boston Area Water Supply* reports results from one of the studies supported by our office.

One source of risk posed by global climate change is the potential for climate change to alter the availability of water. Water runoff into streams and reservoirs is controlled, in part, by the amount of precipitation falling to earth and the amount of water returning to the atmosphere via evaporation and transpiration. The geographic distribution, seasonal patterns, and variability of precipitation, evaporation, and transpiration will change as the global climate system changes. Whether or not these changes will increase or decrease the available supply of water will vary by location and season. Where water supplies are diminished, competition for this vital resource will intensify and water quality may be degraded. Residential, commercial, industrial and agricultural water users may face higher water costs and reduced water consumption. In addition, instream uses of water such as the support of fish populations and water recreation may also suffer.

In this study, Paul Kirshen and Neil Fennessey investigate the potential impacts of global climate change on the municipal water supply of the Boston Metropolitan Area and potential responses to supply changes. The case study finds that Boston area water supply is highly sensitive to climatic change and that the costs of responses are potentially high for some scenarios. The results provide useful insights regarding strategies for adapting to climate change and suggest that climate change risks for municipal water supplies warrant concern and further consideration.

The study was performed for the Environmental Protection Agency under contract with ICF, Incorporated. An earlier version of the report was reviewed by EPA staff and by experts from outside the agency. Participants in the review process are thanked for their efforts to improve the report. The final report is a report to the EPA and does not necessarily reflect the views or policies of the EPA.

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EXECUTIVE SUMMARY

Overview

In this study, the potential effects of global climate change on the municipal water supply of the Boston Metropolitan Area are investigated. The Boston area receives 80 percent of its water from the Quabbin and Wachusett Reservoirs, which are operated by the Massachusetts Water Resources Authority (MWRA). This source of water is found to be highly sensitive to climatic changes that are within the range of changes that climate scientists believe could occur during the coming century. Estimated impacts on the amount of water that can be reliably supplied by the MWRA range from a loss of one-half to a gain of one-third for the climate change scenarios evaluated in the study.

Water supply changes of these magnitudes have important implications for the need to develop new sources of water supply and the cost of water to water users. In the absence of climate change effects, regional growth in water demand is projected to exceed the reliable supply of water from the existing reservoir system and investments to expand water supply will be required to satisfy the growing demand. If climate change decreases water runoff in the region, the need to add to the capacity of the system will be magnified. The result would be higher costs to water users in the Boston area. In one scenario, added capital costs exceed $700 million by the latter half of the next century.[1]

In contrast, if climate change increases water runoff into the MWRA reservoirs, the need for additional supplies and their costs will be offset either partially or entirely. Capital cost savings over coming decades could amount to $15 million relative to a scenario of no climate change.

Methodology of the Study

Estimates of the reliable water supply available from the MWRA to the Boston area are made for fifteen different climate scenarios. One of the scenarios represents a baseline climate which is presumed to exclude the effects of global climate change. It is based on local weather observations for the 1950 to 1979 period. The other scenarios represent changed climates for a world with an enhanced greenhouse effect. Table S1 provides an overview of the climate scenarios examined in the study.

Four of the changed climate scenarios are derived from the simulations of Global Circulation Models (GCMs) and represent the possible effects of doubling the concentration of carbon dioxide in the atmosphere from the preindustrial concentration. The GCMs provide scenarios of regional changes in temperatures, precipitation, relative humidity, cloud cover, solar radiation and wind speed that are internally consistent with current understanding of how the global climate system behaves.[2]

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[1] All cost estimates are reported in 1990 dollars.

[2] The GCM scenarios used in this exercise project warming that is near the upper end of the range of warming that many climate scientists expect to occur

Table S1: Summary of Climate Scenarios

Scenario	Description	Global Temp. Change (°C)	Regional Temp. Change (°C)	Regional Precip. Change (%)
Baseline	Historical observations for the period 1950-1979.	NA	NA	NA
GISS	$2xCO_2$ equilibrium climate projection of the Goddard Institute for Space Studies (GISS) General Circulation Model, 1982.	+ 4.2	+ 3.7	- 1.6
GFDL	$2xCO_2$ equilibrium climate projection of the Geophysical Fluid Dynamics Laboratory (GFDL) General Circulation Model, 1988.	+ 4.0	+ 4.9	- 7.6
OSU	$2xCO_2$ equilibrium climate projection of the Oregon State University (OSU) General Circulation Model, 1984/85.	+ 2.8	+ 3.1	+ 13.0
UKMO	$2xCO_2$ equilibrium climate projection of the United Kingdom Meteorological Office (UKMO) General Circulation Model, 1986.	+ 5.2	+ 8.3	+ 23.0
A,+/-B%	Sensitivity scenarios in which temperature is increased A° C and precpitation is increased or decreased B%.	NA	+2.0 to +4.0	-20 to +20

Streamflows into the Quabbin and Wachusett reservoirs are estimated for each climate scenario. The estimates are made using well known, commonly applied hydrologic models that have been calibrated and validated for the local watersheds. Given climatic inputs, the hydrologic models calculate rainfall, snow, snowmelt, storage of water in the soil, evapotranspiration (evaporation and transpiration) of water to the atmosphere, runoff, and streamflows into the reservoirs.

The other climate scenarios are sensitivity scenarios that impose specified changes in temperatures and precipitation relative to baseline climate. The scenarios incorporate regional warming of 2° and 4° C with precipitation changes of plus and minus 0, 10 and 20 percent. Other climate variables are held constant in these scenarios.[3]

Management of these streamflows to supply the Boston area are modeled using the MWRA's Safe Yield Model. Given the calculated streamflows from the hydrologic models, the safe yield model calculates the amount of water that can be supplied with a reliability of 98.5 percent by the system to meet Boston area water demands. This amount of water is the safe yield of the system. The calculation takes into account evaporation losses from reservoirs, minimum flow and flood control requirements, and the net volume of water stored in reservoirs.

Impacts on Water Supply

The safe yield of the MWRA system for baseline climate is calculated to be 306 million gallons per day (mgd). Together with water yields from other non-MWRA sources of water, the Boston area has adequate water to meet its current water

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by the end of the next century. Climate scientists are not agreed on the probabilities to be assigned to any particular projection within the expected range, nor to the possibility that warming might fall outside the expected range.

[3] The 2° and 4° C warming of the sensitivity scenarios reach roughly from the middle to the upper end of the range of expected warming for the next century. Warming of 2° and 4° C correspond to warming of 3.6° and 7.2° F respectively.

demands of roughly 360 mgd under baseline climate conditions. Figure S1 displays the safe yield for baseline climate alongside the calculated safe yields for GCM-based climate scenarios.

In two of the GCM-based climate scenarios, the GISS and GFDL scenarios, the local climate becomes drier as precipitation decreases and higher temperatures increase water losses to evapotranspiration. Consequently, streamflows decline and the safe yield of water supply from the MWRA declines. Safe yield is projected to decline 23 percent and 43 percent relative to the baseline for the GISS and GFDL climate scenarios respectively. Under these conditions, water supply would be insufficient to satisfy current water consumption in the Boston area.

In contrast, streamflows and safe yield increase in the two other GCM-based climate scenarios, the OSU and UKMO scenarios. In the OSU scenario, a 7 percent increase in safe yield is largely due to increased local precipitation. In the UKMO scenario, precipitation also increases but another major factor increasing streamflow and safe yield is increased relative humidity in summer and fall. With higher relative humidity, evapotranspiration losses are reduced during these periods despite higher temperatures. The projected result for the UKMO scenario is a 38 percent increase in safe yield.

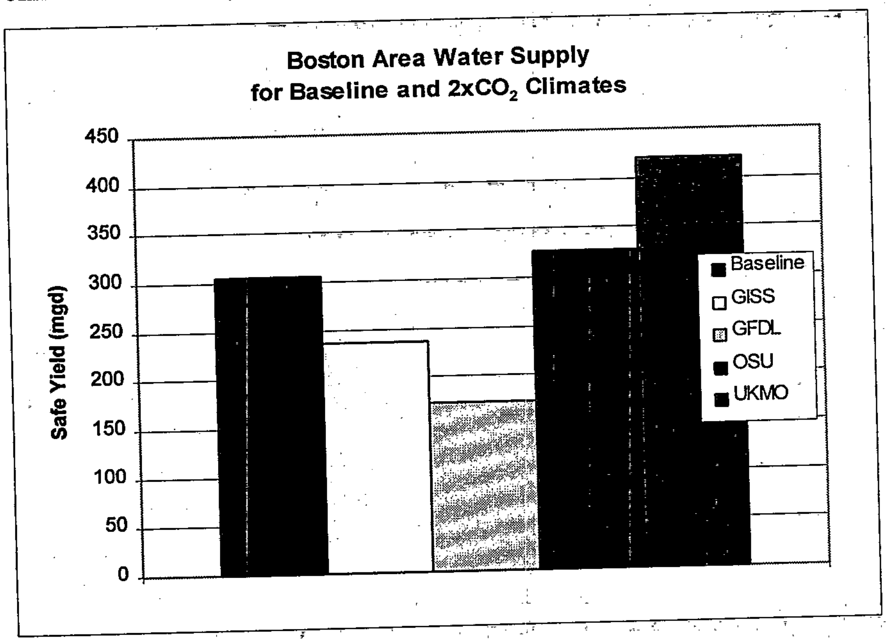


Figure S1: Estimated safe yield of water from Boston area reservoirs for baseline climate and GCM projections of future climate for a doubling of carbon dioxide in the atmosphere above the preindustrial concentration.

Figure S2 displays the results for the sensitivity scenarios. As expected, safe yield of the MWRA reservoir system is found to be negatively correlated with warming and positively correlated with precipitation.

If there is no change in precipitation, warming of 2° and 4° C reduce safe yield by 9 and 18 percent respectively. If warming is combined with decreases in local precipitation, the losses are magnified. In the case of a 20 percent decline in precipitation, safe yield would be cut by half from the normal safe yield of 306 mgd.

If local precipitation increases, however, losses from warming would be ameliorated and the net effect could be an increase in safe yield. A 10 percent increase in precipitation would offset the effects of 4° C warming almost entirely. A 20 percent increase in precipitation would more than offset the effects of 4° C warming and substantially increase safe yield.

Potential Responses and Costs

The above results indicate that global climate change could substantially affect the water supply of the Boston area. If the water supply available from the existing system is diminished, water users may be required to reduce their water consumption and/or new sources of water supply may need to be developed. These impacts represent but one of the risks posed by climate change to human welfare.

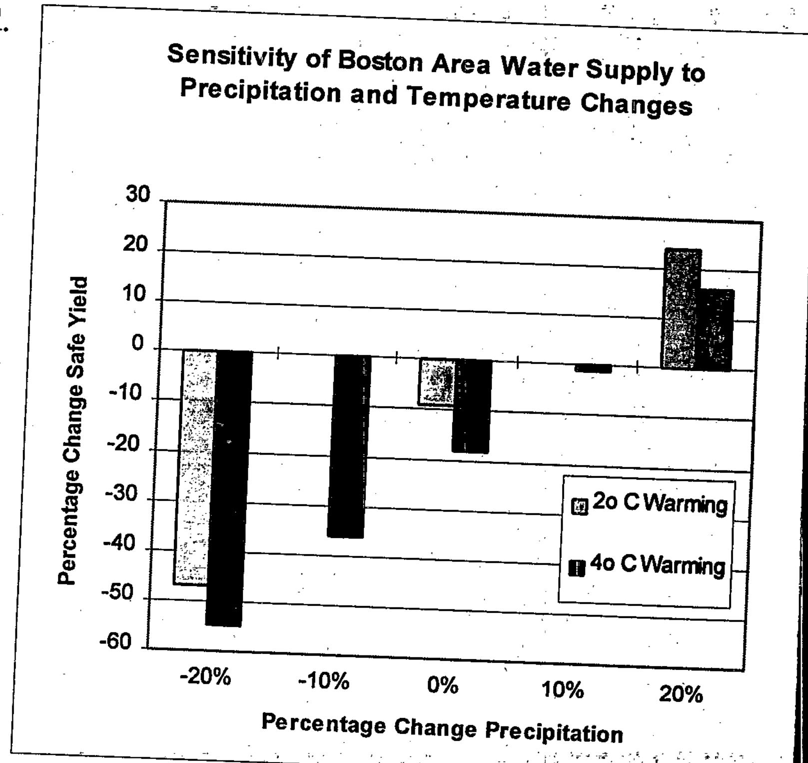


Figure S2: Percentage changes safe yield of water from Boston area reservoirs fo changes in temperature and precipitation. Percentage changes are relative to baseline climate scenario.

Responding to the multiple risks posed by climate change is a challenge that must combine two general strategies. The first is to reduce the risk of damages by limiting or slowing climate change. For example, by conserving energy we can reduce emissions of the greenhouse gases that drive global climate change. The second general strategy is to adapt so as to limit the damages that may result from climatic changes that are not averted. The study's authors, with assistance from the MWRA, have examined potential adaptive responses for the MWRA water supply system.

Adaptive responses are examined for a single climate scenario, the GISS scenario. The GISS scenario is selected for analysis because it represents a case in which climate change is calculated to have a negative effect on local water supply and the authors are interested in examining potential responses to a supply reduction. Because of the focus on a single scenario, the evaluation of adaptive response options is merely illustrative of the types of responses that might be made. A more complete analysis would need to explicitly take into account the uncertainty of global and regional climatic changes, the uncertainty of their impacts, and the implications of these uncertainties for water planning.

To evaluate potential responses to the GISS climate scenario and their costs, the authors first assess future water demand and supply in the absence of climate change. Based upon modest expected population and economic growth, and an aggressive water conservation program, demand is projected to grow by only 5 percent from 1990 to 2050. Under normal climatic conditions and current prices, future demand would exceed the safe yield of the existing water supply system by 11 mgd.

The MWRA has identified a number of local water supply sources that could be developed to supply this deficit under normal climate. The estimated costs of the new sources are $15 million in capital costs and $1 million in annual operation and maintenance costs.

In contrast, assuming that the GISS climate projections for a doubling of carbon dioxide in the atmosphere are realized by the year 2050, the authors estimate that the water deficit in that year would be nearly 100 mgd.[4] Working with MWRA staff, the authors identify a number of responses that would eliminate the projected deficit if implemented. They include development of local water sources, reactivation of an existing but currently unused reservoir on the Sudbury River, a water conservation program for industrial, commercial and institutional water users, and, finally, diverting water from the Merrimack River to Boston area water users.

The total capital costs of these responses are nearly $740 million and annual operation and maintenance costs exceed $20 million. Climate change, under the GISS scenario, would raise costs by more than $700 million for capital needs and $20 million for annual operations and maintenance relative to the scenario of no climate change. Adding these costs to current water system costs would raise a typical household's annual expenditure on water and sewer services $45, or 25 percent, in the year 2050.

[4] The warming projected for the GISS scenario exceeds the range of warming expected by most climate scientists for the year 2050. The estimated water deficit includes a 70 mgd reduction in the safe yield of the MWRA reservoirs, a 10 mgd estimated reduction in water supply from other non-MWRA sources, and an estimated 4 percent increase in water demand as a consequence of climate change.

Conclusions

Whether or not these responses and their costs are warranted is not yet clear. The specifics of how global and regional climate will change, and the time path these changes will follow, are uncertain. As demonstrated by the hydrologic analyses of this study, the uncertainties about climate imply a wide range of potential impacts on the MWRA water supply. As illustrated for the GISS scenario, climate change may require substantial additions to the water supply capacity of the MWRA and/or substantial water conservation efforts in the region. The GISS scenario, however, is but one of many possible outcomes.

Further uncertainty about future water needs is introduced by expected cost increases for Boston area water users that are unrelated to climate change. Costs for new sewage treatment facilities may raise future combined water and sewer rates by 50 percent. Water users are likely to respond to these rate increases by reducing water consumption. The study demonstrates that future needs for new water supplies as a consequence of climate change may be substantially reduced or even eliminated, depending upon how strongly higher rates dampen future water demand.

The MWRA's present strategy regarding the risks posed by climate change is to learn more before acting. Potentially costly commitments to develop new water supply sources or to conserve water will be delayed until more evidence regarding the likelihood of their need accumulates. This strategy appears to be an appropriate one for the Boston area at this time for a variety of reasons.

First, the pace of global climate change is unlikely to be so rapid as to result in local water deficits in the near term given existing water supply infrastructure and modest expected regional growth in population and economic activity. Second, expected water and sewer rate increases may dampen water demand substantially, thereby lessening the risk that climate change would result in a water deficit if supply capacity is not increased. Third, the MWRA currently engages in extensive water supply planning activities. Other than the MWRA's participation in this study, their planning activities have not explicitly addressed risks posed by climate change. Nonetheless, these activities can help the region to adapt to climate change and prevent future water supply deficits.

The planning activities of the MWRA have identified possible water sources for future development and have encouraged their protection in order to preserve them as future options. Should future events and improved understanding of climate science and impacts indicate that the risk of regional water deficits is unacceptably high, the planning efforts of the MWRA will have laid important groundwork for timely and flexible responses. For regions which have not yet done so, the identification and protection of future water supply options represent important first steps in a climate change adaptation strategy that can help to lessen the consequences of adverse impacts.

1: INTRODUCTION

Background

Many scientific sources are predicting global warming and climate change due to an increase in the concentration of greenhouse gases (Intergovernmental Panel on Climate Change (IPCC), 1990). Among major concerns are the potential impacts upon water resources infrastructure and how society might respond to them. A series of water resources studies sponsored by the US Environmental Protection Agency (EPA) for the southeastern, western, and central parts of the United States has been completed and reported in Smith and Tirpak (1989a).

This is a similar study being done for the northeastern United States with the case study being the possible impacts of climate change upon the water supply system operated by the Massachusetts Water Resources Authority (MWRA). This system supplies 82 percent of the water of the 46 municipalities in the Boston metropolitan area and serves 2.4 million people. The remainder of metropolitan water supply is from local groundwater and surface water.

The MWRA is an independent, wholesale, self-financing water and sewer agency created by the Massachusetts legislature. The MWRA system collects water in the western portion of the state, stores it in several reservoirs, and transfers it via aqueducts to users in the metropolitan area. It also provides a small amount to some communities in western and central Massachusetts. This report studies in detail the MWRA system because it is the major source of supply to the region and will be looked upon to supply most future deficits.

This system is also particularly interesting to study because only through an aggressive demand management program (e.g., water conservation, leak control, water supply source protection, and public education) has the MWRA been able to bring its demand below the safe yield of the reservoir system. (Safe yield is defined as the amount of water it is possible to supply from the reservoir system such that, over the long-term, average monthly fluctuating water demands are met 98.5 percent of the time - usually expressed as the average annual demand on the reservoir divided by the number of days per year in units of millions of gallons per day (mgd). 98.5 percent is referred to as the reliability of the system.) Future safe yield information is critical to the MWRA in planning for additional demand management or water supply augmentation activities.

Contents of Report

Included in this report is: (1) a more detailed description of the supply system and its operating constraints, (2) a description of the model the MWRA uses for calculating system safe yield, (3) the procedures for calibrating and verifying the rainfall-runoff model, (4) the procedures for calculating potential evapotranspiration and water surface (reservoir) evaporation, (4) a brief discussion of General Circulation Models, (5) the impacts of potential climate change scenarios upon streamflow, water surface evaporation and safe yield, (6) the financial impacts of the water supply deficit resulting from one of the scenarios, (7) the MWRA policy response, and (8) conclusions and future research needs.

The staff of the MWRA's Planning Section was involved in the entire study. Particularly important contributions were agreeing to serve as a case study, providing engineering and operation data, running the Safe Yield model, commenting upon the draft impact report, attending the First National Conference on Climate change and Water Resources Management held in Albuquerque, New Mexico, November, 1991 to learn about studies in other parts of the United States, and helping to estimate the cost of adapting to the possible impacts of the GISS scenario.

Summary of Methodology

In this climate change impact study, the possible changes in safe yield of the MWRA reservoir system resulting from different scenarios for the equivalent of the doubling of present CO2 in the atmosphere were analyzed and compared to the scenario of no climate change (the base case). The different scenarios included possible climate change impacts upon precipitation, temperature, and other relevant meteorological parameters. The scenarios included those of several General Circulation Models (GCM) of atmospheric circulation and separate arbitrary sensitivity analyses on precipitation, temperature, and several other variables. The GCMs included those of the Goddard Institute of Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU). The scenarios are summarized in Table 1.1 (all tables and figures are at the end of each section).

The first procedure in analyzing the scenarios was to apply a hydrologic model to each of the MWRA's reservoirs' watersheds that estimated the streamflow that resulted from precipitation and evapotranspiration (Et) over the watersheds. The evapotranspiration from the watershed was estimated by a detailed hydrologic model that related evapotranspiration to air temperature, windspeed, possible sunshine, and relative humidity - all variables affected by climate change. Evaporation (Ep) from the reservoirs was similarly estimated.

After the hydrologic models were shown to reasonably represent streamflows under present conditions (the base case or no climate change scenario), the driving climatic variables of the hydrologic models were altered according to the changes expected under each climate change scenario. This resulted in estimates of streamflow into the MWRA's reservoirs and evaporation that could occur under each climate change scenario.

Next the safe yield corresponding to each scenario's altered streamflow and evaporation was determined using the MWRA's Safe Yield computer model. This computer model determined the reservoir system's safe yield for a particular set of streamflow and evaporation.

Summary of Scenario Results

The results of the scenario analyses are in Table 1.2. Both the GISS and GFDL scenarios resulted in less streamflow than under present conditions and therefore less safe yield. The OSU and UKMO scenarios resulted in more streamflow - primarily because of the increase in precipitation under these scenarios. These resulted in increased safe yields.

As stated earlier, other analyses examined the sensitivity of the streamflow and reservoir systems to combinations of changes in temperature and precipitation. The temperature increases ranged from two to four degrees (celsius); precipitation changes ranged from none to increases and decreases of 10 and 20 percent.

As be can seen in Table 1.2, warming alone resulted in decreased yield because of the increases in Et and Ep. An increase in precipitation in most cases mitigated the temperature rise impacts upon safe yield and, in some cases, increased safe yield. If precipitation decreased, yield decreases were amplified. The worst case occurred if temperature increased 4 degrees and precipitation decreased 20 percent.

Another scenario examined the potential impact of vegetation growing in an enriched CO2 environment. Under this scenario, plants may transpire less than normal. This possibility is still an area of research and, while observed under controlled conditions, it may not actually occur in fields and forests in double CO2 climates. The project team examined the sensitivity of the water supply system to this possibility for the climatic conditions represented by the GISS scenario. As shown in Table 1.2, evapotranspiration increased by only 5 percent, which is less than the 20 percent in the GISS scenario. This resulted in higher streamflows and safe yield than in the GISS scenario; but they were still less than the base case.

While there were increases in evapotranspiration during the growing season in each of the previous scenarios, there was no modeling of an increase in the length of the growing season due to increased temperatures. In this scenario, it was assumed that the growing season in the GISS scenario would extend approximately two additional months. Compared to the first GISS scenario, this resulted in decreased streamflows and less safe yield. Therefore if there are increases of a few months in the growing season, streamflows and safe yields will be significantly decreased.

Under the Base Case (present climate), the reliability of the safe yield of 306 mgd was 98.5 percent; there were only four months when the demand could not be met over the thirty year simulation period. The final scenario determined the reliability of supplying 306 mgd under the GISS scenario. It was found to be 83.4 percent; failures occurred in approximately 50 months over the thirty year simulation period.

Presently, it is not a policy option to consider operating the supply system at less than close to 100 percent reliability. The public has come to expect water supply to be like other utilities such as electricity - always available as needed.

Summary of Supply Deficits and Costs under the GISS Scenario

Two analyses were done to examine in more detail the impacts of the GISS climate change scenario compared to the no climate change scenario. The first was to project the water demands over the period of 1990 to 2050 under both the no climate change and the climate change (double CO2) scenarios assuming the demands were fixed requirements and were not price sensitive. The future deficits were then determined and the water conservation strategies and supply sources available to meet the deficits discussed. The second analysis showed how the GISS scenario might financially impact the MWRA and its ratepayers over the planning period. This analysis required examining projected water rates and how water users would respond to rate increases using a value of the price elasticity of the demand.

As described previously, the MWRA fully supplies some communities and partially supplies others. Since the MWRA would have to make up the demand deficits in both totally and partially supplied communities, demands (and sources) in both types of communities had to be considered. The 1990 total water demand in both fully and partially supplied communities from both MWRA and local sources was 361 mgd, with 80 percent supplied by the MWRA reservoir system. In 2050 (the year CO2 is expected to have doubled), the demand under the scenario of no climate change (1 x CO2) would increase to 379 mgd, an increase of five percent over the present demand. The MWRA projected only slight increases in population and economic activity over that period and assumed that local sources were not lost due to contamination and that the present demand management strategies were maintained. Under the GISS scenario, it was assumed that because of the increased temperature and longer warm season, seasonal summer water use would increase from its present amount and the total demand would potentially be 393 mgd. Both demand projections did not consider the impacts of any water rate increases upon demand.

The present approximate total safe yields of the supply sources for MWRA communities is 368 mgd (300 mgd from the MWRA's reservoirs), greater than the present demand of 361 mgd.

The GISS scenario also impacted supply. As previously determined, the safe yield of the MWRA reservoir system would decrease from 306 mgd to 236 mgd. Using engineering judgement, it was assumed that local surface water yield would decrease 20 percent or from 48 mgd to 38 mgd. It was assumed that local groundwater yield would remain the same. In reality, there probably would be a change as evapotranspiration increased under the GISS scenario while precipitation remained approximately the same. These factors were not considered because any changes in groundwater yield would be small compared to the total change in safe yield from all sources. Therefore, the total safe yield would decrease from 368 mgd under no climate change to 294 mgd under the GISS scenario, a reduction of 20 percent.

There is a difference of approximately 100 mgd between the GISS 2050 demand of 393 mgd and the GISS total safe yield of 294 mgd. To supply this deficit, the MWRA would implement over time as needed additional local sources, the reactivation of a water supply reservoir on the present MWRA water supply system, an intensive and relatively expensive water conservation program for industrial, commercial, and institutional water users, and finally, divert water from a major river basin (the Merrimack) north of Boston.

The total capital costs ($1990) to supply the deficit would be $737.5 million with annual operation and maintenance costs of $22.1 million.

Without climate change, the 2050 demand is expected to be 379 mgd, 11 mgd over the system safe yield of 368 mgd. The shortfall would probably be supplied from local sources at a capital cost of $15 million and annual costs of $1 million and by long term water conservation by industry. Therefore, the capital and annual costs of adaptation under the GISS scenario are considerably greater than the costs under no climate change.

The difference in present values of the supply costs depend upon the timing of the implementation of the projects and the opportunity cost of capital used to discount the future costs.

The second analysis considered the sensitivity of changes in water demand to changes in water rates (price elasticity). The general procedure was based upon the annual water rate per equivalent household, which is the total annual rate revenue requirements divided by the number of equivalent households. The number of equivalent households is the number of households that would use as much water as the actual number of households and industrial users.

Since the water rate of most MWRA users consists of both water supply and sewer costs, the combined costs were used in calculating the water rate. The water rate also had added to it community costs. (The MWRA is wholesale service.) Because of new sewage treatment plant requirements, the MWRA's annual sewer rates are expected to increase significantly at least until 1999 - perhaps as much as 400 percent additional if no federal or state aid is received. MWRA water rates could also increase 200 percent additional over the same period because of filtration and aqueduct costs. Local community costs are expected to remain the same over the period.

Once the annual water rate per equivalent household for 1990 was determined, the analysis of financial impacts was done in five year iterations from 1990 to 2050.

At each time step, the following was determined: (1) the number of equivalent households (EH), (2) the total water demand by multiplying the previously determined demand per EH by the number of EHs and then increasing this value by any additional demand under climate change, (3) the cost of meeting the total demand by staging the previously described projects, (4) the resulting water rate per EH, and (5) the water demand per EH for use in the next time step based upon the percentage change in EH annual water rate and the price elasticity.

A bond lifetime of thirty years with an interest rate of seven percent was used. At the end of the bonding period, replacement costs equal to one-third of the capital costs were considered necessary.

The value used for the price elasticity of the demand for water was -0.10. A particularly low value was used because of the considerable uncertainty in the selection of this value.

For the case of no climate change, the analysis showed that the final 2050 demand of 361 mgd was less than the presently projected demand (with no price elasticity impacts) of 379 mgd. This was because of the large demand decrease due the severe price increases for water supply and sewerage infrastructure in 1995 and 2000. In that period, demand is reduced from 225.6 mgd per EH to 214 mgd per EH. More importantly, 2050 demand was below the total system yield of 368 mgd.

For the case of climate change, the final 2050 demand of 358 mgd was less than the projected 2 x CO_2 demand of 393 mgd. As in the case of the no climate change scenario, the major reason for this was the large drop in demand in 1995 and 2000. The GISS scenario in 2050 resulted in 13 percent greater rates and annual costs than the scenario without climate change.

It is very important to realize that these results are very specific to the MWRA and that the demand decreases are more due to the extraordinary increases in costs for water supply and wastewater treatment infrastructure than to extra costs for augmenting deficits caused by climate change. In fact, after 2000, the total costs are so large compared to any incremental costs of supply due to climate change that there is really no change in demand per EH. The analyses do show, however, that sensitivity to price must be considered in these types of analyses.

Analyses are also done at an elasticity of -0.40. This so decreased demand per EH from 1990 to 2000 (from 225 gpd/EH to 181 gpd/EH in both scenarios) that there were no deficits in the no climate change scenario and no major deficit until 2045 in the GISS scenario. This again highlights the need for consideration of price elasticity in these analyses.

As noted previously, the results of these scenarios are unique to areas such as the MWRA which are experiencing extraordinarily high water and associated sewer rates because of exceptional costs for water supply and wastewater treatment infrastructure. Most wastewater treatment plants were largely funded by the federal government under the Clean Water Act. Therefore to investigate the financial impacts that would have occurred on the MWRA if its costs were more typical of other communities, the analyses were repeated assuming that the MWRA's fixed annual costs in 1990 were equivalent to those in 1987 and the MWRA would not be paying for extra infrastructure costs - rates would only change in response to growth in the number of EHs and climate change.

The results for the scenario of no climate change showed future deficits were nonexistent or small, rates and total costs were relatively constant and there were no significant changes in demand compared to the static projection.

The GISS scenario resulted in water supply deficits and in steady rate increases. The 2050 demand was 371 mgd instead of the projected 393 mgd under the static analysis. The final rates and annual costs under the GISS scenario are 28 percent higher than under the no climate change scenario.

These analyses again show that any demand projections are sensitive to price even with low values of elasticity. Even with price elasticities, however, climate change could result in increased water supply costs and rates.

Summary of MWRA Policy Response

The response of the MWRA to the hydrologic and economic impacts of possible climate change are summarized by Estes-Smargiassi (1991); "Given the time-value of money, and the practical considerations of "banking" savings, we at the MWRA are unlikely to (now) propose substantial capital outlays to adapt to climate change. And, while we have, and continue to make conservative decisions about facility locations and elevations, we will not (now) make major policy decisions based on climate change effects."

Further discussions with the MWRA indicated that the reasons for this response are that the impacts of global climate change are too uncertain to presently take direct action - particularly since the MWRA currently has difficulty obtaining approval for funds for basic maintenance or necessary system improvements. The MWRA, however, will continue to remain aware of possible climate change and formulate active policies when they think it is necessary. They also believe that the climate changes will be gradual and they will have time to react; it is possible for them to react to a perceived need within five to ten years.

The MWRA has the luxury of this response because of its already extensive water supply planning activities and options. For example, the MWRA already has future possible local sources located and is working to protect their flexibility and feasibility by, for example, helping member communities protect them. (There are no other large-scale reservoir sites.) The MWRA also knows that there remain some demand reduction measures that could be quickly implemented if necessary. They have not been implemented to date because the MWRA believes they are presently not needed and they do not want to lose their credibility by requiring unnecessary demand reductions.

The MWRA's response of "wait and see" is similar to that of other water supply managers. The relevant conclusions of Schwarz and Dillard's (1990) survey of urban water managers from cities across the United States were that: (1) water managers do not see climate change as a "cause for immediate major concern" (pg. 365); (2) removal of some of the uncertainty by scientific consensus and governmental, professional and scientific endorsement are necessary before water managers will act; and (3) "most impacts of climate change on urban water can be mitigated, albeit at significant cost" (pg. 366).

Schwarz (1992) also notes another dilemma water managers similar to the MWRA face; that is they may not know climate change has occurred until 30 to 40 years after it has. Before that period, temperature and precipitation changes might only be seen as normal variations in weather, not permanent changes. Therefore a response may only occur due to a new extreme event or belief in the scientific validity of climate change.

Summary of Research Needs

The results of this study further emphasize several well known global climate change research needs related to water resources. Scientific research is needed to improve the predictive ability of GCMs, enhance their hydrologic components, and determine how best to apply their results to river basin scales. In spite of these limitations, the study does have enough rigor (for examples, the strong verification of the runoff models and the logic of the results) to conclude that the impacts of possible climate change on streamflow and reservoir yield in the northeastern United States could be similar to the range of impacts shown in this study.

As shown by the MWRA's response to the possible impacts of climate change, many policy making organizations subject to political and financial constraints have difficulty formulating policy given the uncertainty of climate change and the relatively long time horizon before serious impacts may occur. This inaction may hinder the implementation of low risk and inexpensive adaptation strategies in the near-term future to counter the possible long term impacts. An immediate research need is to determine what information is needed, what information can be provided, and how should it be presented to policy making organizations in order for them to formulate policy to respond to possible climate change.

Table 1.1

Summary of Scenarios

Name	Description
Base	Present hydrologic conditions as represented by the climate variables of air temperature, precipitation, incident solar radiation, wind speed, and relative humidity.
GISS	Perturbation of climate variables according to 2 x CO2 results of GISS model.
GFDL	Same as above except GFDL model.
OSU	Same as above except OSU model.
UKMO	Same as above except UKMO model.
A, B%	Base case with A degree Celsius increase in air temperature, B % change in precipitation. For example, 2,+20% is the Base Case with 2 degree increase in temperature, 20% increase in precipitation.
Incr. rc	GISS scenario with decreased potential evapotranspiration because of higher canopy resistance.
Ext. Sea.	GISS scenario with longer growing season.

Table 1.2

Summary of Results

Note: Reported by percent of average change compared to Base Case except for temperature, which is increase in temperature (degrees Celsius) and Yield, which is mgd. Yield is the safe yield of the MWRA reservoir system. 2,+20% means 2 degree increase and 20 percent increase in precipitation. "Incr. rc" is decreasing plant transpiration due to CO2 enrichment. "Ext. Sea" is increasing growing season. More information is in Section 6.

Run	Et	Ep	Precip	Temp	Flow	Yield
	%	%	%	Cel.	%	mgd
Base	-	-	-	-	-	306
GISS	+20	+17	-1.6	+3.67	-16	236
GFDL	+57	+41	-7.6	+4.9	-33	173
OSU	+23	+13	+13	+3.11	+6	328
UKMO	+10	+32	+23	+8.27	+30	421
2,0%	+12	+6	0	+2	-8	278
2,+20%	+12	+6	+20	+2	+23	379
2,-20%	+12	+6	-20	+2	-39	161
4,0%	+24	+11	+0	+4	-15	250
4,+20	+24	+11	+20	+4	+15	355
4,-20%	+24	+11	-20	+4	-44	139
4,+10%	+24	+11	+10	+4	+0.2	302
4,-10%	+24	+11	-10	+4	-30	196
Incr. rc	+5	+17	-1.6	+3.67	-10	262
Ext. Sea.	NA	+17	-1.6	+3.67	NA	195

2: STUDY AREA

Introduction

Boston, its neighboring communities, and some communities in western and central Massachusetts receive water supply from the Massachusetts Water Resources Authority (MWRA), an independent public authority created by the Massachusetts Legislature. Most of the communities are totally supplied; the remainder use the MWRA to augment local supplies (partially supplied). The MWRA service territory includes 46 communities to which the MWRA supplies 82 percent of the water and serves 2.4 million people. The demand is 45 percent residential, 35 percent industrial-commercial-institutional, and 20 percent unaccounted for in mainly unmetered municipal usage, leakage, and inaccurate meters. The rest of this section discusses the MWRA system, the focus of this study.

In 1987, water demand on the MWRA system was 336 millions of gallons per day (mgd). This demand varied throughout the year, being 300 mgd in the winter, 325 mgd in the spring, peaking at 350 mgd in the summer, and falling to 325 mgd in the fall. Through aggressive programs in leak detection and repair, demand management, and water supply protection, by 1989 average demand was decreased to under 290 mgd. The MWRA anticipates that with the expansion of these programs, demand will remain under 300 mgd, the safe yield of the reservoir system, for the next ten years or possibly thirty years. Without expansion of these conservation programs, even without significant increases in population or economic activity, demand could grow to 340 or 350 mgd by the year 2020 as the system deteriorated, water was used inefficiently, and local water supply sources became lost. Future demand is further discussed in Section 7, MWRA Policy Response.

The aggressive nonstructural approach to meet water supply needs was the result of a 1986 study that showed that leaks and inefficient water use practices were resulting in an annual demand ten percent greater than the safe yield of the reservoir system and that if present practices continued demand could increase by 50 percent in 2010 (MWRA, 1990). Rather than follow the traditional response of developing costly new supply sources, the MWRA decided to implement a nonstructural approach and investigate over a three year period how successful the nonstructural approach could be in meeting the long-term water supply requirements of the MWRA.

As reported in MWRA (1990, page 3), over the three year period, the MWRA, among other related activities,:

"- found and repaired MWRA pipes leaking 5 mgd;

- found 25 mgd in leaks in 5000 miles of community lines;

- developed, and issued for comments, regulations requiring leak detection and accurate metering;

- distributed over a million pieces of conservation information and educated school children throughout the service area;

- helped change the Massachusetts Plumbing Code to require low flow toilets;

- installed water saving devices in over 7000 homes...;

- helped hundreds of industrial, commercial, and institutional users to save water."

During this same three years, the MWRA started (1) studying the feasibility of developing more local sources to augment supplies, (2) protecting the existing and potential sources of both partially and non-MWRA supplied communities so that demand would not grow due to loss of supplies, (3) evaluating the impacts of reactivating a previously used reservoir (the Sudbury), and (4) developing better tools for management and planning.

The MWRA also reviewed demand projections and, because of low projections of future population and water-consuming economic activities in the service area, determined that at least until 2020 there may not be a significant increase in demand as long as there is no loss of local supplies, no growth of the service territory, and the demand management strategies are maintained.

The end result of these efforts is that because demand may not grow and the cost of these small scale or nonstructural programs are less or equally expensive as major structural alternatives ($50-$800/mg versus $500-$1600/mg), the MWRA is committed to trying "all reasonable means of continuing to supply the system's needs without a major new source; only if that failed after a fair trial, would the more traditional water supply planning route of augmentation be considered" (MWRA, 1990, page 8). The MWRA is planning to review these policies in 1995, but as stated earlier, the MWRA anticipates that with the expansion of these programs, MWRA demand will remain below the reservoir system's safe yield of 300 mgd for the next ten years or possibly thirty years.

Water Supply System and Operation

The main sources of supply for the MWRA are the Quabbin and Wachusett Reservoirs, located in central Massachusetts and shown in Figure 2.1. From these reservoirs, water flows east under gravity to the distribution system in the Boston metropolitan area. There are also several reservoirs used for emergency supply.

Quabbin Reservoir is located on the Swift River. It collects water from 186 square miles of Swift River drainage as well as water transferred to the reservoir from the Ware River watershed by the Quabbin Aqueduct (see additional information below). The reservoir has a total storage volume of 412 billion gallons and an active storage volume of 256 billion gallons. The active storage volume, or the minimum volume the reservoir is permitted to obtain, is necessary to maintain the water quality of the water supply releases.

Quabbin has a mandated minimum downstream flow release to the Swift River of 20 mgd for fishery maintenance. During the months of June through November, the minimum is increased to 45 mgd if the flow on the Connecticut River (to which the Swift River is tributary, see Figure 2.1) at Montague is less than 4900 cfs. The minimum release is increased to 71 mgd if the Montague flow is below 4650 cfs. The average flow at Montague during June through November is 7,421 cfs.

Water diverted from the Ware River, the next river basin to the east of the Swift River basin, can be transferred either to Quabbin Reservoir or Wachusett Reservoir. The decision is based upon the time of year and storage in each reservoir. The diversion structure controls 96.8 square miles of the Ware River basin. Water may only be taken during the period of October 15 through June 14 when the flow exceeds 138.5 cfs. This is referred to as flood skimming. The average monthly flow of the Ware River during this period is 229 cfs.

Wachusett Reservoir receives inflow from the Nashua River watershed and water transferred from the Ware River. Its storage volume is 65 billion gallons. It also has a minimum downstream release.

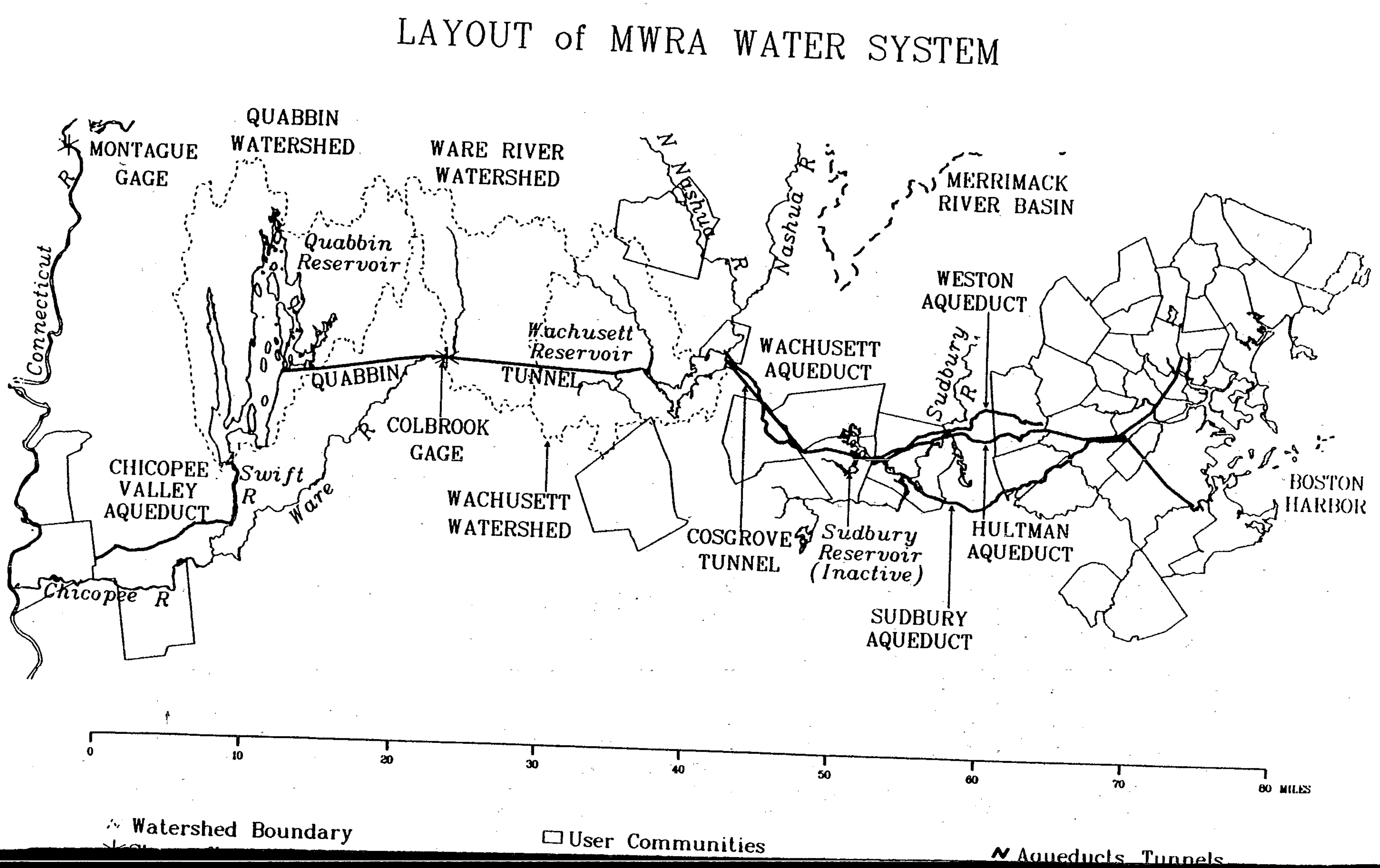
Spills from the reservoirs under flood conditions are rare and the impacts are minor.

Hydrology

The United States Geological Survey (1986) reports the average annual precipitation over the Swift and Nashua watersheds is approximately 42 inches. It is distributed relatively evenly throughout the year. There is snow from approximately December through March. The average annual runoff is approximately 23 inches, with a peak flow in the Spring from snow melt (see Ware River hydrograph, Figure 4.3).

There is approximately 40 inches of precipitation per year over the Connecticut River Basin above Montague with an average annual runoff of 23 inches (see Connecticut River hydrograph, Figure 4.5).

Figure 2.1 Study Area



3: SAFE YIELD MODEL

Introduction

The MWRA's Safe Yield Model is described in MWRA (1989). It uses reservoir simulation techniques to determine the average annual yield that can be supplied from the MWRA water supply system with a specified reliability. The average monthly release that satisfies the reliability constraint is referred to as the safe yield. The model functions on a monthly time step; during each time step the model reads the streamflows entering the system, calculates the net reservoir volume changes due to direct precipitation and evaporation, determines minimum flow release requirements from Quabbin reservoir based upon streamflow at Montague, and determines the amount of flood skimming (see discussion at end of Section 2) permissible from the Ware River and the Wachusett flow release. Then reservoir volume balances are calculated and a determination is made if that month's demand can be met. The reservoir volumes are then adjusted to reflect the amount of demand supplied. If the entire monthly demand can not be met, a failure is recorded. The system reliability is measured by the ratio of successful supply months to the total number of months simulated.

At the option of the user, the model can also simulate drought management scenarios. These scenarios attempt to model how the MWRA might respond to a drought situation. That is, when the MWRA noticed that the system storage had decreased to a "trigger" amount, it would start to ration water supply releases so that the shortfall would be spread over several months instead of just one. The amount of rationing (expressed as a function of the demand) depends upon the volume of the combined storage in Quabbin and Wachusett reservoirs. If the decreased demand can not be met, then a failure is recorded.

Data Requirements

In the Safe Yield Model, monthly demand is specified as a percentage of the average annual demand. They are derived from historic data and are:

January	97 %	July	112 %
February	96 %	August	111 %
March	95 %	September	104 %
April	94 %	October	98 %
May	97 %	November	96 %
June	105 %	December	95 %

Generally, when the MWRA uses the model for studies, they use historic hydrologic data for the period 1930 to 1979 (which contains the worst drought of record). These data include monthly precipitation on the reservoirs, monthly streamflow of the Ware River at the Colbrook gage (the location of the diversion and also used to estimate monthly streamflow into Quabbin reservoir on the Swift River using the ratio of drainage areas), the number of days each month during flood skimming months that water can be transferred from the Ware River to reservoir storage, the possible monthly volume that can be transferred from the Ware River, and the minimum flow release requirements from Quabbin Reservoir based upon the flow of the Connecticut River at Montague. The latter three inputs are determined by pre-processing the historic daily flow data for the Ware and Connecticut Rivers to model the impacts of the flood skimming and downstream low flow requirements. Monthly evaporation from the reservoirs is also a data requirement (the same value is used for each reservoir; it is the long term monthly average).

Since in this study, streamflows were simulated on a monthly basis (see Section 4 on the runoff model), regression and curve fitting were used to develop relations between the possible monthly skim volume and the Ware River monthly discharge, between the possible number of transfer days and the discharge, and the Quabbin low flow release and the Connecticut River flow. These were done by using daily historic data on flows to determine the monthly skim volumes and days, and low flow requirements and then fitting them against the monthly flow discharges. The fitting was done using ordinary least square fitting to a polynomial. The results of some of these analyses are in Figures 3.1 and 3.2.; they all were reliable enough to warrant use of this methodology.

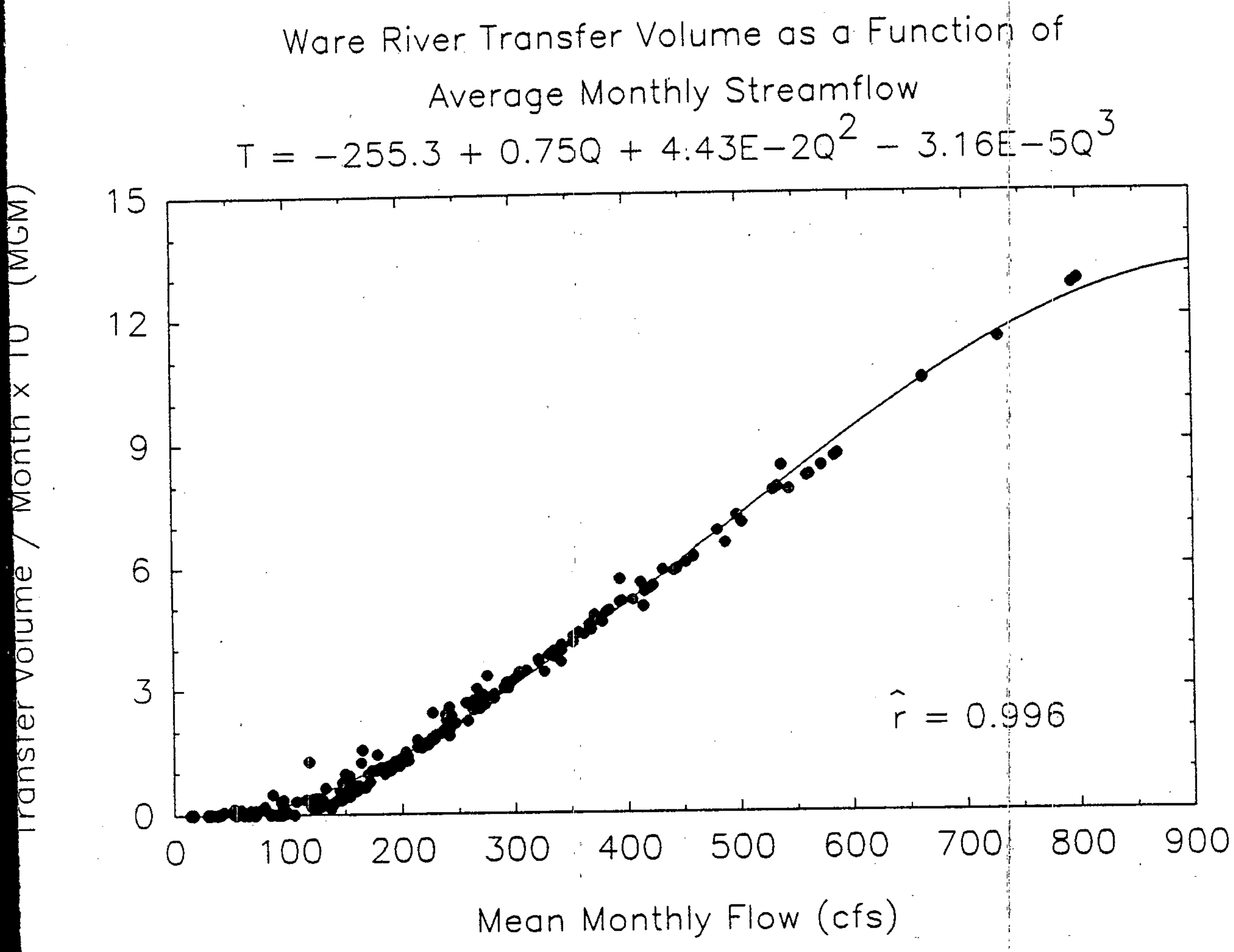


Figure 3.1 Ware River Monthly Transfer Volume

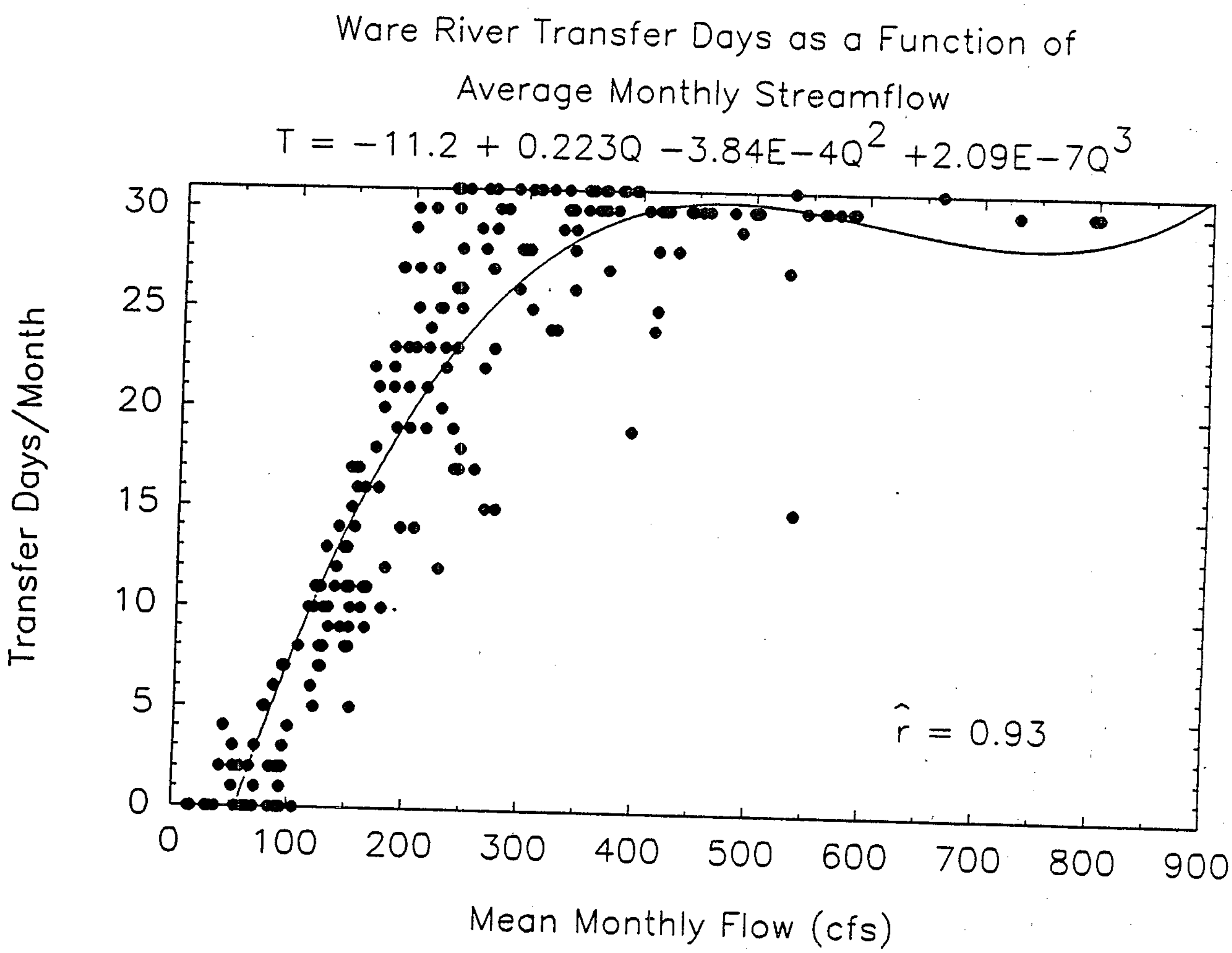


Figure 3.2 Ware River Monthly Transfer Days

4: CALIBRATION AND VERIFICATION OF RUNOFF MODEL

Introduction

As described in Section 3, Safe Yield Model, it is necessary to be able to simulate the streamflows at the Ware River at Colbrook (the location of the transfer intake structure) and the Connecticut River at Montague. A conceptual runoff model with climate input data of precipitation, temperature, and potential evapotranspiration was calibrated and verified for each location. Then changed values of these variables corresponding to possible climate change scenarios were used in the runoff model to simulate possible impacts upon streamflow. This section briefly describes the runoff model, and the procedures and results of the calibration and verification. The resulting simulated flows for present conditions are referred to as Base Case flows.

Rainfall-Runoff Model

The rainfall-runoff model consists of two major modules, the National Weather Service River Forecast System (NWSRFS) snow accumulation and ablation model (Anderson, 1973) and the Sacramento Soil Moisture Model (Burnash et al, 1973). FORTRAN computer codes of each module are available from the US National Weather Service, Silver Spring, Maryland. The project team wrote drivers for the codes that allowed for entry of input data and retrieval and display of the output. Each module is well known and used in operational and research hydrology.

The snow melt model is summarized in Figure 4.1. It uses an energy balance approach to calculate snowmelt during rain-on-snow periods and a temperature index approach during non-rain periods. The input data used by the model for each time step (24 hours in this application) are temperature and precipitation. Major parameters include sub-basin area, a factor to adjust precipitation gage catch efficiency during snowfall, melt factors which relate snowmelt to temperature, an areal depletion curve which describes the change in areal extent of snow as water-equivalence changes, and the temperature which delineates rain from snow. With these data the model internally determines the areal-extent, water-equivalent and heat deficit of the snow pack at each time step, and the resulting melt and rain in the sub-basin.

The Sacramento soil moisture model represents the passage of the daily (as in the case of the snow model, the time step for the soil moisture model was 24 hours) rain and melt over the soil surface or through the soil into water bodies such as rivers. It is shown in Figure 4.2. It effectively models direct runoff, interflow, and slower responding baseflow. Evapotranspiration is possible from both upper and lower soil layers. Major parameters include maximum storage amounts of tension and free water in each zone, and rates of passage and transfer between zones based upon storage volumes. The output of the model is runoff.

Since the time of travel in both the Ware and Connecticut river basins is on the order of days and the time step for the Safe Yield Model is one month, the daily runoffs were aggregated monthly and used as the monthly streamflow values in the Safe Yield Model. As shown in the results of the calibration and verification of the models, this assumption did not limit the results.

Calibration and Verification for the Ware River

As discussed in more detail in Section 6, Potential Climate Change Impacts, the US EPA requested the project team use the period of 1950 to 1980 as representative of hydrologic conditions before potential climate change. Therefore data from this period were used to calibrate and verify the runoff model.

An eleven year period (1960 - 1970) was chosen to calibrate the model and a different approximately ten year period (1950-1959) was used to verify the model. The periods included a range of hydrologic conditions with the annual flows in the 1950's being above average and the 1960's having the lowest drought of record. In each case, there was a "warm-up" period of three years starting in May (when there is no snow on the ground) before the start of the calibration or verification simulation run to set the initial groundwater storage values. Since precipitation and temperature records were unavailable for the "warm-up" period of 1947 - 1949 for the verification run, a period of record was determined that had similar streamflow values (1969 - 1971) and the corresponding precipitation and temperature values were used as the values for the warm-up period.

Since the United States Geological Survey (USGS) has maintained a gage at Colbrook, it was not necessary to transform streamflows from one measured location to an ungaged site. After analyzing relevant precipitation and temperature records in the vicinity of the basin for period of record, quality and completeness of record, and representativeness of record, it was decided to use the average of the daily precipitation at the Worcester, MA and Birch Hill, MA gages and the average of the daily maximum and minimum temperatures at Birch Hill as inputs to the model.

Initial values of the parameters were selected after reviewing daily streamflow and precipitation records and parameters values that were used by Anderson (1991) in an application of the model to a nearby basin. Then through iteration, parameter values and constant monthly values of potential evapotranspiration were determined that produced monthly values of streamflow that best matched historical data for the period of 1960 - 1970. Without changing parameter values, the monthly streamflow for the period 1950 - 1959 was then simulated. The comparison to historical values for this period (the verification period) is shown in Figure 4.3. During this period, the historic mean flow was 184 cfs, the simulated mean flow, 171 cfs. As a final check, the period of 1950 - 1979 was simulated to obtain Base Case flows for comparison to historical data. In addition to using daily values of historic precipitation and temperature, monthly values of potential evapotranspiration for the growing season were calculated using the Penman-Monteith evapotranspiration model, which required the use of historic monthly values of temperature, wind speed, sunshine, and relative humidity. The Penman-Monteith model had been calibrated with the monthly values of potential evapotranspiration determined from the initial calibration of the runoff model. This procedure is discussed in more detail in Section 5, Evapotranspiration. As can be seen in Figures 4.4a and 4.4b, the monthly streamflow time series agree well. This is also shown in Table 4.1, where the closeness of the values of the means, standard deviations, and skewness indicate that the distribution shapes of the historic and simulated flows are very similar. The high correlation coefficients indicate that the monthly variations of the flows are also similar. Therefore the model reasonably represents monthly flows in the Ware River basin.

Calibration and Verification for the Connecticut River

Similar procedures for the Connecticut River at Montague, where there is also a USGS gage, were followed as for the Ware. The entire 7,865 square mile drainage area was modeled as one sub-basin; this is suitable accuracy for the Safe Yield Model. Daily precipitation and temperature values used in the model were the average of values at Newport, VT, Chelsea, VT, Cavendish, VT, and Keene, NH. Since some stations were missing values for the period of 1950 to 1953, ordinary least square regression relations between Cavendish, VT, where there are complete records, and average precipitation and temperature were determined and used to fill-in missing values. The model was calibrated for the period 1960 - 1970 and verified for the period 1971 - 1979. The results for the verification are in Figure 4.5. Using the same years of 1969-1971 as in the Ware River verification to provide "warm-up" years for the period 1947-1949, a simulated monthly record for the period 1950 - 1979 (Base Case flows) was developed. As in the case of the Ware River, monthly values for the potential evapotranspiration for the growing season were used that were determined using the Penman-Monteith model and historic data. Figures 4.6a and 4.6b and Table 4.1 compares historical and simulated values for the entire period of simulation. As can be seen, the model with this set of parameters effectively represents the flows in the Connecticut River.

Use of Simulated Flows in Safe Yield Model

A final check on the calibration and verification procedures was to execute the Safe Yield Model with historical measured streamflow and evaporation data for the period 1950 - 1979 and then with simulated streamflows derived with the procedures above using historic precipitation and temperature data for the same period. The evaporation and potential evapotranspiration values corresponding to the simulated streamflows were determined using the Penman-Monteith and Penman equations and historic climate data (see Section 5, Evapotranspiration). The values of the safe yield at the 98.5 % reliability level agreed very well; 294 mgd with historic data, 306 mgd with the simulated flows. Other parameter values such as minimum flow releases and water transfers also agreed well. Therefore the project team had confidence that the modelling procedures provided adequate representation of the flows in the river basins and of system safe yield.

Table 4.1

Comparison of Historic and Simulated Time Series for Present Climate

Time Series	Mean (cfs)	Std. Dev (cfs)	Skewness
Ware Hist.	169.2	148.3	1.4
Ware Simul.	169.0	166.8	1.5

Correlation Coefficient between Hist. and Simul. = 0.8118

Time Series	Mean (cfs)	Std. Dev (cfs)	Skewness
Conn. Hist.	14550.	11810.	1.5
Conn. Simul.	14029.	11852.	1.7

Correlation Coefficient between Hist. and Simul. = 0.8451

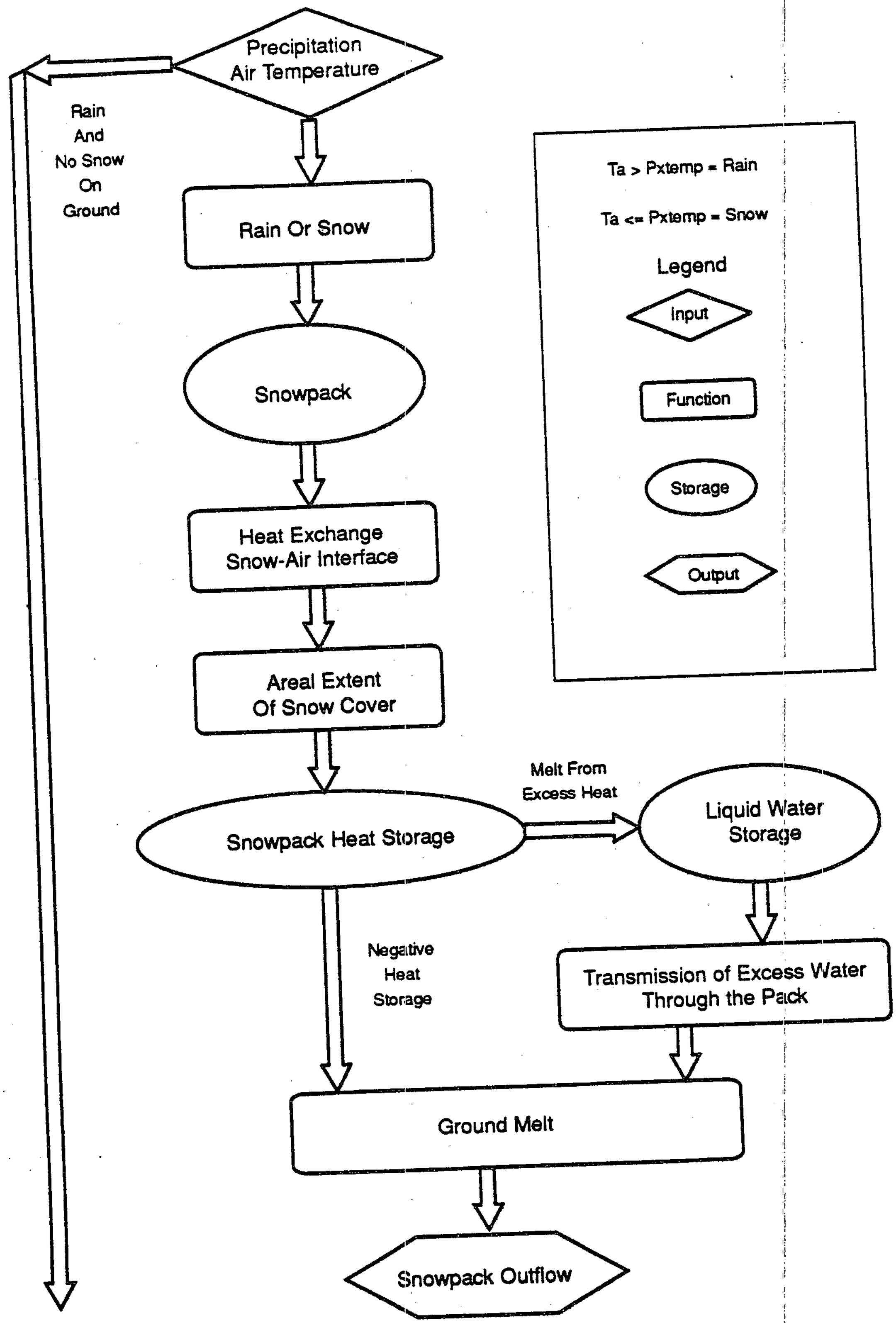


Figure 4.1 Structure of Snow Model

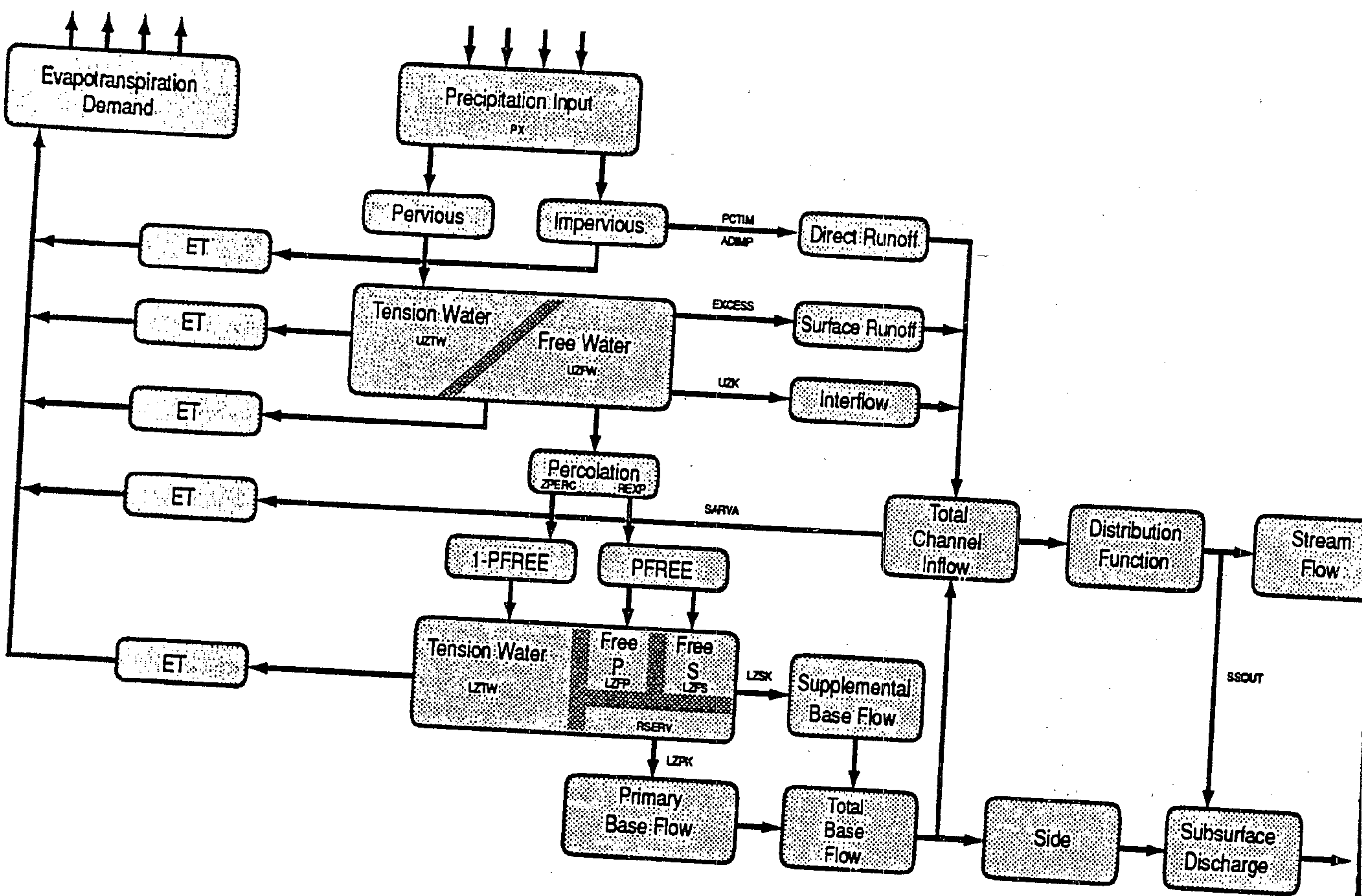


Figure 4.2 Sacramento Soil Moisture Accounting Model

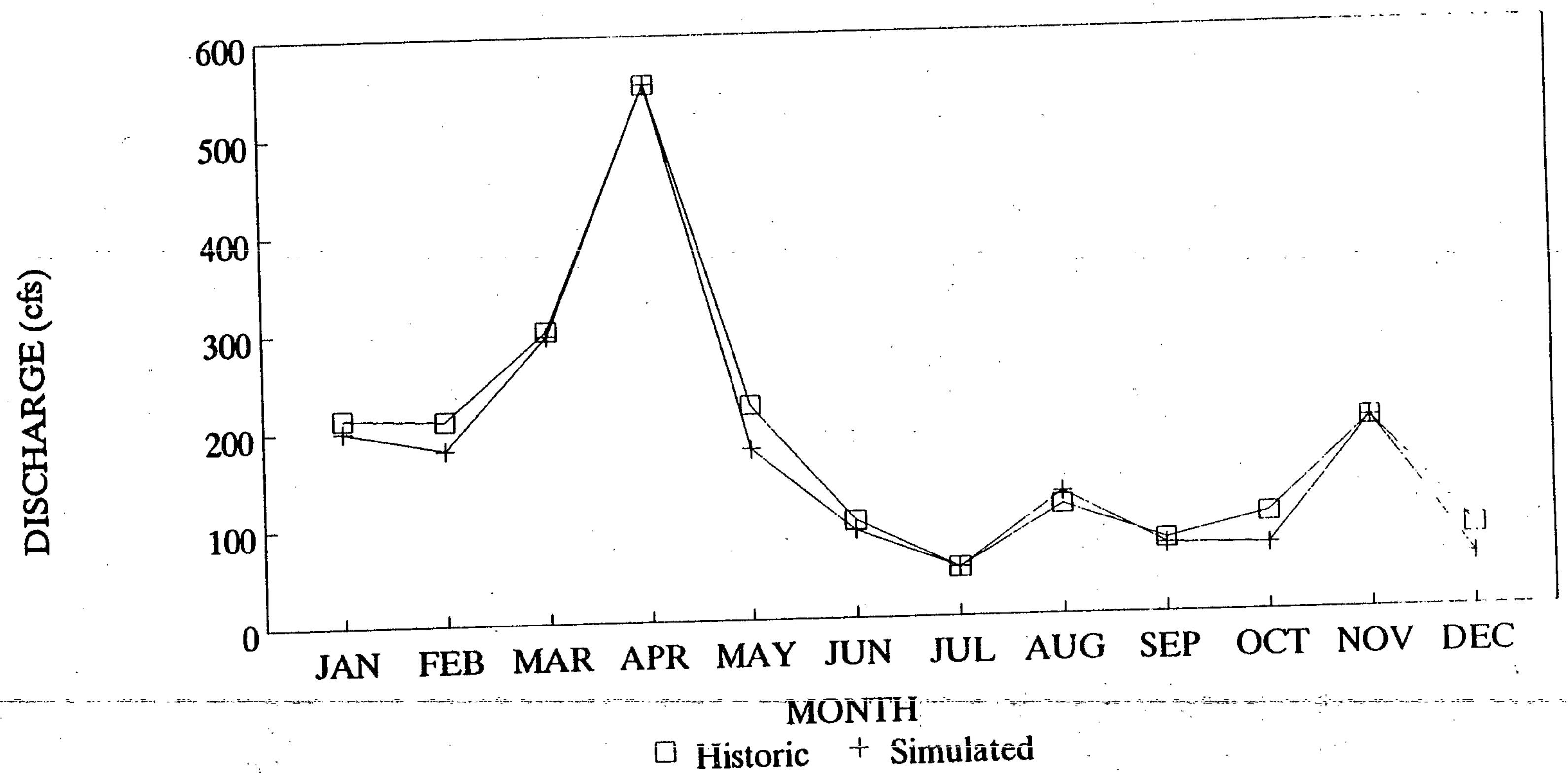


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Figure 4.3 Ware River Verification

Figure 4.4a Ware River Entire Series (1950 - 64)

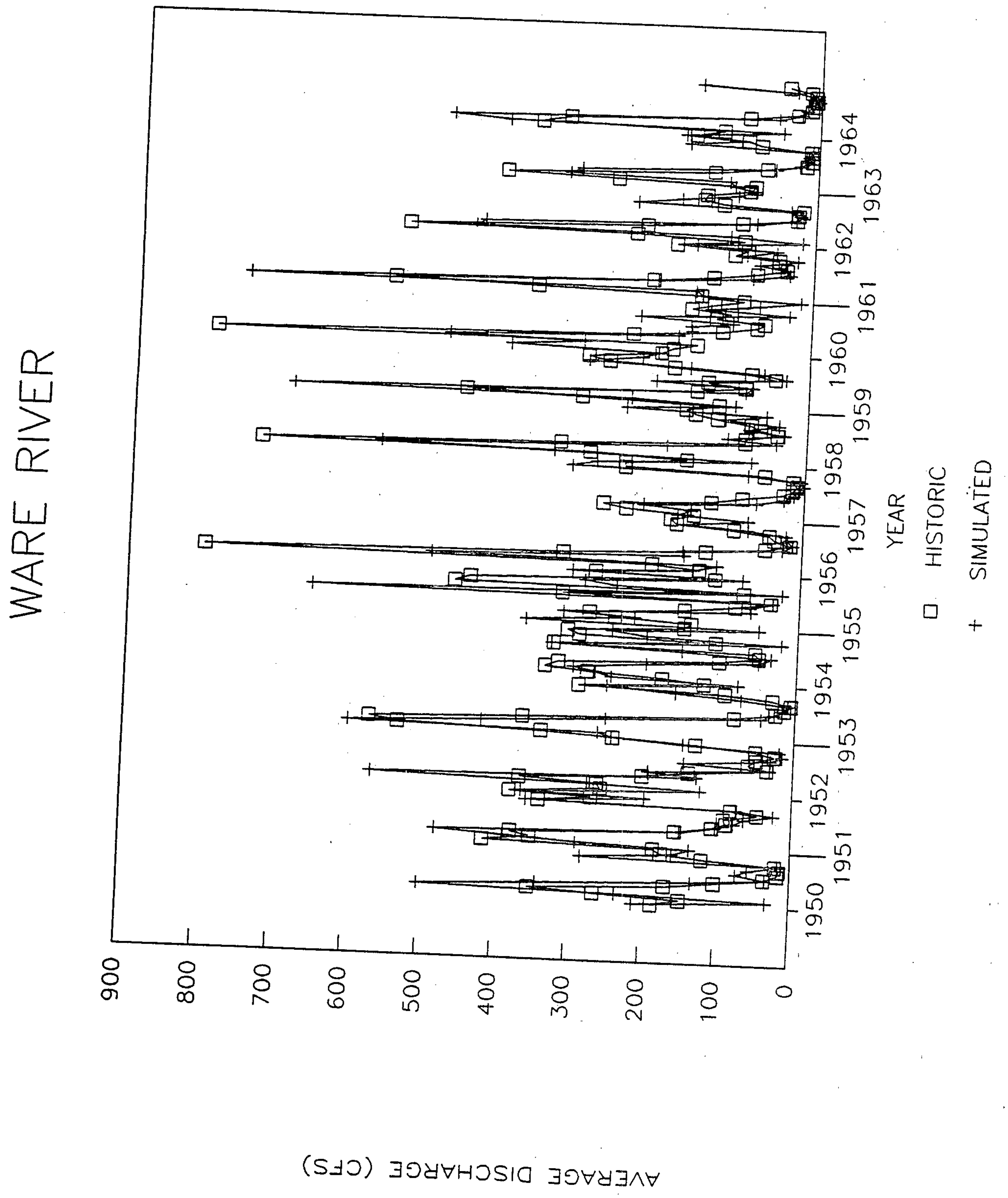
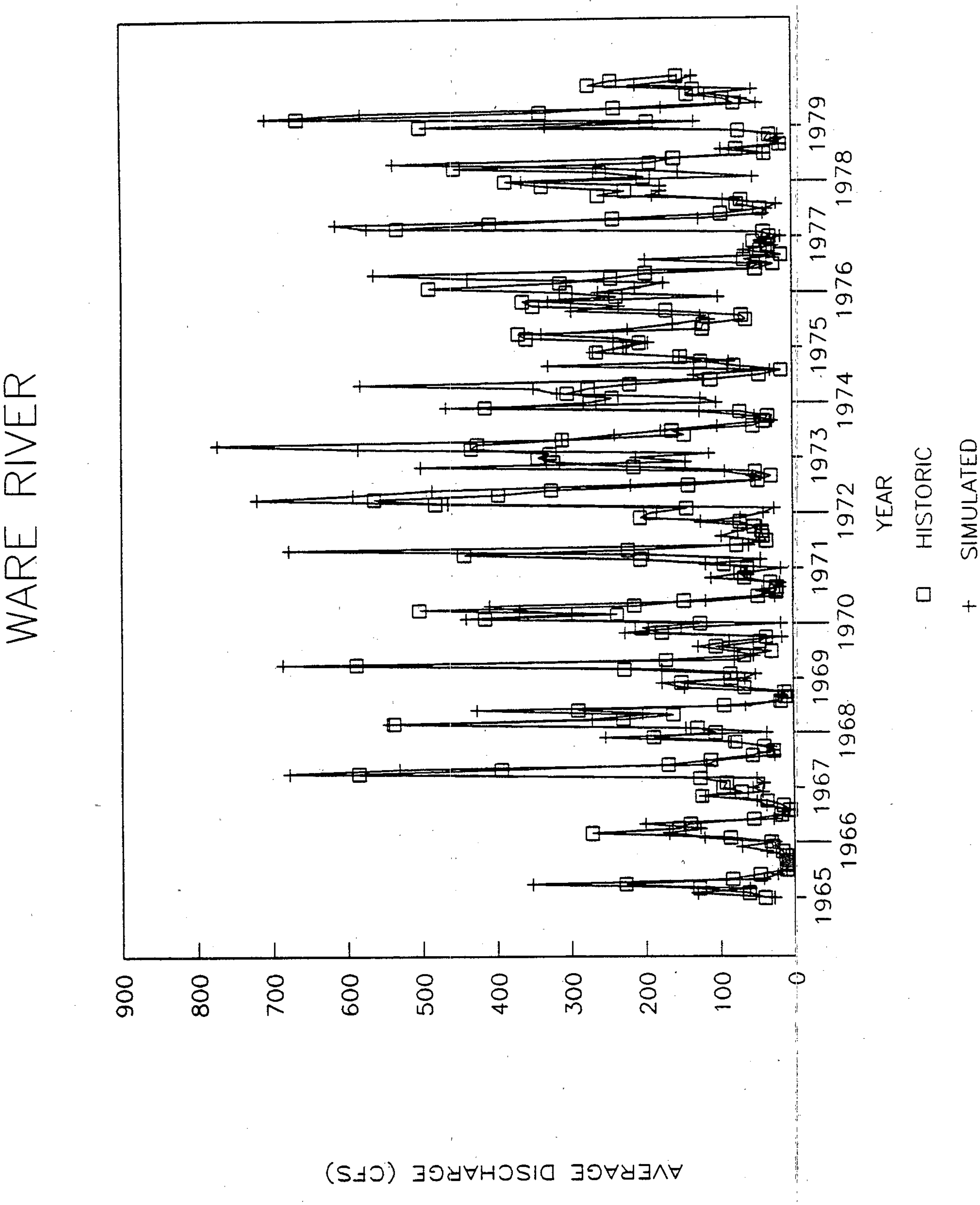


Figure 4.4b Ware River Entire Series (1965 - 79)



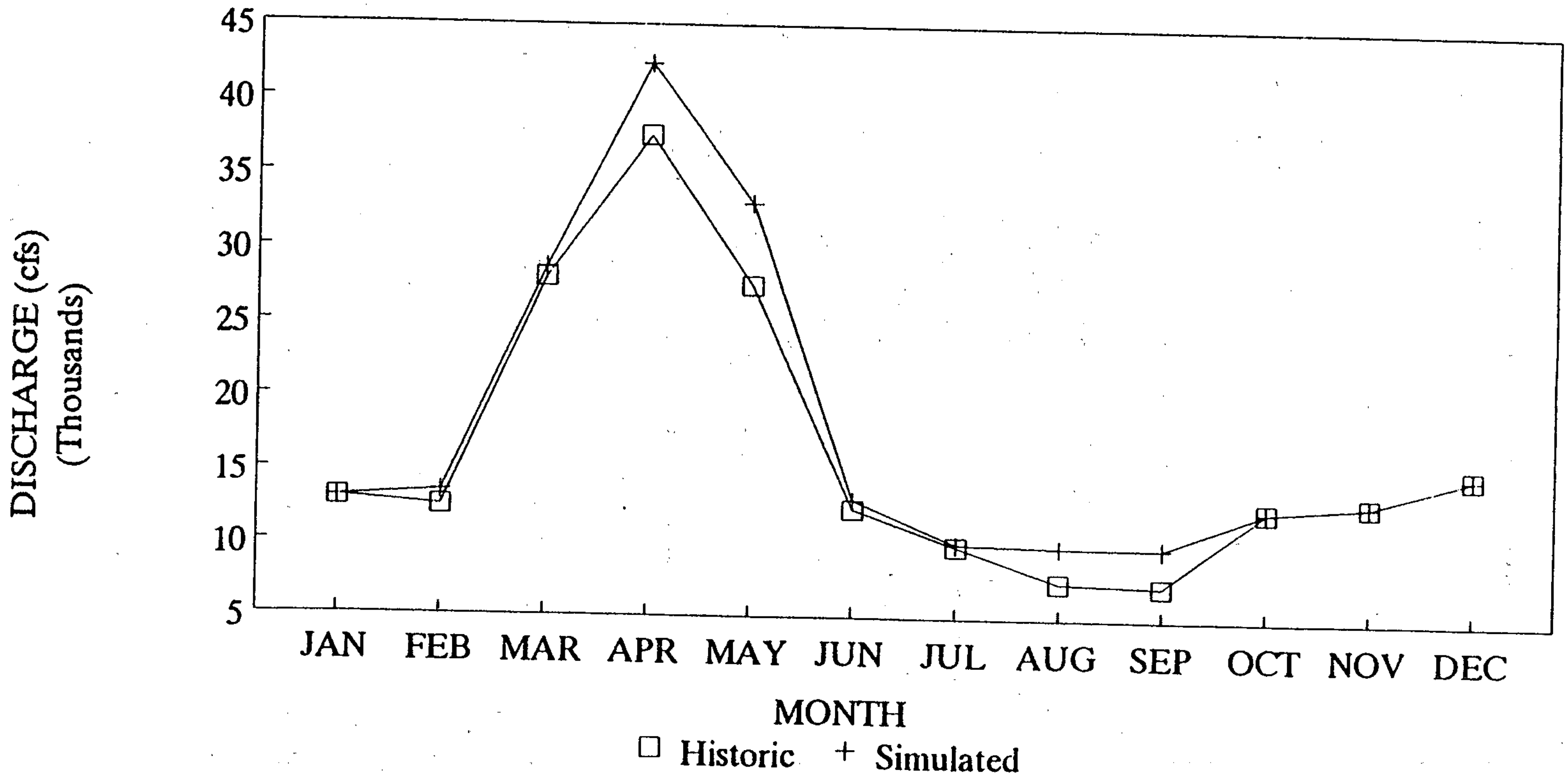


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Figure 4.5 Connecticut River Verification

Figure 4.6a Connecticut River Entire Series (1950 - 64)

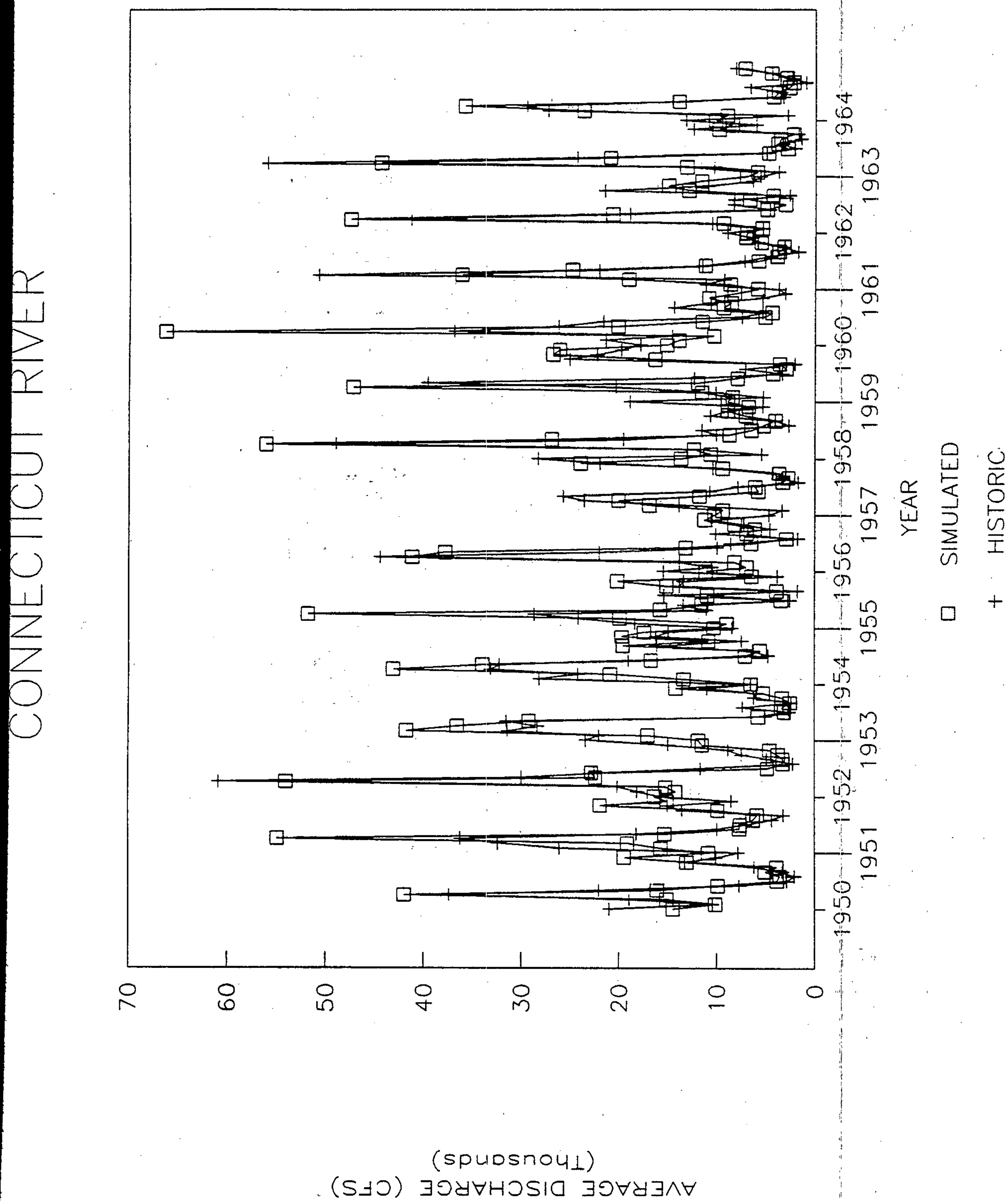
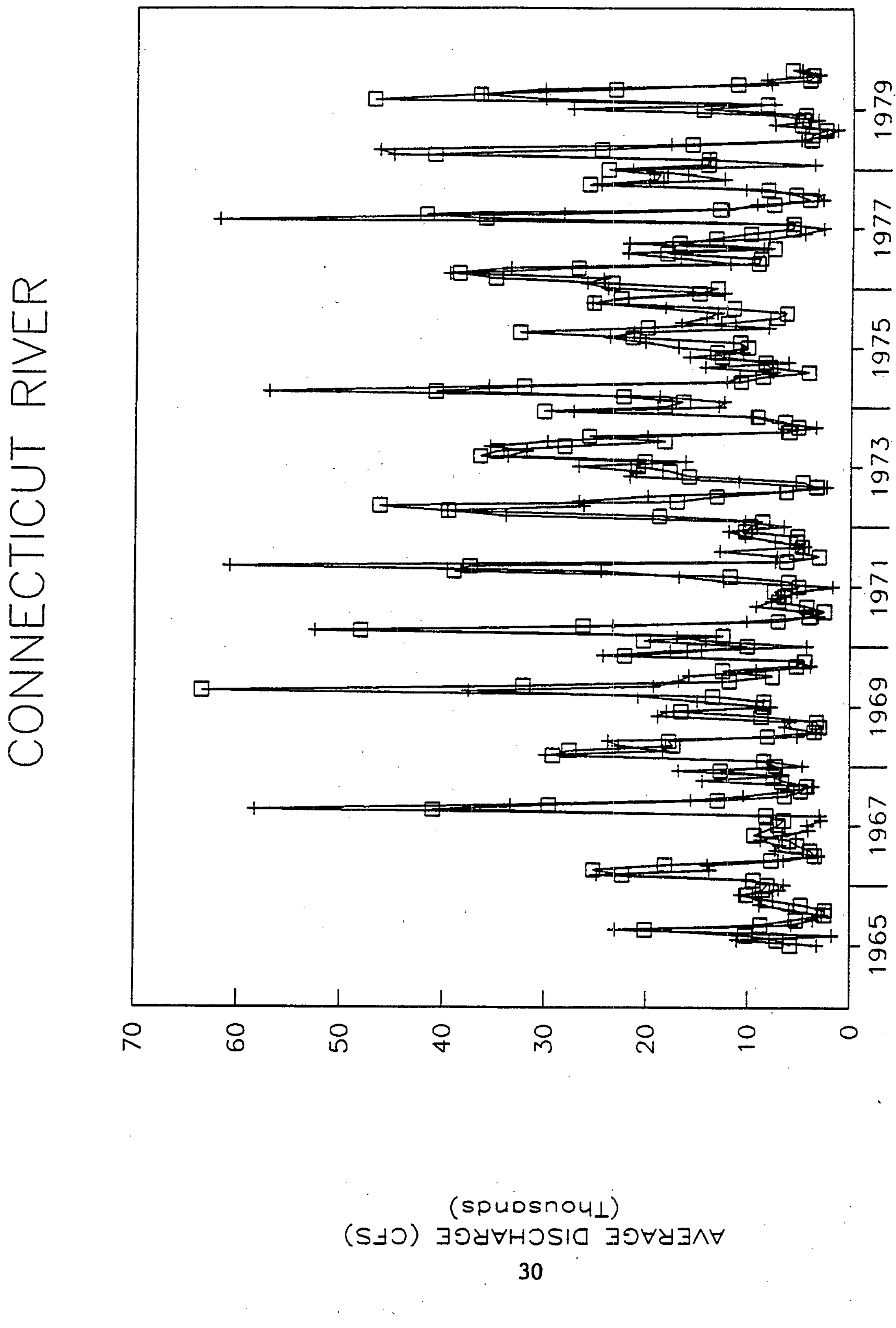


Figure 4.6b Connecticut River Entire Series (1965 - 79)



5: POTENTIAL EVAPOTRANSPIRATION AND EVAPORATION

Introduction

In a humid climate, such as New England, actual evapotranspiration, Et', may account for up to one half of the long-term average annual water budget. Thus, in a hydroclimatologic sensitivity analysis of a water supply system, careful attention to Et, the potential evapotranspiration, is necessary. In this study, the Penman-Monteith equation is employed to estimate Et and the Penman equation is used to estimate the potential (free surface) evaporation, Ep. With these methods, daily values of Et could be generated to be used in the Runoff Model and monthly values of Ep for use in the Safe Yield Model.

Potential Evapotranspiration

The primary reason for differentiating between potential evaporation, Ep, and potential evapotranspiration, Et, is that the diffusion of water vapor into the atmosphere follows very different physical pathways from vegetation (transpiration) than it does from a free water surface. Shuttleworth (1979) cites Penman (1948) who defines Ep as "the quantity of water evaporated from an idealized, extensive free water surface per unit area, per unit time under existing atmospheric conditions". Shuttleworth (1979) cites Gangopadhyaya et al (1966) who defines Et as "the maximum quantity of water capable of being lost, as water vapor, in a given climate, by a continuous, extensive stretch of vegetation covering the whole ground when the soil is kept saturated". His definition of Et therefore recognizes the combined process of transpiration by vegetation and evaporation from saturated bare soil. Estimating Et is more difficult than Ep because several vegetation species specific model parameters are required. Furthermore, ways to estimate these parameters are still being developed.

There are several reasons why the Penman-Monteith energy budget equation was chosen to estimate potential evapotranspiration. First, the Penman-Monteith equation "big leaf" model is presently used by a number of General Circulation Models (GCMs) to estimate the flux of energy and moisture between the atmosphere and the land surface/water surface boundaries as discussed by Milly (1991). Secondly, the model is composed of a number of the GCM prognostic variables, thereby lending itself to easy perturbation by climate change scenarios. Lastly, the model is derived from the energy conservation equations and therefore it is generally considered to be universally applicable. The Penman-Monteith evapotranspiration model (Monteith, 1965) is shown below as Eq. 5.1.

$$\lambda Et = \frac{\Delta(Rn - G) + \rho Cp(e^\circ(z) - e(z))/ra}{\Delta + \gamma(1 + rc/ra)} \qquad (5.1)$$

where λ is the latent heat of vaporization of water; Δ is the gradient of the saturation vapor pressure-temperature function; Rn is the net radiation; G is the soil heat flux; ρ is the air density; Cp is the specific heat of the air at constant pressure; e°(z) is the saturated vapor pressure of the air, a function of air temperature, measured at height z; e(z) is the vapor pressure of the air measured at height z; ra is the aerodynamic resistance to water vapor diffusion into the atmospheric boundary layer; γ is the psychrometric constant; and rc is the vegetation canopy resistance to water vapor transfer. Notation is summarized in Appendix B.

One of the limitations of the Penman-Monteith equation is its data requirements. At a minimum, the model requires air temperature, windspeed, solar radiation and the saturation vapor pressure deficit. The surrogate of solar radiation employed in the present study is empirical clear sky estimates of solar radiation combined with observed cloud cover or percent of possible sunshine. The surrogate for the saturation vapor pressure deficit, e°(z) - e(z), usually estimated from air and dewpoint temperatures, is relative humidity. For this study, which spans 1950 through 1979, average monthly observations of air temperature, windspeed, percent of possible sunshine and relative humidity were obtained for several First Order Summary of the Day NOAA climate stations.

In Eq. 5.1, the net radiation, Rn, is described by Eq. 5.2, which is shown below.

$$Rn = (1-\alpha)Rs - Rb \tag{5.2}$$

where Rs is the shortwave (solar) radiation, α is the surface reflectivity or albedo; and Rb is the longwave backscatter radiation. In this study the values of α determined by Brest (1987) are employed. He derived mean monthly values of albedo for coniferous and deciduous forests and unfrozen surface water bodies for the region around Hartford, CT. Brest (1987) conducted ground-truth radiometer measurements against Landsat satellite band 4 and 7 observations. The forest albedo values used here assumes an equal mix of deciduous and conifers in the study watersheds. Therefore, the forest albedo used is an average of Brest's (1987) deciduous and confer forest values, shown in Table 5.1. It is also assumed that the forest vegetation will not evolve sufficiently to alter the albedo within the next 100 years, as discussed by Nicholson (1988).

In Eq. 5.2, the incoming shortwave radiation, Rs, is determined using the methods described by Heerman et al (1985) and Fritz and MacDonald (1949). The net longwave back radiation, Rb, which is a function of air temperature and relative humidity, is estimated using methods described by Wright and Jensen (1972), Wright (1982) and Linsley, Kohler and Paulus (1982). Relative humidity, which is not a variable output from General Circulation Models (GCM, see Section 6), is derived from the GCM variables of specific humidity and mixing ratio. This is described more in Appendix A.

In the estimation of Et, the term G in Eq. 5.1, represents the soil heat flux. During the spring and summer months in the New England climate, energy that might otherwise be available for evaporating soil moisture instead heats the soil. Similarly, the flux of energy from the soil to the atmosphere during the fall months (soil cooling) will contribute to the evaporation of soil moisture. The soil heat flux, G, is estimated using a single soil layer model described by American Society of Civil Engineers (ASCE, 1990).

The right-hand term of the numerator of Eq. 5.1 is referred to as the sensible heat flux. The saturation vapor pressure deficit is estimated by Eq. 5.3.

$$e^{\circ}(z) - e(z) = e^{\circ}(z,Ta)(1 - S/100) \quad (5.3)$$

where S is the relative humidity; and Ta is the air temperature.

In Eq. 5.3, the saturated vapor pressure, e°(z,Ta) measured at height z is estimated by the methods described by Tetens (1930) and Murray (1967).

In Eq. 5.1, the slope of the saturation vapor pressure temperature curve, Δ, is estimated by the methods described by Tetens (1930) and Murray (1967). The latent heat of vaporization of water ,λ, is estimated using the method described by Harrison (1963). The psychrometric constant, γ, is estimated by Eq. 5.4, shown below.

$$\gamma = \frac{Cp\ Pa}{0.662\ \lambda} \quad (5.4)$$

In Eq. 5.4, the specific heat of moist air, Cp, is assumed to equal 1.013 kJ/kg°K as reported by Brutsaert (1982). Functions describing the estimation of the atmospheric pressure, Pa, and the air density, ρ, (of Eq. 5.1) are reported by List (1984).

rc and ra in Eq. 5.1 are respectively dependent upon characteristics of the vegetation and the surface windspeed drag conditions. In this study, it is assumed that the vegetation of the study areas can be appropriately modeled as an equal mix of eastern deciduous and conifer forests as discussed above.

Rauner (1976), pp. 257, defines the low level drag coefficient CaM by Eq. 5.5.

$$CaM = \left\{ \frac{U*}{U(z)} \right\}^{2} \qquad (5.5)$$

such that

$$ra = \frac{1}{CaM\ U(z)} \qquad (5.6)$$

where U* is the friction velocity, defined by Monteith (1973), and U(z) is the windspeed measured at height z.

Rauner (1976) reports values of CaM of 0.019 and 0.046 for a birch and pine forest respectively for windspeeds in the range of the present study observed values. These drag coefficient values are chosen to represent those of a deciduous and conifer forest. Therefore, based on the reasonable assumption that the study watersheds are comprised of an equal mix of this forest vegetation, Eq. 5.6 is simplified to Eq. 5.7.

$$ra = \frac{37.5}{U} \qquad (5.7)$$

Eq. 5.7 illustrates an important assumption regarding windspeed. Although Rauner (1976) measured windspeed profiles above the forest canopy, this sort of observation is unavailable for this study. Therefore, it has been assumed that the First Order Climate station windspeed observations, although measured at the 2 meter height, may be suitably employed in Eq. 5.7.

Detailed discussion about empirical estimates of the canopy resistance, rc, has been left for last. Ways to estimate this Et parameter, either empirically or through physically based models of vegetation, are still being developed. Furthermore, the focus of most research has been on estimating rc for cultivated crop irrigation requirement purposes, such as alfalfa. Monteith (1965) assumes that the ratio of rc/ra equals 15 for forest canopies, and Eagleson (1984) suggests that rc/ra approximately equals 10.

Unfortunately, no long-term empirical measurements of rc for forest canopies have been reported in the literature. This is due in part to the difficulty in measuring forest evaporation rates as discussed by Byrne et al (1988). Verma et al (1986) report mid-day values of 75-160 s/m over a six day period in August for a fully leafed deciduous forest in eastern Tennessee. McNaughton and Black (1973), pp. 1587, report a rc value of 75 s/m over an eighteen day period in July for a Douglas Fir forest in British Columbia. To circumvent the difficulty of defining a precise value of the canopy resistance, rc, in this study, it was decided to employ it as a runoff model calibration parameter. Monthly values of rc were adjusted so that the long-term monthly average of the daily Penman-Monteith model simulations for Et using historical data agreed with the monthly values of Et determined in the calibration of the Runoff Model during the growing season (April through October for the Ware Basin, May through October for the Connecticut Basin). As a check on this procedure, the monthly values of rc determined for both the Ware and Connecticut Basins were within one or two orders of magnitude of the diverse values reported in literature.

Potential Evaporation

Eq. 5.1 for Et reduces to the potential free surface evaporation, Ep, by substituting the water body heat flux G' for the soil heat flux G, and by equating the canopy resistance, rc, to zero. This is the well known Penman equation. Energy that might otherwise be available for evaporating water heats the water column of the reservoir. As with soil in the New England climate, one would expect this to occur in the spring and early summer. Similarly, the flux of energy from the reservoir to the atmosphere as it cools during the fall will contribute to the evaporation of water. In this study, however, time did not permit a detailed examination of the reservoir energy budgets. Instead it is assumed that the reservoirs are fully mixed and isothermal.

For a fully mixed, vertically isothermal surface water body, G' will equal zero and evaporation may occur at the potential rate, Ep. Clearly, the aerodynamic drag will be different over water than over a forest canopy. In this study, the form of the reservoir surface aerodynamic resistance is defined as that reported by Eagleson (1970), pp. 230, shown below as Eq. 5.8.

$$ra = \frac{\ln^2 (z/z^o)}{\kappa^2 U(z)} \qquad (5.8)$$

$$= \frac{\ln^2 (200/0.001)}{(0.41)^2\ U(z)}$$

where z and z° are the measurement and surface roughness heights (here in centimeters) and κ is Von Karmen's coefficient.

Solving for the values in Eq. 5.8 results in Eq. 5.9.

$$ra = \frac{886}{U} \tag{5.9}$$

Comparison to Observed Data

Long-term monthly average values of potential free-surface evaporation determined in this study for the present climate were compared with the Class A evaporation pan measurements reported by Farnsworth and Thompson (1982), for Norfolk, CT. and Lakeport, N.H. The monthly values reported here is the average monthly value of both stations. The available records are for only May through October because the water in the pans typically freezes during the other months of the year. Monthly values of temperature, windspeed, possible sunshine and relative humidity, which are all used as input variables to the Ep model, are from the Hartford, CT. and Concord, N.H. NOAA stations. The Ep results reported are an average of both Hartford and Concord Ep time series. Figure 5.1 shows that the long-term monthly estimates of Ep are within 0.5 and 1.0 mm/day of the evaporation pan values. The generated Ep values were multiplied by 0.70 to estimate reservoir evaporation in the Safe Yield model.

Generation of Ep and Et Time Series

The Connecticut River Et series was generated using the Concord, N.H. NOAA data. While there is a climate station in Burlington, VT., located near Lake Champlain, it was felt that this large water body might influence the data needed for the present study in an unrepresentative way. Furthermore, the Green Mountains of Vermont separate the Hudson river basin, where Lake Champlain is located, from the Connecticut River basin. The Ware River Et and the MWRA Quabbin and Wachusett reservoir Ep time series were generated using a composite monthly average of the Concord, N.H and Hartford, CT. data.

Table 5.1

Monthly Forest and Surface Water Albedo

Month	Deciduous(%)	Evergreen(%)	Mean(%)	Water(%)
Jan.	10.0	9.0	9.5	3.1
Feb.	10.8	9.5	10.2	2.8
March	12.2	10.7	11.5	2.4
April	14.0	12.5	13.1	2.0
May	16.0	14.6	15.3	1.7
June	17.4	16.0	16.7	1.6
July	17.7	16.3	17.0	1.7
Aug.	16.7	15.3	16.0	2.0
Sept.	14.7	13.5	14.1	2.3
Oct.	12.6	11.6	12.1	2.7
Nov.	10.9	10.1	10.5	3.0
Dec.	10.0	9.3	9.7	3.2

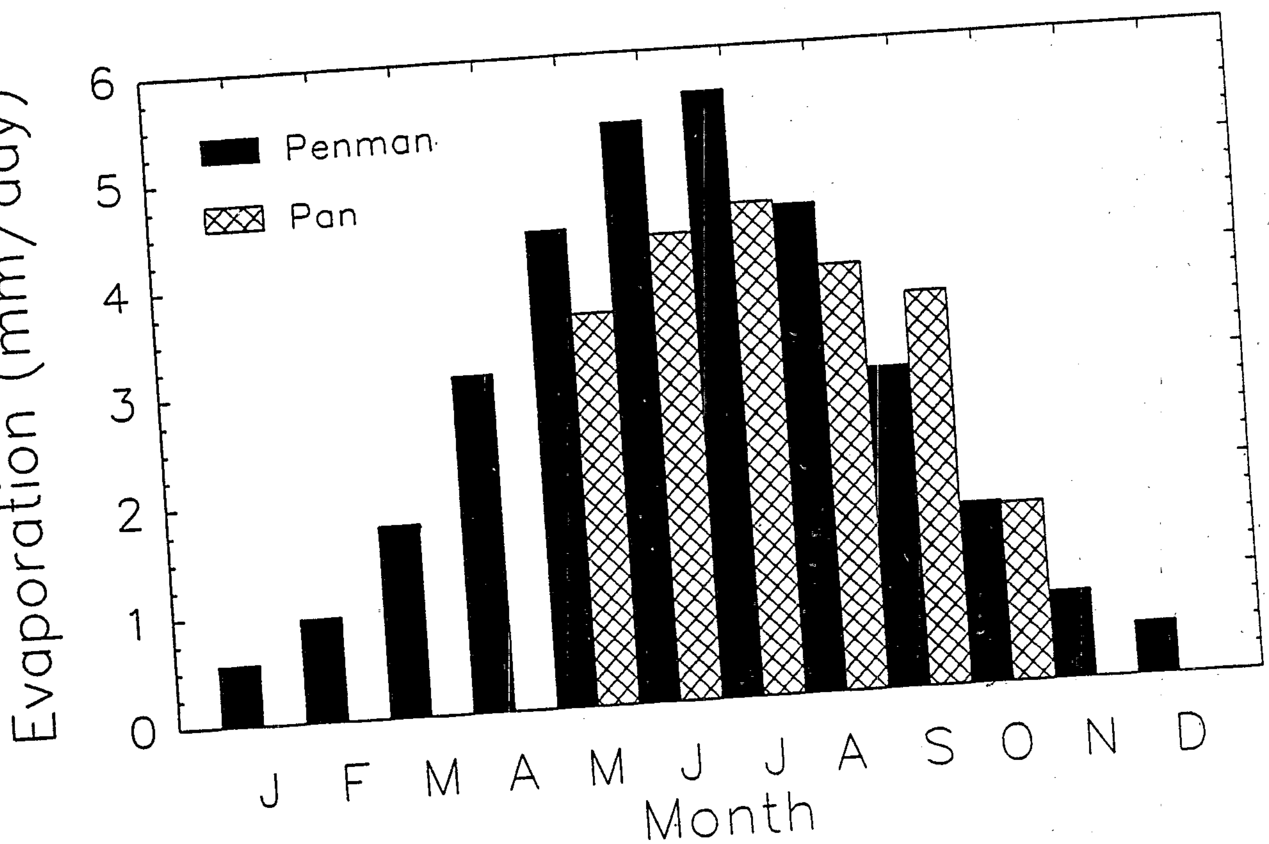


Figure 5.1 Comparison of Estimated Ep and Measured Pan Evaporation

6: POTENTIAL CLIMATE CHANGE IMPACTS

Introduction

Since there is considerable uncertainty on the exact meteorological impacts that may occur under climate change, the US EPA requested that the project team run a set of scenarios that may occur if the equivalent of CO2 doubling occurs. The scenarios include changes predicted by several General Circulation Models (GCM) and separate arbitrary sensitivity analyses to precipitation, temperature, and other variables. In this section, the GCMs are briefly reviewed (actual data from the GCMs and comparisons to present climate data from the study area are given in Appendix A), and then the scenario procedures and impacts are presented. Since the MWRA reservoir system is the major supply source in the study area, only the possible impacts of climate change upon its yield are determined in this section. In Section 7, estimates are given of the impacts of one of the GCM scenarios upon the yield of the other supply sources in the study area.

General Circulation Models

GCM's are complex numerical models of atmospheric circulation that model variables such as winds, precipitation, temperature, radiation transfer, cloud cover, air pressure, and humidity. Because of their complexity, they use large scale grid systems - a typical grid size is 4 degrees latitude by 8 degrees longitude. Within a grid, parameters values are averaged over the atmospheric, land, and sea conditions within the grid. The advantage of using GCM's over sensitivity analysis of selected variables to study the possible impacts of climate change are their internal consistency and strong physical basis (McCabe and Ayers, 1989).

Results from several GCMs were obtained with grid squares centered near 42° degrees north latitude and 72° degrees west longitude, the approximate centroid of the present study area. These GCMs specifically investigated the response of the climate to a doubling of atmospheric carbon dioxide concentration. The GCM output data sets were provided by the National Center for Atmospheric Research (NCAR) and are summarized by Jenne (1989, 1990a,b). As of 1992, these are the most recent GCM data sets NCAR has available. The GCMs used in this study are described below.

The Goddard Institute for Space Studies GCM (GISS) is described by Hansen et al (1983). The model has two soil layers, a 65 meter deep slab ocean, and nine atmospheric layers. The grid square resolution is 7.83° latitude by 10° longitude. The GISS GCM is the only model among the four described here that accounts for partial coverage of ocean and land surface within a single grid square. The model results used in the present study that are for a grid square centered at 43.04° by 70°. The model runs were made in 1982.

The Geophysical Fluid Dynamics Laboratory GCM (GFDL) is described by Wetherald and Manabe (1991). The Q-flux R-15 GISS GCM model has a slab ocean, two soil and nine atmospheric layers with a grid square resolution of 4.44° latitude by 7.5° longitude. The model results provided for the present study are for a grid square centered at 42.22° by 75°. The model runs were made in 1988.

The United Kingdom Meteorological Office (UKMO) GCM is described by Wilson and Mitchell (1987). This model has a 50 meter thick slab ocean and eleven atmospheric layers with a grid square resolution of 5° latitude by 7.5° longitude. The run results provided for the present study are from a grid square centered in northeastern Massachusetts at 42.5° by 71.25°. The model runs were completed in 1986.

The Oregon State University (OSU) GCM is described by Schlesinger and Zhao (1988). It has two atmospheric layers with a 60 meter deep slab ocean and a surface boundary with 4.0° latitude by 5.0° longitude resolution. The run results provided for the present study are from a grid square centered in south-central Massachusetts at 42° by 72°. The model runs used to generate these results were conducted in 1984 and 1985.

As stated previously, the GCM data used in this study and comparisons to present climate are in Appendix A.

Procedures

The procedures used for each scenario were generally similar. The US EPA considers the period of 1950 to 1980 as representative of present climate conditions. Therefore, since the reservoir Safe Yield model requires streamflow, precipitation, and evaporation (Ep) time series, the objective was to determine how these time series might change under the various doubling of CO2 (or 2 x CO2) scenarios and impact the safe yield of 98.5 percent reliability. Because of hydrologic data and Safe Yield model limitations, the actual period used in this study was October 1950 to September 1979. While an improved estimate of safe yield may have been obtained using a longer period of simulation than 30 years, the 30 year period is certainly adequate to determine the types of impacts climate change may have on the safe yield of the reservoir system.

The time series variables necessary to generate streamflow are precipitation, temperature, and potential evapotranspiration (Et). As discussed earlier, both Et and Ep can be determined from incident solar radiation, temperature, wind speed, and relative humidity (which can be determined by either specific humidity or mixing ratio - see Appendix A). Therefore it must be determined how the driving variables may change under 2 x CO2. Since the GCMs do not agree well with the present climate, but may be generally representative, it is reasonable to adjust each of the measured present values of the driving variables by the monthly ratios of each corresponding 2 x CO2 scenario value to the 1 x CO2 scenario value. The one exception is temperature; there the present temperature is increased by the monthly absolute temperature change predicted by the GCM. These methods have been used in previous studies (for example, in those summarized by Smith and Tirpak (1989a)).

The actual variables used from the GCMs are shown in Table 6.1. The longwave backscatter radiation was not perturbed to avoid double counting: longwave back radiation depends upon relative humidity and air temperature, which are already perturbed. The data from the GCMs are in Appendix A.

GISS

The GCM data indicate that, compared to the present climate, the GISS 2 x CO2 climate will be warmer with slightly less precipitation, be slightly less windy, have slightly less relative humidity, and have higher solar radiation with less cloud cover. This resulted in an average increase in Et of 20 percent. The resultant changes in average monthly streamflow for the Ware River compared to the Base Case are shown in Figure 6.1. The impact in the Connecticut River is similar. The major cause of the average decrease in flow of 16 percent is the increase in Et. The peak occurs earlier because snow melt occurs sooner and the low flow season has less flow and extends longer. The impact of these flow changes upon safe yield is a decrease in Base Case (representative of present climate) yield of 306 mgd to 236 mgd (23 percent decrease). Besides less inflows to the reservoirs from tributary streams, the large decrease is also due to increased evaporation from the reservoir surfaces (an average increase of 17 percent), increased releases from Quabbin due to lower flows in the Connecticut River at Montague and less flood skimming from the Ware River. The results are summarized in Table 6.2

GFDL

Compared to the its present climate, the GFDL 2 x CO2 climate will be warmer, be windier, have less precipitation, have somewhat less relative humidity, and have more radiation with less cloud cover. These conditions result in the GFDL Et and Ep being significantly higher than those of the present climate. Figure 6.1 shows the impacts on Ware River streamflow. As shown in Table 6.2, streamflows are 33 percent less and the safe yield is decreased by 43 percent.

OSU

The OSU 2 x CO2 climate will be warmer, more windy, have more precipitation, have less relative humidity, and less cloud cover than its present climate. Figure 6.2 shows that for the Ware River, there is more streamflow in the fall and winter than the base case. There is a similar impact on Connecticut River flows. As shown in Table 6.2, this results in an increase of six percent in streamflows and a safe yield increase by seven percent.

UKMO

This climate will be warmer, less windy, and have more precipitation and less humidity (cloud cover is not reported). As shown in Table 6.2, streamflows increase by 30 percent and safe yield by 38 percent. The streamflow and safe yield increase extraordinarily under the UKMO scenario because, unlike in the other GCMs, there is actually a decrease in evapotranspiration during the late summer and early fall months. As shown in Table A-6, the decrease occurs because of the significant increase in relatively humidity in the UKMO 2 x CO2 scenario in these seasons. Figure 6.2 shows the significant increases in streamflow in fall and winter.

Sensitivity to Temperature and Precipitation Changes

Another series of analyses examined the sensitivity of the streamflow and reservoir systems to combinations of changes in temperature and precipitation. The temperature increases ranged from two to four degrees (celsius); precipitation changes ranged from none to increases and decreases of 10 and 20 percent. The results are summarized in Table 6.2. In the calculations of Et and Ep, only the temperature term in the equations was changed; no allowance was made, for example, for increases in vegetation canopy resistance (rc) as the soil dries.

As be can seen in Table 6.2, the worst case occurs if temperature increases 4 degrees and precipitation decreases 20 percent. In all the scenarios in this set, if precipitation were to increase ten to twenty percent, it would mitigate the impacts of a two to four degree temperature rise. In some cases, safe yield would actually increase. Unfortunately, some researchers (for example, Rind(1991)) and several GCMs indicate that precipitation will remain the same or decrease in the northeastern United States. As the results in Table 6.2 show, if these occur, with or without accompanying changes in other climatic features as shown by GCMs, the impacts on streamflow and safe yield will be severe.

Sensitivity to Canopy Resistance

Rosenberg et al. (1990) present a comprehensive discussion of the potential impact of vegetation growing in an enriched CO2 environment. They suggest that under this scenario, the canopy resistance (rc) could increase by 22 percent because the decrease in transpiration due to stomatal narrowing would be greater than the increase in transpiration due to increased leaf areas. They also report that this is still an area of research and may not actually occur in fields and forests in 2 x CO2 climates. The project team examined the sensitivity of the water supply system to this possibility by increasing the monthly values of rc by 22 percent, and then determining the resulting Et, streamflow, and safe yield for the GISS scenario. As shown in Table 6.2, Et increased by only 5 percent (compared to 20 percent in the other GISS scenario), and streamflows and the safe yield were higher than in the first GISS scenario. Therefore, if rc did increase under enriched CO2, some of the impacts of climate change might be mitigated. Ep, which is independent of rc, however, would still probably increase and cause increased reservoir losses.

Sensitivity of Length of Growing Season

While there were increases in Et during the growing season in each of the previous scenarios, there was no modeling of an increase in the length of the growing season due to increased temperatures. In this scenario, it was assumed that the growing season would extend from March through November in both river basins instead of April through October in the Ware River basin and May through October in the upper Connecticut River basin. To model these impacts using the GISS scenario, the monthly Et values used in the runoff model corresponding to the extra growing season months (originally calibration parameters in the models) were increased by the ratio of the Et values for first GISS scenario to the Base Case Et values. Compared to the first GISS scenario, this resulted in an increase in Et of 12 percent in the Ware basin and five percent in the Connecticut basin, a streamflow decrease of 14 percent in the Ware basin and 5 percent in the Connecticut basin, and a safe yield decrease of 17 percent from 236 mgd to 195 mgd (see Table 6.2). Therefore if there are increases of a few months in the growing season, streamflows and safe yields will be significantly decreased.

Reliability of 306 mgd

Under the Base Case (present climate), the reliability of the safe yield of 306 mgd is 98.5 percent; there are only four months when the demand can not be met over the thirty year simulation period. The reliability of supplying 306 mgd under the GISS scenario is 83.4 percent; failures occur in approximately 50 months over the thirty year simulation period. If drought management practices are simulated, the reliability increases to only 86 percent. As discussed in the description of the Safe Yield Model (Section 3), drought management practices include decreasing demand during times of low reservoir storage.

Presently, it is not a policy option to consider operating the supply system less than close to 100 percent reliability. The public has come to expect water supply to be like other utilities such as electricity - always available as needed.

Comparisons to Other Studies

The magnitudes of the decreases in streamflow are similar to those found in other studies. McCabe et al (1989) found possible decreases in the flow of the Delaware River Basin. For example, in the scenario assuming a 2 degree temperature increase and a 20 percent precipitation decrease, they found a 51 percent flow decrease. This study showed a decrease of 39 percent. The impact of the GISS scenario for the Delaware River basin was a flow decrease of 25 to 39 percent. For the Ware and Connecticut basins, the flow decrease was 16 percent. Schaake (1990) calculated similar possible decreases of flows in the southeastern United States. Rosenberg et al. (1990) also found that in a forest in Tennessee, there would be no change in Et under the GISS scenario if rc is increased due to CO_2 enrichment.

Table 6.1

GCM Variables Perturbed

1.Oregon State University GCM

a) Absolute Change in Temperature
b) Windspeed ratio
c) Ratio of the mixing ratio
d) Incident solar radiation ratio
e) Total cloud cover ratio
f) Modified soil heat flux (Et only)

2.United Kingdom Meteorology Office GCM

a) Absolute Change in Temperature
b) Windspeed ratio
c) Specific humidity ratio
d) Incident solar radiation ratio
e) Modified soil heat flux (Et only)

3.Goddard Institute for Space Studies GCM

a) Absolute Change in Temperature
b) Windspeed Ratio
c) Ratio of the specific humidity
d) Incident solar radiation
e) Total cloud cover ratio
f) Modified soil heat flux (Et only)

4.Geophysical Fluid Dynamics Laboratory GCM

a) Absolute Change in Temperature
b) Windspeed Ratio
c) Ratio of the mixing ratio
d) Incident solar radiation
e) Total cloud cover ratio
f) Modified soil heat flux (Et only)

Table 6.2

Summary of Results

Note: Reported by percent of average change for Ware and Connecticut Rivers compared to Base Case except for temperature, which is increase in temperature (degrees Celsius) and Yield, which is mgd. Yield is the safe yield of the MWRA reservoir system. 2,+20% means 2 degree increase and 20 percent increase in precipitation. "Incr. rc" is increasing value of rc due to CO2 enrichment. "Ext. Sea" is increasing growing season.

Run	Et %	Ep %	Precip %	Temp Cel.	Flow %	Yield mgd
Base	-	-	-	-	-	306
GISS	+20	+17	-1.6	+3.67	-16	236
GFDL	+57	+41	-7.6	+4.9	-33	173
OSU	+23	+13	+13	+3.11	+6	328
UKMO	+10	+32	+23	+8.27	+30	421
2,0%	+12	+6	0	+2	-8	278
2,+20%	+12	+6	+20	+2	+23	379
2,-20%	+12	+6	-20	+2	-39	161
4,0%	+24	+11	+0	+4	-15	250
4,+20	+24	+11	+20	+4	+15	355
4,-20%	+24	+11	-20	+4	-44	139
4,+10%	+24	+11	+10	+4	+0.2	302
4,-10%	+24	+11	-10	+4	-30	196
Incr. rc	+5	+17	-1.6	+3.76	-10	262
Ext. Sea.	NA	+17	-1.6	+3.67	NA	195

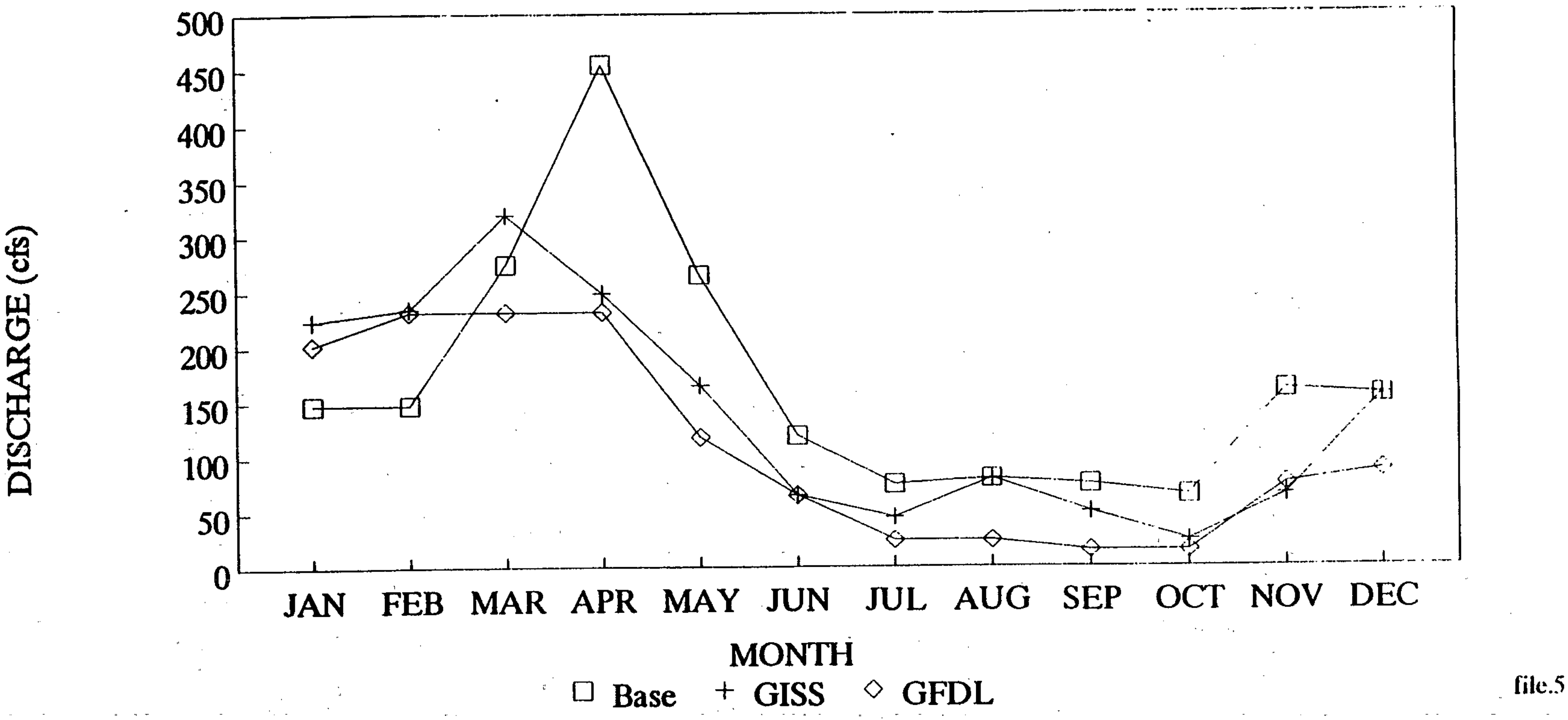
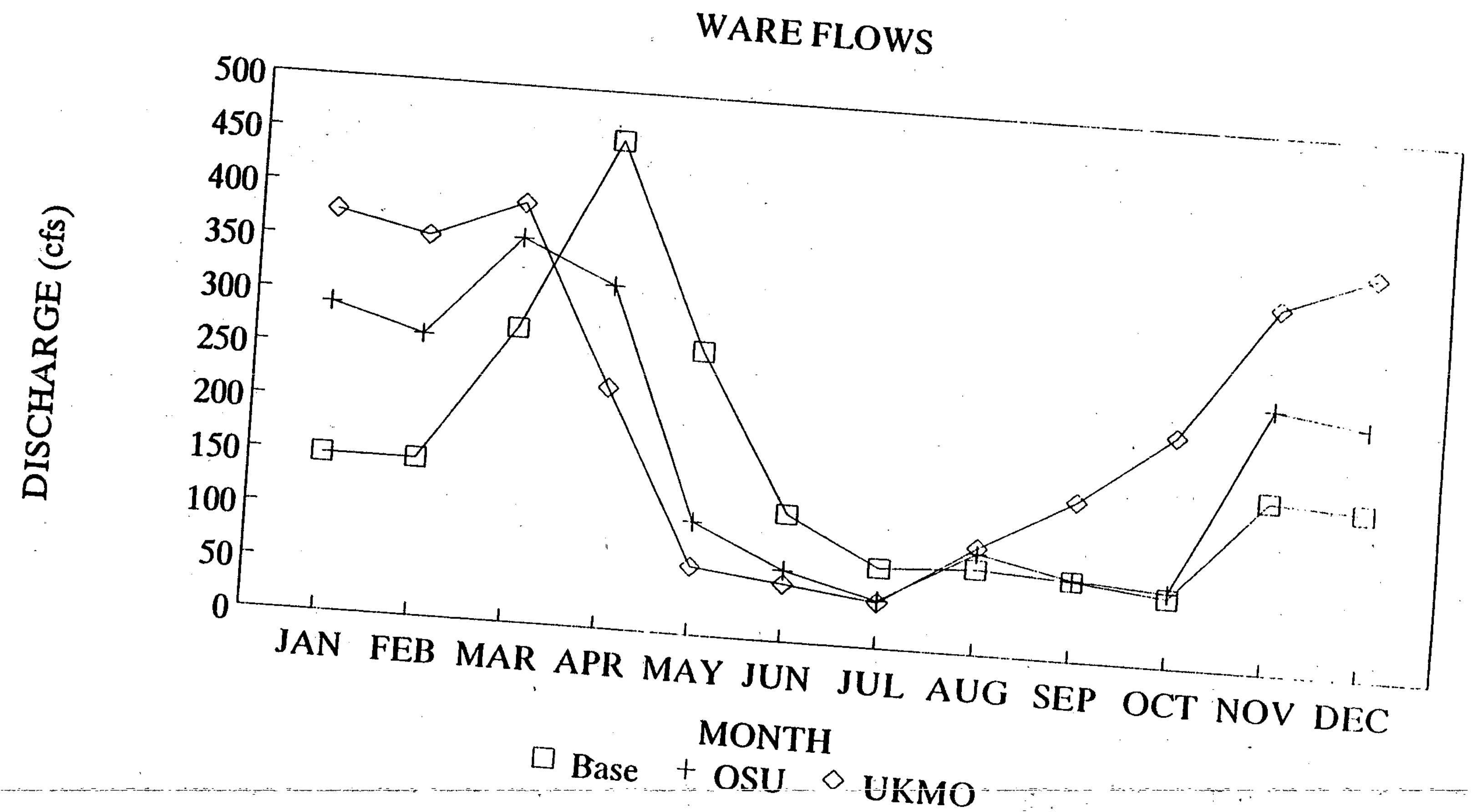


Figure 6.1 GISS and GFDL Impacts upon Mean Monthly Flows of Ware River



WARE

Figure 6.2 OSU and UKMO Impacts upon Mean Monthly Flows of Ware River

7: MWRA POLICY RESPONSE

Introduction

The previous work in this study has concentrated upon the possible impacts of climate change upon the yield of the MWRA water supply system. As was shown, depending upon the scenario, yield may increase or decrease. This section reports upon the reaction of the Planning Section of the MWRA Waterworks Division to these results. In order to accomplish this, the researchers and the MWRA decided to initially examine in more detail the possible impacts of the GISS scenario and then develop a more general response. The GISS scenario was chosen because its impacts are generally mid-range compared to the other scenarios that decrease yield. Use of the GISS Scenario, however, can be considered a high estimate of the worldwide air temperature increase under CO_2 doubling; the GISS increase estimate of 4.2 degree Celsius (Smith and Tirpak (1989b)) is more than the IPCC (1990) Business-as-Usual scenario increase of 1.8 degrees (with an uncertainty range of 1.2 to 3.0 degrees). On the other hand the impacts analyses can be considered conservative because, as Cline (1992) notes, it is very likely that global warming and its impacts will continue to occur pass the year 2050; in fact possibly for several centuries.

General Methodology

Two analyses are done to examine the impacts of the GISS scenario. The first is to project the water demands over the period of 1990 to 2050 under both the 1 X CO_2 and 2 X CO_2 scenarios assuming the demands are fixed requirements and are not price sensitive. The future deficits are then determined and the water conservation strategies and supply sources available to meet the deficits are discussed. The second analysis shows how the GISS scenario might financially impact the MWRA and its ratepayers over the planning period. This analysis requires examining projected water rates and how water users will respond to rate increases using a value of the price elasticity of the demand.

Water Demands

As described in Section 2, the MWRA fully supplies some communities and partially supplies others. Since the MWRA will have to make up the demand deficits in both totally and partially supplied communities, demands (and sources) in both types of communities have to be considered.

Shown in Table 7.1 are the preliminary projections prepared for this study of water supply demand for 1990 and 2050 (the year CO_2 is expected to have doubled) for both fully and partially supplied communities. The demand estimate for the partially supplied communities is the total demand from all sources for those communities, not just the amount supplied by the MWRA. As can be seen, the demand in the 1 x CO_2 scenario increases by only five percent over the present demand. The MWRA projects only slight increases in population and economic activity over that period and assumes that local sources are not lost due to contamination and that the present demand management strategies are maintained. Under the GISS scenario, it is assumed that because of the increased temperature and longer warm season, seasonal summer water use will increase from its present amount of four percent of the total to approximately eight percent. This is also shown in Table 7.1. Therefore under the GISS scenario, the demand could potentially be 393 mgd.

Yields

Shown in Table 7.2 is the present approximate safe yields of the supply sources for MWRA communities. As can be seen, the present total system safe yield of 368 mgd exceeds the present demand of 361 mgd.

The GISS scenario will also impact supply. As previously determined, the safe yield of the MWRA reservoir system will decrease to 236 mgd. Because the locally supplied sources only provide 20 percent of the supply, engineering judgement was used to estimate their yield changes under the GISS scenario. Since the streamflows decreased approximately 20 percent under the GISS scenario (see Table 6.2), it is assumed that local surface water yield will also decrease 20 percent or from 48 mgd to 38 mgd. It was assumed that groundwater yield would remain the same. In reality, there probably would be a change as evapotranspiration increased under the GISS scenario while precipitation remained approximately the same. These factors were not considered because any changes in groundwater yield would be small compared to the total change in safe yield from all sources. Therefore, the total safe yield will decrease from 368 mgd under no climate change to 294 mgd under the GISS scenario, a reduction of 20 percent.

Water Supply Sources and Costs

There is a difference of approximately 100 mgd between the GISS demand of 393 mgd and the GISS total safe yield of 294 mgd. Using data from previous MWRA studies, additional water conservation measures and supply sources were identified to supply this deficit. As discussed in Estes-Smargiassi (1991), many of the inexpensive conservation measures such as leak detection and control have already been implemented for the MWRA system. Therefore, the costs of providing the 100 mgd shortfall are not insignificant.

Shown in Table 7.3 are the various measures the MWRA would implement and their costs. Initially, 5 mgd of additional local sources would be developed. The next source would be to reactivate the water supply reservoir on the Sudbury River, which is 20 miles west of Boston (see Figure 2.1). This reservoir was built as part of the MWRA's system in the late nineteenth century and since 1951 has been on standby service. Reactivation would require a filtration plant. The decreased downstream flows would have tolerable impacts (Parsons,1984). There next would be an intensive and relatively expensive water conservation program for industrial, commercial, and institutional water users. It would consist of more intensive water audits and the provision of engineering services to industries for process changes and improved technologies. The $90 million cost for this would be paid by the MWRA. Annual operation and maintenance costs are assumed to be too little to consider. Even though the total unit costs of the conservation program are slightly less than those of the Sudbury Reservoir project, the Sudbury Reservoir would be reactivated first by the MWRA because it is institutionally easier to implement. The MWRA has full control over the Sudbury project whereas the conservation program requires that the MWRA intrude directly into the activities of water users and other agencies. The next additional source would be the Merrimack River, northwest of Boston. This source would probably be developed in conjunction with the MWRA extending its service territory to the northwest; the local communities there would probably need to significantly augment local supplies under climate change as many only have small reservoirs. The yield and costs shown in Table 7.3 are the amount of the Merrimack River yield and the associated costs that would be allocated to meet the deficit of the present MWRA service territory (i.e., it does not include the costs of service territory expansion to the northwest).

As can be seen in Table 7.3, the total capital costs ($1990) would be $737.5 million with annual operation and maintenance costs of $22.1 million. These costs are conservative because they ignore: (1) the impacts of higher water temperatures on water quality and hence possible additional water treatment costs; and (2) impacts of sea level raise which may require increased flows in the Connecticut River to prevent significant salt water intrusion at the mouth of the river (contamination of local aquifers from salt water intrusion is not a direct concern for the MWRA as none of its service territory rely upon coastal aquifers for water supply).

Without climate change, the 2050 demand is expected to be 379 mgd, 11 mgd over the system safe yield of 368 mgd. The shortfall will probably be supplied from local sources at a capital cost of $15 million and annual costs of $1 million and by long term water conservation by industry. The capital costs of adaptation under the GISS scenario are considerably greater than the cost under no climate change. Annual costs are also significantly impacted.

The difference in present values of the supply costs depends upon the timing of the implementation of the projects and the opportunity cost of capital used to discount the future costs.

Financial Impacts on MWRA and Ratepayers over Planning Period

In this analysis, possible water rates for MWRA users are estimated for both the cases of no climate change and the GISS scenario climate change. The sensitivity of water demand to price is considered in projecting future water demands, conservation and supply requirements and costs, and hence rates. The general procedure is based upon the annual water rate per equivalent household, which the total annual rate revenue requirements divided by the number of equivalent households. The number of equivalent households is the number of households that would use as much water as the actual number of households and industrial users. Since approximately fifty percent of present and projected water demands are from residential customers, the equivalent number of households is twice the actual number of households. Since the water rate of most MWRA users consists of both water supply and sewer costs, the combined costs is used in calculating the water rate. The water rate also has added to it community costs. (The MWRA is wholesale service.)

Because of new sewage treatment plant requirements, the MWRA's annual sewer rates are expected to increase significantly at least until 1999 - perhaps as much as 400 percent additional if no federal or state aid is received. MWRA water rates could also increase 200 percent additional over the same period because of filtration and aqueduct costs. Local community costs are expected to remain the same over the period.

Since the actual change in these infrastructure costs are unknown after 1999 because of possible regulatory changes and funding programs, it is assumed that there are no major infrastructure improvements after 1999 except those incurred for meeting additional demand. Therefore these infrastructure costs are added to the rate requirements through 1999 and it is assumed that because of high operation and maintenance requirements, their annual costs remain even after the bonds are paid off.

Once the annual water rate per equivalent household for 1990 is determined, the analysis of financial impacts is done in five year iterations from 1990 to 2050. It is assumed that the supply shortage under the GISS scenario decreases linearly from the present value of 368 mgd to 294 mgd and that the number of equivalent households increases linearly by five percent over the same period (five percent is the present projected demand increase without climate change and without consideration of demand sensitivity to price from 1990 to 2060 (see Table 7.1)).

As shown in Table 7.1, summer demand is expected to increase under the GISS scenario and result in 14 mgd additional demand over the 1 x CO2 2050 demand of 379 mgd. It is assumed that this additional demand is phased in at the rate of 0.23 mgd per year (14 mgd/60 years) with adjustment each year by the demand change due to price sensitivity.

At each time step, the following is determined: (1) the number of equivalent households (EH), (2) the total water demand by multiplying the previously determined demand per EH by the number of EHs and then increasing this value by any additional demand under climate change, (3) the cost of meeting the total demand by staging the projects in Table 7.3, (4) the resulting water rate per EH, and (5) the water demand per EH for use in the next time step based upon the percentage change in EH annual water rate and the price elasticity.

A bond lifetime of thirty years with an interest rate of seven percent. At the end of the bonding period, replacement costs equal to one-third of the capital costs are necessary.

The value used for the price elasticity of the demand for water is -0.10. A particularly low value was used because of the considerable uncertainty in the selection of this value. It is assumed that the value would probably be less than values reported in the literature for smaller changes in price and over shorter durations of time. Water users respond to price increases by making easy adjustments first, followed by less adjustments (less elasticity) unless new technologies are introduced. Therefore, it is unlikely that demand would be reduced by, for example, 10 percent over a few years if price increased 25 percent (elasticity of -0.40). The IWR Main Training Course Workbook (US Army Corps of Engineers, 1991) reviewed the literature and found an annual residential average price elasticity of -0.20 to -0.40 (pg. 100). They also report an industrial range of -0.50 to -0.80 (pg 106). Stevens et al. (1992) report long-run domestic values in New England of -0.32 and -0.38 based upon average price. Therefore, the value of -0.10 is certainly conservative.

Results of Financial Analysis

According to Estes-Smargiassi (1992), the 1991 MWRA annual wholesale water supply cost was $59.5 million (M). The average community charge totaled $89.3 M for maintaining and administering the local water supply system. The wholesale sewage cost was $185.0 M. The local costs were $71.4 M. The total cost is therefore $405.2 M. The cost is approximately equally divided between residential and industrial-commercial-institutional customers. Since there are approximately 800,000 households in the service territory, there are 1,600,000 equivalent households (EH). Therefore the average annual cost of water supply and sewage is $253 per EH. The 1990 value is assumed to equal this. (This is different than the published rate of the MWRA; among other differences, the MWRA uses an estimated number of households based upon a usage of 90,000 gallons per year per household instead of the actual number.) Since the 1990 total system demand was 361 mgd (Table 7.1), the 1990 demand per EH is 225.6 gallons per day (gpd).

<u>No Climate Change</u> The number of EH's is expected to increase by 5 percent or 80,000 over the sixty year period. Therefore the annual growth increase is 1,333. In 1995, the expected number of EH's is 1,606,665. Therefore the expected 1995 demand, using the 1990 EH demand, is 362.4 mgd. Since the 1 x CO_2 scenario safe yield of 368 mgd (see Table 7.2) exceeds this demand, supply expansion is not necessary at this time. According to data provided by the MWRA, the expected 1995 MWRA wholesale water and sewer rate requirements are $337.4 M. Added to this are community costs of $160.7 M. Therefore the total cost is $498.1 M or $310 per EH. Compared to the 1990 value of $253 per EH, this is an 22 percent increase. Using the demand elasticity of -0.10, the expected demand will be reduced by 2.2 percent to 220.5 gpd.

In the 2000, the expected number of EH's is 1,613,330 and the demand is 355.8 mgd (see Table 7.4). (Tables 7.4 through 7.7 contain the following information; the population in million of equivalent households (Pop), the water demand per household (Demand), the water demand derived from the EHs (Pop Dmd), the incremental increase in Summer demand during climate change (Inc Dmd), the sum of the two demands (Tot Dmd), the total available supply (Supply), the difference between the total demand and the supply (Surplus), the total annual cost of supply in $million (Cost), the total annual cost divided by the number of EHs or the rate (Rate), the change in the rate over this time period (Rate Chg), the resulting change in demand because of price elasticity (Dmd Chg), and the resulting new demand used for the next time period (New Dmd)). Since this is also below the safe yield of the present system, no expansion is necessary. 2000 MWRA and community rate revenue requirements are expected to be $644.6 M (this is based upon actual requirements projected by the MWRA for 1999, the last year MWRA projections are available - the same value is used for 2000). The 2000 rate, based upon 1,613,330 EH's, is $399 per EH. This is an rate increase of 29 percent. This results in a demand decrease of 2.9 percent to 214.2 gpd/EH.

For the years beyond 2000 for the scenario of no climate change, additional supplies will not needed. As shown in Table 7.4, the expected demand in 2050 of 361 mgd is below the system safe yield of 368 mgd. It is interesting to note that Table 7.4 shows the possibility of a slight increase in consumption of water per EH as the unit price drops as population increases.

The final 2050 demand of 361 mgd is less than the presently projected demand of 379 mgd (see Table 7.1) mainly because of the large demand decrease due the severe price increases in 1995 and 2000. In that period, demand is reduced from 225.6 mgd per EH to 214 mgd per EH.

<u>Climate Change</u> Shown in Table 7.5 is the scenario of climate change. After 2005, there is a steady increase in the total cost until 2045 when the Merrimack Diversion is implemented. Up until that time there is also a slight increase in demand per EH as the increase in EH's exceeds the increase in total revenue requirements.

The final 2050 demand of 358 mgd is less than the 2 x CO2 demand of 393 mgd projected without considering price sensitivity. As in the case of the no climate change scenario, the major reason for this is the large drop in demand in 1995 and 2000.

This scenario also allows the construction of the Merrimack Diversion to be delayed until 2045 where it is needed to supply only approximately 15 mgd through 2050 (instead of its entire safe yield of 48 mgd).

The GISS scenario in 2050 results in 13 percent greater rates and annual costs than the scenario without climate change.

Conclusions It is very important to realize that these results are very specific to the MWRA and that the demand decreases are more due to the extraordinary changes in costs for water supply and wastewater treatment infrastructure than to extra costs for augmenting deficits caused by climate change. In fact, after 2000, the total costs are so large compared to any incremental costs of supply due to climate change that there is really no change in demand per EH. The analyses do show, however, that sensitivity to price must be considered in these types of analyses.

Sensitivity Analysis on Price Sensitivity

Higher Elasticity Analyses are also done at an elasticity of -0.40. This so decreased demand per EH from 1990 to 2000 (from 225 gpd/EH to 181 gpd/EH in both scenarios) that there are no deficits in the no climate change scenario and no major deficit until 2045 in the GISS scenario. This again highlights the need for consideration of price elasticity in these analyses.

Less Mandated Costs As noted previously, the results of these scenarios are unique to areas such as the MWRA which are experiencing extraordinarily high water and associated sewer rates because of exceptional costs for mandated water supply and wastewater treatment infrastructure. Most wastewater treatment plants were largely funded by the federal government under the Clean Water Act. Therefore to investigate the financial impacts that would have occurred on the MWRA if its costs were more typical of other communities, the analyses are repeated assuming that the MWRA's fixed annual costs in 1990 are equivalent to those in 1987, $111.1 M, and the local costs are the same as previously, $160.7 M. Therefore the assumed 1990 total annual cost is $271.8 M and the unit cost is $170 per EH.

The results for the scenario of no climate change are shown in Table 7.6. As can be seen, because the deficits are nonexistent or small, total costs are relatively constant and the increases in demand are similar to the static projections in Table 7.1.

The GISS scenario results are in Table 7.7. The costs of meeting the water supply deficits result in steady rate increases that result in a total 2050 demand of 371 mgd instead of the projected 393 mgd in Table 7.1. The 2050 deficit is 77 mgd. While the final rates and annual costs are lower than with the infrastructure costs included, under the GISS scenario rates are 28 percent higher than the no climate change scenario.

Conclusions The type of results shown in Tables 7.6 and 7.7 would apply more to an area without the extraordinary high water supply and wastewater treatment infrastructure costs of the MWRA. They again show that any demand projections are sensitive to price even with low values of elasticity. Even with price elasticities, however, climate change could result in increased water supply costs and rates. Additional sensitivity analysis could be done on the trade-off between various levels of system reliability (assumed to always be 98.5 percent for this study) and supply cost.

Reaction of MWRA Staff to Results of Study

As discussed in Section 1, through their involvement in the project, the MWRA's Waterworks Planning Section learned about the possible impacts of climate change on the yield of their system. Their response is summarized by Estes-Smargiassi (1991) in his paper written after the Albuquerque Conference; "Given the time-value of money, and the practical considerations of "banking" savings, we at the MWRA are unlikely to (now) propose substantial capital outlays to adapt to climate change. And, while we have, and continue to make conservative decisions about facility locations and elevations, we will not (now) make major policy decisions based on climate change effects."

Further discussions with the MWRA indicated that the reasons for this response are that the impacts of global climate change are too uncertain to presently take direct action - particularly since the MWRA currently has difficulty obtaining approval for funds for basic maintenance or necessary system improvements. The MWRA, however, will continue to remain aware of possible climate change and formulate active policies when they think it is necessary. They also believe that the climate changes will be gradual and they will have time to react; it is possible for them to react to a perceived need within five to ten years.

The MWRA has the luxury of this response because of its already extensive water supply planning activities and options. For example, the MWRA already has future possible local sources located and is working to protect their flexibility and feasibility by, for example, helping member communities protect them. (There are no other large-scale reservoir sites.) The MWRA also knows that there remain some demand reduction measures that could be quickly implemented if necessary. They have not been implemented to date because the MWRA believes they are presently not needed and they do not want to lose their credibility by requiring unnecessary demand reductions.

The MWRA's response of "wait and see" is similar to that of other water supply managers. The relevant conclusions of Schwarz and Dillard's (1990) survey of urban water managers from cities across the United States were that: (1) water managers do not see climate change as a "cause for immediate major concern" (pg. 365); (2) removal of some of the uncertainty by scientific consensus and governmental, professional and scientific endorsement are necessary before water managers will act; and (3) "most impacts of climate change on urban water can be mitigated, albeit at significant cost" (pg. 366).

Schwarz (1992) also notes another dilemma water managers similar to the MWRA face; that is they may not know climate change has occurred until 30 to 40 years after it has. Before that period, temperature and precipitation changes might only be seen as normal variations in weather, not permanent changes. Therefore a response may only occur due to a new extreme event or belief in the scientific validity of climate change.

Table 7.1

MWRA System Demands (MGD)

Demand	1990	2050 (1xCO2)	2050 (2xCO2)
Fully Supplied	242	248	258
Partially Supplied	89	104	108
Other	10	12	12
Unaccounted For (MWRA)	20	15	15
TOTAL	361	379	393

Table 7.2

Total MWRA System Safe Yield (MGD)

Source	1 x CO_2	2 x CO_2
Quabbin System	300	236
Local Groundwater	20	20
Local Surface Water	48	38
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TOTAL	368	294

Table 7.3

Additional Sources of Supply Under 2 x CO_2

$1990

Source	GISS Yield (MGD)	Capital Cost ($millions)	Annual Oper & Maint ($millions)
Local Sources	5	7.5	0.5
Sudbury River	16	40	1.6
Consrvt	30	90	0.0
Merrimack River	48	600	20.0
TOTAL	99	737.5	22.1

Table 7.4

Financial Analysis - No Climate Change - e = -0.10

Year	Pop MEH	Demand gpd/EH	Pop Dmd mgd	Inc Dmd mgd	Tot Dmd mgd	Supply mgd
1990	1.6000	225.6	361.0	0.0	361.0	368.0
1995	1.6066	225.6	362.4	0.0	362.4	368.0
2000	1.6132	220.5	355.8	0.0	355.8	368.0
2005	1.6198	214.2	346.9	0.0	346.9	368.0
2010	1.6264	214.3	348.5	0.0	348.5	368.0
2015	1.6330	214.3	350.0	0.0	350.0	368.0
2020	1.6396	214.4	351.6	0.0	351.6	368.0
2025	1.6462	214.5	353.1	0.0	353.1	368.0
2030	1.6528	214.6	354.7	0.0	354.7	368.0
2035	1.6594	214.7	356.3	0.0	356.3	368.0
2040	1.6660	214.8	357.8	0.0	357.8	368.0
2045	1.6726	214.9	359.4	0.0	359.4	368.0
2050	1.6792	214.9	360.9	0.0	360.9	368.0

Year	Surplus mgd	Cost $M	Rate $/EH	Rate Chg	Dmd Chg	New Dmd mgd
1990	7.0	405.2	253.3	0.000	0.0000	225.6
1995	5.6	498.1	310.0	0.224	-0.0224	220.5
2000	12.2	644.6	399.6	0.289	-0.0289	214.2
2005	21.1	644.6	398.0	-0.004	0.0004	214.3
2010	19.5	644.6	396.3	-0.004	0.0004	214.3
2015	18.0	644.6	394.7	-0.004	0.0004	214.4
2020	16.4	644.6	393.1	-0.004	0.0004	214.5
2025	14.9	644.6	391.6	-0.004	0.0004	214.6
2030	13.3	644.6	390.0	-0.004	0.0004	214.7
2035	11.7	644.6	388.5	-0.004	0.0004	214.8
2040	10.2	644.6	386.9	-0.004	0.0004	214.9
2045	8.6	644.6	385.4	-0.004	0.0004	214.9
2050	7.1	644.6	383.9	-0.004	0.0004	215.0

Table 7.5

Financial Analysis - Climate Change - e = -0.10

Year	Pop MEH	Demand gpd/EH	Pop Dmd mgd	Incr Dmd mgd	Tot. D mgd	Supply mgd
1990	1.6000	225.6	361.0	0.0	361.0	368.0
1995	1.6066	225.6	362.4	1.2	363.6	361.9
2000	1.6132	220.5	355.7	1.1	356.9	357.4
2005	1.6198	214.2	346.9	1.1	348.0	351.3
2010	1.6264	214.2	348.4	1.1	349.5	345.1
2015	1.6330	214.1	349.7	1.1	350.8	358.3
2020	1.6396	214.2	351.3	1.1	352.4	352.1
2025	1.6462	214.3	352.8	1.1	353.9	346.2
2030	1.6528	214.3	354.3	1.1	355.4	347.8
2035	1.6594	214.4	355.7	1.1	356.8	349.2
2040	1.6660	214.4	357.2	1.1	358.3	350.7
2045	1.6726	214.5	358.8	1.1	359.9	352.1
2050	1.6792	212.4	356.6	1.1	357.7	394.0

Year	Surplus mg	Cost $M	Rate $/EH	Rate Chg	Dmd Chg	New Dmd mgd
1990	7.0	405.2	253.3	0.000	0.0000	225.6
1995	(1.7)	498.5	310.3	0.225	(0.0225)	220.5
2000	0.5	645.0	399.8	0.289	(0.0289)	214.2
2005	3.3	645.0	398.2	(0.004)	0.0004	214.2
2010	(4.4)	650.5	400.0	0.004	(0.0004)	214.1
2015	7.5	650.5	398.3	(0.004)	0.0004	214.2
2020	(0.3)	650.6	396.8	(0.004)	0.0004	214.3
2025	(7.7)	652.3	396.2	(0.001)	0.0001	214.3
2030	(7.6)	654.1	395.8	(0.001)	0.0001	214.4
2035	(7.6)	656.0	395.3	(0.001)	0.0001	214.4
2040	(7.6)	655.4	393.4	(0.005)	0.0005	214.5
2045	(7.8)	723.3	432.4	0.099	(0.0099)	212.4
2050	36.3	723.3	430.7	(0.004)	0.0004	212.5

Table 7.6

Financial Analysis - No Climate Change - e = -0.10

Reduced Costs

Year	Pop MEH	Demand gpd/EH	Pop Dmd mgd	Incr Dmd mgd	Tot Dmd mgd	Supply mgd
1990	1.6000	225.6	361.0	0.0	361.0	368.0
1995	1.6066	225.6	362.4	0.0	362.4	368.0
2000	1.6132	225.7	364.1	0.0	364.1	368.0
2005	1.6198	225.8	365.7	0.0	365.7	368.0
2010	1.6264	225.9	367.4	0.0	367.4	368.0
2015	1.6330	226.0	369.0	0.0	369.0	368.0
2020	1.6396	226.0	370.6	0.0	370.6	369.0
2025	1.6462	226.1	372.2	0.0	372.2	370.6
2030	1.6528	226.2	373.8	0.0	373.8	372.2
2035	1.6594	226.2	375.4	0.0	375.4	373.8
2040	1.6660	226.3	377.0	0.0	377.0	375.4
2045	1.6726	226.4	378.6	0.0	378.6	377.0
2050	1.6792	226.4	380.2	0.0	380.2	378.6

Year	Surplus mgd	Cost $M	Rate $/EH	Rate Chg	Dmd Chg	New Dmd mgd
1990	7.0	271.8	169.9	0.000	0.0000	225.6
1995	5.6	271.8	169.2	(0.004)	0.0004	225.7
2000	3.9	271.8	168.5	(0.004)	0.0004	225.8
2005	2.3	271.8	167.8	(0.004)	0.0004	225.9
2010	0.6	271.8	167.1	(0.004)	0.0004	226.0
2015	(1.0)	272.0	166.6	(0.003)	0.0003	226.0
2020	(1.6)	272.3	166.1	(0.003)	0.0003	226.1
2025	(1.6)	272.6	165.6	(0.003)	0.0003	226.2
2030	(1.6)	273.0	165.2	(0.003)	0.0003	226.2
2035	(1.6)	273.3	164.7	(0.003)	0.0003	226.3
2040	(1.6)	273.6	164.2	(0.003)	0.0003	226.4
2045	(1.6)	273.9	163.8	(0.003)	0.0003	226.4
2050	(1.6)	274.2	163.3	(0.003)	0.0003	226.5

Table 7.7

Financial Analysis - Climate Change - e = -0.10

Reduced Costs

Year	Pop MEH	Demand gpd/EH	Pop Dmd mgd	Incr Dmd mgd	Tot D mgd	Supply mgd
1990	1.6000	225.6	361.0	0.0	361.0	368.0
1995	1.6066	225.6	362.4	1.2	363.6	361.9
2000	1.6132	225.7	364.0	1.2	365.2	357.4
2005	1.6198	225.3	364.9	1.1	366.1	370.6
2010	1.6264	225.4	366.6	1.1	367.7	364.4
2015	1.6330	225.4	368.1	1.1	369.3	361.6
2020	1.6396	225.4	369.5	1.1	370.6	363.1
2025	1.6462	225.3	370.9	1.1	372.0	364.5
2030	1.6528	225.2	372.3	1.1	373.4	365.9
2035	1.6594	225.2	373.7	1.1	374.8	367.3
2040	1.6660	220.0	366.5	1.1	367.6	409.1
2045	1.6726	220.1	368.1	1.1	369.2	403.0
2050	1.6792	220.2	369.8	1.1	371.0	396.8

Year	Surplus mgd	Cost $M	Rate $/EH	Rate Chg	Dmd Chg	New Dmd mgd
1990	7.0	271.8	169.9	0.000	0.0000	225.6
1995	(1.7)	272.2	169.4	(0.003)	0.0003	225.7
2000	(7.8)	277.7	172.1	0.016	(0.0016)	225.3
2005	4.5	277.7	171.4	(0.004)	0.0004	225.4
2010	(3.3)	278.5	171.2	(0.001)	0.0001	225.4
2015	(7.7)	280.3	171.7	0.003	(0.0003)	225.4
2020	(7.5)	282.2	172.1	0.003	(0.0003)	225.3
2025	(7.6)	284.0	172.5	0.003	(0.0003)	225.2
2030	(7.5)	285.8	172.9	0.002	(0.0002)	225.2
2035	(7.6)	353.7	213.1	0.233	(0.0233)	220.0
2040	41.5	353.1	212.0	(0.005)	0.0005	220.1
2045	33.7	351.9	210.4	(0.007)	0.0007	220.2
2050	25.8	350.7	208.8	(0.007)	0.0007	220.4

8: CONCLUSIONS AND ADDITIONAL RESEARCH

Conclusions

Even though this project has been as thorough as time and budget allowed in its investigation of the potential impacts of global climate change, it shares many of limitations of similar studies. Some of these limitations include:

- Limitations of GCMs.

- Disagreement among the GCMs.

- The methodology to apply results of GCMs to river basin studies.

- Uncertainty of the impacts of doubling CO2 upon vegetation changes, transpiration characteristics, growing season, and albedo.

- Uncertainty of the impacts of doubling CO2 upon the temporal characteristics of precipitation.

- Assumptions in the Et, Ep, and runoff models that may be violated under climate change.

- Possible changes in the operating policies of water resource systems in response to climate change.

- Inconsistencies in doing sensitivity analysis on just precipitation and temperature when other important variables will also be impacted by climate change.

- Ignoring impacts of higher water temperatures on water quality and hence possible additional water treatment costs.

- Uncertainty in price elasticity

In spite of these limitations, the study does have enough rigor (for examples, the strong verification of the Et, Ep, and runoff models and the logic of the results) to conclude that the impacts of possible climate change on Et, Ep, streamflow, and reservoir yield could be similar to the range of impacts shown in this study. These show serious decreases in streamflow and yield due to the scenarios of the GFDL and GISS GCMs, temperature changes alone, and increases in growing seasons. If precipitation is also decreased, the impacts are even more severe. Impacts are only mitigated if there are increases in precipitation or canopy resistance increase due to enriched CO2 (which may or may not occur). The negative impacts in reservoir yield occur not only because there is less streamflow, but also because flow maintenance requirements mean less of the flows are available; the low flow season under these types of climate change scenarios is of longer duration and has lower streamflows. Therefore, it appears that climate change could have significant detrimental impacts upon streamflows and reservoir yields in the northeast.

The OSU and UKMO GCM scenarios, however, indicate that precipitation in New England may increase. The increases are significant enough to offset the increases in evaporation and evapotranspiration and result in increases in streamflows and system safe yield.

The contradictory results of the GCMs are not surprising and have been reported upon by others (for example, Stone, 1992). This again indicates the present uncertainty in climate change impacts.

Even though further analysis of the impacts of a moderately negative 2 x CO2 scenario (the GISS scenario) upon the MWRA supply system showed that present supplies would be grossly inadequate and the costs of adaption would be high, the MWRA is presently not taking any direct action to adapt to the possible impacts of climate change. They believe the impacts of global climate change are too uncertain and the costs of direct action (that is either increasing conservation and/or supply) are too high. The MWRA, however, will continue to remain aware of possible climate change and formulate active policies when they think it is necessary. They also believe that the climate changes will be gradual and they will have time to react; it is possible for them to react to a perceived need within five to ten years.

The MWRA has the luxury of this response because its already extensive water supply planning activities and options.

The MWRA's response of "wait and see" is similar to the that of other water supply managers. The relevant conclusions of Schwarz and Dillard's (1990) survey of urban water managers from cities across the United States were that: (1) water managers do not see climate change as a "cause for immediate major concern" (pg. 365); (2) removal of some of the uncertainty by scientific consensus and governmental, professional and scientific endorsement are necessary before water managers will act; and (3) "most impacts of climate change on urban water can be mitigated, albeit at significant cost" (pg. 366).

Additional Research

As all researchers in the area of climate change and water resources have stated, a major scientific research need is to improve the predictive ability of GCMs, enhance their hydrologic components, and determine how best to apply their results to river basin scales. In terms of policy, Fiering and Matalas (1990) state that better methods are needed on decision-making under uncertainty.

As shown by the MWRA's response to the possible impacts of climate change, many policy making organizations subject to political and financial constraints have difficulty formulating policy given the uncertainty of climate change and the relatively long time horizon before serious impacts may occur. This inaction may hinder the implementation of low risk and inexpensive adaptation strategies in the near-term future to counter the possible long term impacts. An immediate research need is to determine what information is needed, what information can be provided, and how should it be presented to policy making organizations in order for them to formulate policy to respond to possible climate change.

REFERENCES

American Society of Civil Engineers (ASCE), 1990. Evapotranspiration and Irrigation Water Requirements, edited by M.E. Jensen, R.D. Burman, and R. G. Allen, ASCE Manual and Reports on Engineering Practice, Number 70.

Anderson, Eric, 1973. National Weather Service River Forecast System--Snow Accumulation and Ablation Model, NOAA Technical Memorandum NWS HYDRO-17, US Department of Commerce, Silver Spring, MD.

Anderson, Eric, 1991. Personal Communication, US National Weather Service, Silver Spring, MD.

Bras, R.L., 1990. Hydrology, An Introduction to the Hydrologic Science, Addison-Wesley, Reading, MA., 643 pp.

Brest, C.L., 1987. "Seasonal albedo of an urban/rural landscape from satellite observations", J. of Climate and Applied Meteorology, Vol.26, No. 9, pp. 1169-1187.

Brutsaert, W.H., 1982. Evaporation into The Atmosphere, D. Reidel Publishing Co., Boston, 299 pp.

Burnash, R. J. C., R. L. Ferral, and R. A. McGuire, 1973. A Generalized Streamflow Simulation System, Conceptual Model for Digital Computers, US National Weather Service and California Department of Water Resources, Sacramento, CA, March.

Byrne, G.F., Dunn, F.X. and Diggle, P.J., 1988. "Forest evaporation and meteorological data: a test of a complimentary theory advection-aridity approach", Water Resources Research, Vol. 24, No. 1, pp. 30-34.

Choudhury, B.J., 1991. "Multispectral satellite data in the context of land surface heat balance", Reviews of Geophysics, Vol. 29, No. 2, pp. 217-236.

Cline, W.R., 1992. The Economics of Global Warming, Institute for International Economics, Washington, DC.

Dickinson, R.E., Henderson-Sellers, A., Kennedy, P.J. and Wilson, M.F., 1986. "Biosphere-Atmosphere Transfer Scheme (BATS) for the NCAR Global Climate Model, Tech. Note TN-275+STR, National Center for Atmospheric Research, Boulder, CO., 69. pp.

Eagleson, P.S., 1970. Dynamic Hydrology, New York, McGraw-Hill, 462 pp.

Eagleson, P.S., 1984. Hydroclimatology 1.721 Class Notes, Massachusetts Institute of

Technology, Cambridge, MA.

Estes-Smargiassi, S.A., 1991. Coping with Climate Change, Boston's Experience with Demand Management. Paper presented at the First National Conference on Climate Change and Water Resources Management, Albuquerque, NM, November.

Estes-Smargiassi, S.A., 1992. Personal Communication. Massachusetts Water Resources Authority, Boston, MA, October.

Farnsworth, R.K., and Thompson, E.H. 1982. Mean Monthly, Seasonal, and Annual Pan Evaporation for the United States, NOAA TR NWS34.

Fiering, M.B. and Matalas, N.C., 1990. Decision-Making under Uncertainty, from Climate Change and U.S. Water Resources, P.A. Waggoner, editor, John Wiley & Sons.

Fritz, S. and MacDonald, J.H., 1949. "Average solar radiation in the United States", Heating and Ventilating, Vol. 46, pp. 61-64.

Gangopadhyaya, M., Uryvaev, V.A., Omar, M.H., Nordenson, T.J., and Harbeck, G.E., 1966. 'Measurement and estimation of evaporation and evapotranspiration', WMO Technical Note No. 83, Geneva, Switzerland.

Hansen, J., Russell, G., Rind, D., Stone, P., Lacis, A., Lebedeff, S., Ruedy, R., and Travis, L., 1983. "Efficient three-dimensional global models for climate studies: Models I and II", Monthly Weather Review, Vol. 111, pp. 609-662.

Harrison, L.P., 1963. "Fundamental concepts and definitions relating to humidity", in Wexler (ed.). Humidity and Moisture, Vol 3, Reinhold Publishing, New York.

Heerman, D.F. Harrington, G.J., and Stahl, K.M., 1985."Empirical estimation of clear sky solar radiation", J. of Climate and Applied Meteorology, Vol 24, No. 3, pp. 206-214.

Intergovernmental Panel on Climate Change (IPCC) 1990. Climate Change, The IPCC Scientific Assessment, edited by J.T. Houghton, G.J. Jenkins, and J.J. Ephraums, Cambridge University Press.

Jarvis, P.G., James, G.B., and Landsberg, J.J., 1976. "Coniferous Forest", pp. 171-240, in Vegetation and the Atmosphere, Vol. 2, Edited by J.L. Monteith, London, Academic Press.

Jenne, R.L., 1989. Data from Climate Models; The CO2 Warming, Draft Document, National Center for Atmospheric Research, Boulder, CO, March.

Jenne, R.L., 1990a. Information about Several Climate Model Runs, NCAR/EPA Doc 7, National Center for Atmospheric Research, Boulder, Co, July.

Jenne, R.L., 1990b. Status of Selected CO2 Climate Model Runs, NCAR Document.

Kalkstein, L.E. (editor), 1991. Global Comparisons of Selected GCM Control Runs and Observed Climate Data, report prepared for US EPA, Office of Policy, Planning, and Evaluation, Washington, DC, April.

Linsley, R.K., Kohler, M.A. and Paulus, J.L.H., 1982. Hydrology for Engineers, 3rd edition, New York, McGraw-Hill, 508 pp.

List, R.J., 1984. Smithsonian meteorological tables, 6th revised edition, Washington, 539 pp.

Martin, P, Rosenberg, N.J, and McKenney, M.S., 1989. "Sensitivity of evapotranspiration in a wheat field, a forest and a grassland to changes in climate and direct effects of carbon dioxide", Climatic Change, Vol. 14, pp.117-151.

Massachusetts Water Resources Authority, 1989. Water Supply Study and Environmental Impact Report - 2020, Safe Yield Model Documentation, prepared by Wallace, Floyd, Associates, Inc., and Arthur D. Little, Inc., Boston, MA, January.

Massachusetts Water Resources Authority, 1990. MWRA Long Range Water Supply Program, Program Briefing and Recommendations to the Board of Directors, January 24, 1990, Boston, MA.

McCabe, G.J., and M. A. Ayers, 1989. Hydrologic Effects of Climate Change in the Delaware River Basin, Water Resources Bulletin, Vol 25(6), December.

McNaughton, K.D., and Black, T.A., 1973. "A study of evapotranspiration from a Douglas Fir forest using the energy balance approach", Water Resources Research, Vol.9, No. 6, pp. 1579-1590.

Milly, P.C.D., 1991. "Potential evaporation and soil moisture in general circulation models", Journal of Climate, Vol. 5, No. 3, pp 209-226.

Monteith, J.L., 1965. "Evaporation and the Environment.", pp. 205-234, in The state and movement of water in living organisms, XIXth Symposium. Society for Experimental Biologists, Swansea, Cambridge University Press.

Montheith, J.L., 1973. Principles of Environmental Physics, Edward Arnold, London, 241 pp.

Murray, F.W., 1967. "On the computation of saturation vapor pressure", J. of Applied Meteorology, Vol. 6, pp. 203-204.

Nicholson, S.E., 1988. "Land surface atmosphere interaction: physical processes and surface changes and their impact", Progress in Physical Geography, Vol. 12, No. 1, pp. 37-65.

Parsons Brinckerhoff Quade and Douglas, Inc, 1984. Sudbury Reservoir Water Treatment Plant, Draft Environmental Impact Report (EOEA No. 03621), prepared for Metropolitan District Commission, Boston, MA.

Penman, H.L., 1948. "Natural evaporation from open water, bare soil and grass", Proc. of the Royal Society, London, A193, 120 pp.

Rauner, J.L., 1976. "Deciduous Forests", pp. 241-264, in Vegetation and the Atmosphere, Vol. 2, Edited by J.L. Monteith, Academic Press, London.

Rind, D., 1991. What Climate Modeling May Tell Us, paper presented at The First National Conference on Climate Change and Water Resources Management, Albuquerque, NM, November, 5-7.

Rosenberg, N.J, Kimball, B.A., Martin, P., and Cooper, C.F., 1990. "From climate and CO2 Enrichment to Evapotranspiration", pp. 151-175, in Climate Change and U.S. Water Resources, Edited by P.E. Wagonner, J. Wiley & Sons, New York.

Schaake, J.C., 1990. From Climate to Flow, from Climate Change and U.S. Water Resources, Edited by P.E. Wagonner, J. Wiley & Sons.

Schlesinger, M.E., and Zhao, Z.C., 1988. "Seasonal climate changes induced by doubled CO2 as simulated by the OSU atmospheric GCM/mixed-layer ocean model", J. of Climate, Vol. 2, No. 5, pp. 459-495.

Schwarz, H.E., and Dillard, L.E., 1990. Urban Water, from Climate Change and U.S. Water Resources, Edited by P.E. Wagonner, J. Wiley & Sons.

Schwarz, H.E., 1992. Personal communication to Paul Kirshen, June 2.

Shuttleworth, W.J., 1979. "Evaporation", Institute of Hydrology, Rep. No. 56, Wallingford, Oxon.

Smith, J.B., and Tirpak, D.A., (editors) 1989a. The Potential Effects of Global Climate Change on the United States, Appendix A - Water Resources, Office of Policy, Planning and Evaluation, US EPA, Washington, DC. May.

Smith, J.B., and Tirpak, D.A., (editors) 1989b. The Potential Effects of Global Climate Change on the United States, Report to Congress, Office of Policy, Planning and Evaluation, US EPA, Washington, DC. December.

Stevens, T.H., Miller, J., and Willis, C., 1992. Effect of Price Structure on Residential Water Demand, Water Resources Bulletin, 28(4), August.

Stone, P.H. and Risbey, J.S., 1990. "On the limitations of general circulation models", Center for Global Climate Change Science, Report No. 2, Massachusetts Institute of Technology, 12 pp.

Stone, P.H., 1992. "Forecast Cloudy: The Limits of Global Warming Models", Technology Review, February/March.

Tetens, O, 1930. "Uber einige meteorologische Begriffe", Z. Geophys., Vol 6, pp. 297-309.

United States Army Corps of Engineers, 1991. Participant Training Workbook, Water Supply and Conservation Planning with IWR-Main Water Use Forecasting System. Prepared by Planning and Management Consultants, Ltd. for Institute for Water Resources, Ft. Belvoir, Virginia.

United States Geological Survey, 1986. National Water Summary 1985, USGS Water-Supply Paper 2300, United States Government Printing Office, Washington, DC.

Verma, S.B, Baldocchi, D.D., Anderson, D.E., Matt, D.R., and Clement, R.J., 1986. "Eddy fluxes of CO2 and sensible heat over a deciduous forest", Boundary Layer Meteorology, Vol 36, pp. 71-91.

Wetherald, R.T., and Manabe, S., 1991. "A re-evaluation of CO_ induced hydrologic change as obtained from low and high resolution versions of the GFDL general circulation model", Journal of Climate, (in review).

Wilson, C.A., and Mitchell, J.F.B., 1987. "A doubled CO2 climate sensitivity experiment with a global climate model including a simple ocean", J. Geophysical Research, Vol. 92, No. D11, pp. 13,315-13,343.

Wright, J.L., 1982. "New Evapotranspiration Crop Coefficients", ASCE J. Irrigation and Drainage Division, Vol. 108,IR2, pp. 57-74.

Wright, J.L. and Jensen, M.E., 1972. "Peak water requirements of crops in southern Idaho", ASCE J. Irrigation and Drainage Division, Vol. 96,IR1, pp. 193-201.

APPENDIX A:
GCM DATA AND COMPARISONS TO PRESENT CLIMATE

Introduction

Presented in this Appendix are the GCM data used in the analyses under both present climate (1 X CO2) and doubled CO2 (2 X CO2). In addition, there is discussion of how the GCM data for specific humidity and mixing ratio were used to calculate relative humidity. Relative humidity is needed to calculate the saturation vapor pressure term in the Et and Ep equations (see Eq 5.1) and the longwave back radiation. There is also a comparison of the GCM present climates to observed climate data.

GCM DATA

Present climate (1xCO2) and doubled atmospheric CO2 concentration (2xCO2) GCM model results relevant to this study are presented in Tables A-1 through A-7. Table A-1 reports GCM values for air temperature; Table A-2 reports windspeed values; Table A-3 reports air pressure; Table A-4 reports total cloud cover; Table A-5 reports specific humidity and mixing ratio; Table A-6 reports calculated relative humidity (see discussion below). Table A-7 reports precipitation.

Estimation of Relative Humidity

The mixing ratio, w, defined by Bras (1990), pp. 85, is shown below as Eq. A-1.

$$w = \frac{0.622\, e(z)}{P - e(z)} \qquad \text{(A-1)}$$

where P is the atmospheric pressure (kPa, note that 1 kPa equals 10 millibars).

The specific humidity, qh, also defined by Bras (1990), pp. 85, is shown below as Eq. A-2.

$$qh = \frac{0.622\, e(z)}{P - 0.378 e(z)} \qquad \text{(A-2)}$$

Given values of w, Eq. A-1 can be inverted to solve for the corresponding relative humidity as shown below by Eq. A-3.

$$S = \frac{100}{e^{\circ} \; (0.622/P) \; (1/w + 1/0.6220)} \qquad \text{(A-3)}$$

Similarly, given values of qh, Eq. A-2 can be inverted to solve for the corresponding relative humidity as shown below by Eq. A-4.

$$S = \frac{100}{e^{\circ} \; (0.622/P) \; (1/qh + 0.378/0.622)} \qquad \text{(A-4)}$$

By using Eqs. A-3 and A-4, monthly values of GCM relative humidity can be calculated, which are shown in Table A-6. As Table A-6 shows, there is something irregular with the UKMO and GFDL relative humidities. The fact that the GFDL results are slightly greater than 100% for several months is probably due to the truncation of the reported values of air pressure, temperature and the mixing ratio. In the case of the UKMO, several months have relative humidity values well in excess of 100%. Jenne (1990b) reports that the temperature value provided for this study is actually a "skin" temperature for which "it may be not too far off to think of this temperature as a quasi-surface air temperature". Because e°(z) is calculated as a function of this temperature, this might be one source of the problem. The value of relative humidity used to calculate the saturation vapor pressure deficit was set to 100 percent if it exceeded 100 percent.

Comparison to Present Climate

Kalkstein Study

While GCMs function at scales considerably larger than the project study area and were not originally designed to accurately model surface phenomenon, it is useful to compare GCM results for present climate to actually measured climate conditions.

A study was recently completed comparing the outputs of GCM's for present climate (referred to as 1 x CO2) to actually measured temperature and precipitation (Kalkstein, 1991). In the comparison study, the data nearest to New England (approximately centered at 43.5 degrees north and 72 degrees west) is for grid centers located at 42 degrees north latitude and 60 and 90 degrees west longitude. Since the grid located at 60 degrees is an ocean grid point and that at 90 degrees is too far west to model ocean influences, the most representative grid to examine in the comparison study is the land grid at 50 degrees north and 60 degrees west, a land grid located near Newfoundland, Canada, which has a climate similar to New England. At this location, the GISS 1 x CO2 temperature was one to two degrees Celsius warmer than the actual climate for Spring, Summer, and Fall, and 5 degrees warmer for Winter. Precipitation was generally one to two mm/day greater for all seasons except Winter, when it was 0.1 degrees less. The annual difference is 1.1 mm/day greater. The average actual present precipitation is 2.5 mm/day.

The 1 x CO2 climate of the GFDL GCM is 2 degrees cooler than present climate in the Winter, Spring and Fall, and the same in the Summer. The GFDL 1 x CO2 precipitation is approximately 1 mm/day greater in all seasons except Winter, when it is 0.3 mm/day greater. The annual difference is 0.9 mm/day greater.

The OSU GCM shows present climate 10 degrees warmer in Winter, 4 degrees warmer in Spring, 1 degree cooler in Summer, and 2 degrees warmer in Fall. The OSU precipitation is approximately 0.8 mm/day less in Winter and Summer, and the same as present climate in Spring and Fall. The annual difference is 0.2 mm/day less.

The UKMO GCM present climate is 5 to 7 degrees cooler in all seasons except summer, when it is 2 degrees warmer. UKMO precipitation is 0.5 to 1.1 mm/day less for all seasons with an average difference of 0.7 mm/day.

<u>Project Study</u>

The project team also conducted a comparison study using regional data. The comparisons presented here include: air temperature; windspeed; percent possible sunshine (assumed to equal one minus total cloud cover); relative humidity and precipitation. The observed climate data used for this comparison are the average of three long-term (1950-1980) First Order NOAA climate stations. The stations used are located at: Bradley Airport, near Hartford, CT.; Concord Airport, Concord, N.H.; and Logan Airport, Boston, MA. These stations were selected for this comparison because they surround the "ideal" present study New England grid square centered at 42° N by 72° W. These data are shown in Tables A-8 through A-12.

<u>Temperature</u>

Many of the terms in the Penman and Penman-Monteith equations are non-linearly temperature dependent. Figure A-1 illustrates the difference between the observed study area temperatures and the 1xCO2 base-case GCM temperatures. In the upper plot, the OSU GCM monthly temperatures are somewhat higher than those observed in the winter months and somewhat lower in the summer months. The UKMO GCM monthly temperatures are somewhat lower than those observed during the winter months and roughly the same during the summer months. In the lower plot, the GISS GCM monthly temperatures are somewhat higher than those observed in the winter months and approximately equal to the observed values during the summer months. The GFDL GCM monthly temperatures are somewhat lower than those observed in the winter months and roughly equal to the observed values during the summer months. Kalkstein (1991) found similar results.

Windspeed

Windspeed is a factor used to determine the aerodynamic resistance term in the Penman and Penman-Monteith equations. Figure A-2 illustrates the difference between the observed monthly windspeed and the 1xCO2 base-case GCM windspeed. In the upper plot, the OSU GCM monthly windspeed is substantially lower higher than that observed during the entire year. The UKMO GCM monthly windspeed is somewhat higher than that observed during all months of the year. In the lower plot, the GISS GCM monthly windspeed generally matches that observed during the entire year. The GFDL GCM monthly windspeed matches that observed during the winter months and is somewhat smaller than the observed values during the summer months.

Cloud Cover

Cloud cover attenuates the incoming solar radiation and traps longwave backscatter radiation. Both are factors in the Penman and Penman-Monteith equations. Here, the complement of cloud cover, percent of possible sunshine, is employed for this comparison. Figure A-3 illustrates the difference between the observed percent of possible sunshine and the 1xCO2 base-case GCM percent of possible sunshine. In the upper plot, the OSU GCM monthly sunshine is substantially lower than that observed during the winter months, and somewhat lower than that observed during the summer months. The UKMO GCM monthly percent cloud cover was not reported. In the lower plot, the GISS GCM monthly sunshine generally matches that observed during the entire year. The GFDL GCM sunshine matches the observations reasonably well during the winter months, but under predicts the observed summer monthly values.

Relative Humidity

The relative humidity term is employed to estimate the saturation vapor pressure deficit and the longwave backscatter radiation, as discussed earlier. Figure A-4 illustrates the difference between the observed monthly relative humidity and the calculated 1xCO2 base-case GCM relative humidity. In the upper plot, the OSU GCM monthly relative humidity values are somewhat higher than the observed values during the winter and spring, but agree quite well with those observed during the summer months. The UKMO GCM monthly relative humidity values are somewhat lower than the observed values during the late summer and fall, but seriously disagree with the winter and spring observed values possibly for the reasons discussed earlier. In the lower plot, the GISS GCM relative humidity values are consistently low during most of the year. The GFDL GCM monthly relative humidity values seriously disagree with the observed values during the entire year.

Precipitation

Figure A-5 illustrates the difference between the observed monthly precipitation and the 1xCO2 base-case GCM precipitation. In the upper plot, the OSU GCM monthly precipitation values agree quite well with the observed during the entire year. Kalkstein (1991) found similar results. The UKMO GCM monthly precipitation values are somewhat lower than the observed values during the winter, but are a good deal greater than the observed values during the summer. This differs from the Kalkstein (1991) study. In the lower plot, the GISS GCM precipitation values are consistently high during most of the year, particularly during the summer months. This is similar to the Kalkstein (1991) study. The GFDL GCM precipitation values are also consistently greater than the observed values for all months of the year. This is also similar to Kalkstein (1991).

Conclusions

It is not really possible to draw any conclusions on the validity of any particular GCM since comparison of a model's results to one set of data are not sufficient to calibrate or verify that model. In addition, the surface areas being modeled by a GCM are not exactly the same as the areas from which historic data were analyzed, particularly in the case of the project comparison. Generally, however, except for relative humidity and precipitation, the GCM results are reasonable in that they have the same range of values as observed data and follow the monthly trends of historic data. In this study, GCM results were not considered predictors of future conditions; rather they were considered to be possible scenarios of the future.

Table A-1

Reported GCM Temperatures (°C)

	OSU		UKMO		GISS		GFDL	
Mon.	1xCO2	2xCO2	1xCO2	2xCO2	1xCO2	2xCO2	1xCO2	2xCO2
Jan.	0.08	4.36	-12.68	-0.64	-0.02	4.97	-9.81	-2.78
Feb.	0.67	4.28	-9.6	3.14	1.96	6.24	-8.43	-2.26
March	2.48	6.27	-6.25	5.53	4.03	7.59	-1.74	3.72
April	6.53	8.63	1.18	9.61	7.32	11.66	7.0	10.93
May	9.43	12.59	7.35	14.70	9.79	13.78	12.64	15.97
June	13.78	17.11	15.70	23.23	14.95	17.57	17.60	20.92
July	16.43	19.37	22.54	27.35	19.76	23.25	21.39	26.82
Aug.	16.68	19.71	21.42	26.31	19.39	22.68	22.36	28.52
Sept.	13.69	16.89	15.32	20.27	16.59	20.53	17.10	21.42
Oct.	8.54	12.08	4.54	11.51	10.43	12.89	7.56	12.26
Nov.	5.13	7.15	-4.29	3.96	5.56	8.46	-1.77	3.92
Dec.	2.74	5.10	-10.20	-0.75	2.18	6.54	-6.50	-3.33

Table A-2

Reported GCM Windspeed (m/s)

Month	OSU		UKMO		GISS		GFDL	
	1xCO2	2xCO2	1xCO2	2xCO2	1xCO2	2xCO2	1xCO2	2xCO2
Jan.	1.8	1.2	5.5	5.2	3.9	4.0	4.0	4.0
Feb.	1.1	0.9	5.5	5.1	2.0	4.0	4.7	4.7
March	1.1	1.1	5.3	5.1	2.6	2.9	3.7	3.5
April	0.6	0.8	5.3	5.3	3.0	2.9	2.6	3.1
May	0.9	1.5	4.9	4.8	2.9	3.8	2.2	1.8
June	2.2	2.1	4.3	3.6	3.4	2.8	2.0	2.4
July	2.4	2.7	3.6	3.2	3.6	3.2	2.6	3.6
Aug.	1.9	1.9	3.6	3.4	2.4	2.7	2.1	2.9
Sept.	1.8	0.9	4.1	4.1	2.9	3.0	0.8	1.0
Oct.	1.4	1.8	4.9	4.5	3.7	3.7	0.6	2.0
Nov.	1.1	2.1	5.2	4.7	3.4	4.3	3.1	3.1
Dec.	0.4	1.3	5.0	4.9	3.8	5.0	3.9	4.2

Table A-3

Reported GCM Atmospheric Pressure (kPa)

Month	OSU		UKMO		GISS		GFDL	
	1xCO2	2xCO2	1xCO2	2xCO2	1xCO2	2xCO2	1xCO2	2xCO2
Jan.	99.90	100.26	101.35	101.14	101.74	101.49	99.28	99.40
Feb.	100.23	100.16	101.19	101.18	101.51	101.23	99.27	99.15
March	100.11	100.21	101.17	101.05	101.17	101.41	99.03	99.22
April	100.37	100.16	101.20	101.11	101.27	101.62	99.25	99.20
May	100.73	100.61	101.26	101.20	101.47	101.42	99.19	99.04
June	100.66	100.63	101.22	100.83	101.27	101.30	99.15	99.24
July	100.70	100.82	100.86	100.54	100.61	100.95	99.26	99.33
Aug.	100.94	100.90	100.80	100.57	100.80	100.89	99.37	99.24
Sept.	100.84	100.76	101.42	101.27	101.10	100.74	99.55	99.33
Oct.	100.37	100.44	101.83	101.56	101.01	101.35	99.44	99.41
Nov.	100.54	100.30	101.53	101.53	101.33	101.24	99.39	99.23
Dec.	100.24	100.22	101.33	101.35	101.67	101.38	99.34	99.37

Table A-4

Reported GCM Total Cloud Cover (%)

Month	OSU 1xCO2	OSU 2xCO2	UKMO[1] 1xCO2	UKMO[1] 2xCO2	GISS 1xCO2	GISS 2xCO2	GFDL 1xCO2	GFDL 2xCO2
Jan.	82	77	-	-	66	66	58	53
Feb.	80	77	-	-	70	69	55	49
March	80	78	-	-	65	61	52	53
April	79	79	-	-	59	50	60	58
May	67	61	-	-	58	58	65	63
June	55	47	-	-	53	51	66	61
July	48	56	-	-	46	50	66	50
Aug.	52	49	-	-	42	40	53	35
Sept.	72	61	-	-	43	34	60	42
Oct.	80	73	-	-	58	52	55	44
Nov.	75	80	-	-	67	62	50	45
Dec.	79	80	-	-	65	63	58	53

1 UKMO total cloud cover not reported

Table A-5

Reported GCM Specific Humidity or Mixing Ratio ($\times 10^4$)

Month	OSU[1] 1xCO2	OSU[1] 2xCO2	UKMO[2] 1xCO2	UKMO[2] 2xCO2	GISS[2] 1xCO2	GISS[2] 2xCO2	GFDL[1] 1xCO2	GFDL[1] 2xCO2
Jan.	32.9	43.6	16.7	40.6	18.0	23.9	18.3	31.4
Feb.	33.5	43.0	21.1	49.4	21.5	29.2	21.1	32.0
March	37.9	48.8	37.3	50.4	27.0	29.4	34.4	49.5
April	48.4	56.1	54.1	63.3	28.7	39.7	63.7	81.4
May	54.4	65.0	89.8	85.2	35.7	45.1	91.0	113.7
June	69.1	79.9	139.9	145.3	52.6	59.2	124.3	153.5
July	78.6	91.9	130.1	185.7	66.0	81.3	157.0	202.8
Aug.	78.2	93.7	90.3	173.6	56.1	71.4	159.6	195.2
Sept.	69.4	82.0	49.5	122.5	47.2	62.9	114.1	137.7
Oct.	54.3	66.2	29.7	77.6	37.2	40.2	64.0	83.9
Nov.	44.4	51.4	19.9	52.5	27.8	30.3	33.3	47.8
Dec.	39.6	46.2	16.7	40.6	23.2	28.6	24.6	29.0

1. Mixing Ratio reported

2. Specific Humidity reported

Table A-6

Calculated GCM Relative Humidity (%)

	OSU		UKMO[1]		GISS		GFDL	
	1xCO2	2xCO2	1xCO2	2xCO2	1xCO2	2xCO2	1xCO2	2xCO2
Month								
Jan.	85.5	83.6	117.9	112.9	48.2	44.7	100.4	100.3
Feb.	83.7	82.9	116.4	104.6	49.8	49.9	103.8	98.1
March	83.0	81.8	158.1	90.1	53.8	45.8	101.3	98.2
April	79.9	79.9	131.8	85.6	45.5	47.2	100.4	98.0
May	73.9	71.3	141.6	82.4	48.0	46.5	97.7	97.9
June	70.1	65.4	126.5	81.9	50.2	47.8	96.5	96.5
July	67.2	65.2	76.6	81.5	46.1	46.0	95.9	88.8
Aug.	66.0	65.2	57.0	81.1	40.2	41.8	91.9	77.5
Sept.	71.0	68.1	46.2	83.2	40.5	42.4	91.9	84.3
Oct.	78.0	75.0	57.4	92.8	47.7	43.9	97.2	92.7
Nov.	80.9	81.2	73.0	105.3	49.8	44.5	98.6	93.5
Dec.	85.2	84.0	96.6	114.1	53.0	47.9	104.2	96.5

1. See appendix text for explanation of values greater than 100 percent.

Table A-7

Reported GCM Precipitation (mm/day)

Month	OSU 1xCO2	OSU 2xCO2	UKMO 1xCO2	UKMO 2xCO2	GISS 1xCO2	GISS 2xCO2	GFDL 1xCO2	GFDL 2xCO2
Jan.	2.72	3.01	1.74	2.23	3.21	3.41	4.78	4.98
Feb.	2.63	2.80	1.76	2.32	4.12	4.41	4.27	4.83
March	2.72	2.75	2.16	2.89	3.81	3.99	4.42	3.90
April	2.37	2.67	3.13	3.12	3.51	3.28	4.13	4.16
May	2.04	1.93	3.24	3.74	2.88	4.16	4.29	4.91
June	2.11	2.10	4.22	5.83	4.62	3.53	5.48	4.70
July	2.26	2.26	6.32	7.11	5.65	5.41	5.27	3.62
Aug.	1.93	2.40	5.07	5.26	3.76	4.45	2.77	2.41
Sept.	2.94	3.31	2.87	3.25	3.54	3.23	4.68	3.92
Oct.	3.89	4.71	1.91	2.59	4.43	3.29	5.33	4.95
Nov.	2.76	4.09	1.73	2.29	4.44	3.20	4.02	4.04
Dec.	2.98	3.52	1.49	1.95	3.33	3.34	5.23	3.03

Table A-8

Observed Air Temperature (°C)

Month	Hartford	Concord	Boston	Mean
Jan.	-3.71	-6.59	-1.42	-3.91
Feb.	-2.54	-5.55	-0.99	-3.02
March	2.48	-0.05	3.24	1.89
April	9.30	6.65	9.09	8.35
May	15.09	12.88	14.63	14.20
June	20.23	18.14	19.98	19.45
July	22.91	20.83	23.10	22.28
Aug.	21.78	19.59	22.14	21.17
Sept.	17.24	14.96	18.02	16.74
Oct.	11.34	9.05	12.61	11.00
Nov.	5.33	2.99	7.22	5.18
Dec.	-1.56	-4.14	0.84	-1.62

Table A-9

Observed Windspeed (m/s)

Month	Hartford	Concord	Boston	Mean
Jan.	4.1	3.3	6.4	4.6
Feb.	4.2	3.5	6.4	4.7
March	4.4	3.7	6.3	4.8
April	4.5	3.5	6.1	4.7
May	4.0	3.2	5.6	4.3
June	3.6	2.8	5.2	3.9
July	3.3	2.5	4.9	3.6
Aug.	3.2	2.4	4.8	3.5
Sept.	3.2	2.4	5.1	3.6
Oct.	3.5	2.7	5.4	3.9
Nov.	3.8	2.9	5.9	4.2
Dec.	4.0	3.2	6.2	4.4

Table A-10

Observed Possible Sunshine (%)

Month	Hartford	Concord	Boston	Mean
Jan.	55.2	53.1	55.4	54.6
Feb.	57.8	56.3	57.7	57.2
March	56.7	52.5	56.7	55.3
April	56.4	53.6	57.6	55.9
May	57.7	57.4	61.1	58.7
June	61.2	58.9	65.1	61.7
July	65.2	64.8	68.0	66.0
Aug.	62.1	61.1	65.8	63.0
Sept.	59.2	56.9	64.1	60.1
Oct.	56.4	54.9	61.6	57.6
Nov.	46.5	43.5	50.7	46.9
Dec.	49.2	48.1	54.0	50.4

Table A-11

Observed Relative Humidity (%)

Month	Hartford	Concord	Boston	Mean
Jan.	66.5	68.7	63.9	66.4
Feb.	64.9	66.0	62.6	64.5
March	63.7	66.6	63.4	64.6
April	60.8	63.8	62.6	62.4
May	64.5	65.3	65.2	65.0
June	68.6	70.5	67.7	68.9
July	69.4	70.6	67.2	69.1
Aug.	72.2	73.5	69.8	71.8
Sept.	74.7	75.2	70.7	73.5
Oct.	71.4	72.3	68.5	70.7
Nov.	70.5	73.4	67.9	70.6
Dec.	70.0	71.9	65.8	69.2

Table A-12

Observed Precipitation (mm/day)

Month	Hartford	Concord	Boston	Mean
Jan.	3.26	2.84	2.32	2.81
Feb.	3.36	2.85	2.23	2.81
March	3.34	3.37	2.41	3.04
April	3.12	3.34	2.55	3.00
May	2.83	2.71	2.37	2.64
June	2.43	2.88	2.46	2.59
July	2.16	2.51	2.35	2.34
Aug.	3.00	3.27	2.73	3.00
Sept.	2.82	3.32	2.58	2.91
Oct.	2.72	2.82	2.50	2.68
Nov.	3.62	3.41	3.13	3.39
Dec.	3.64	3.41	2.81	3.29

Figure A.1 Temperature Comparison

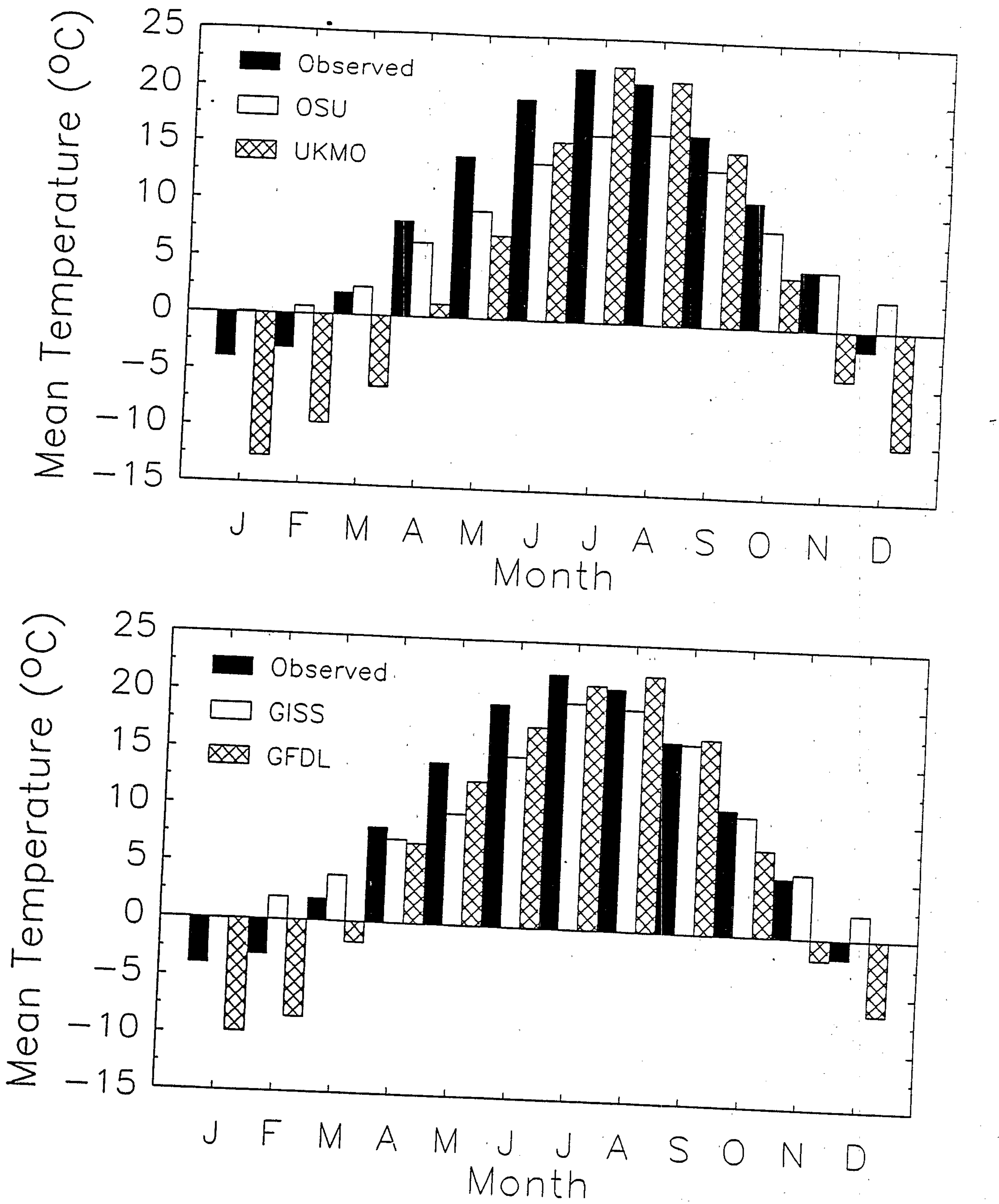


Figure A.2 Windspeed Comparison

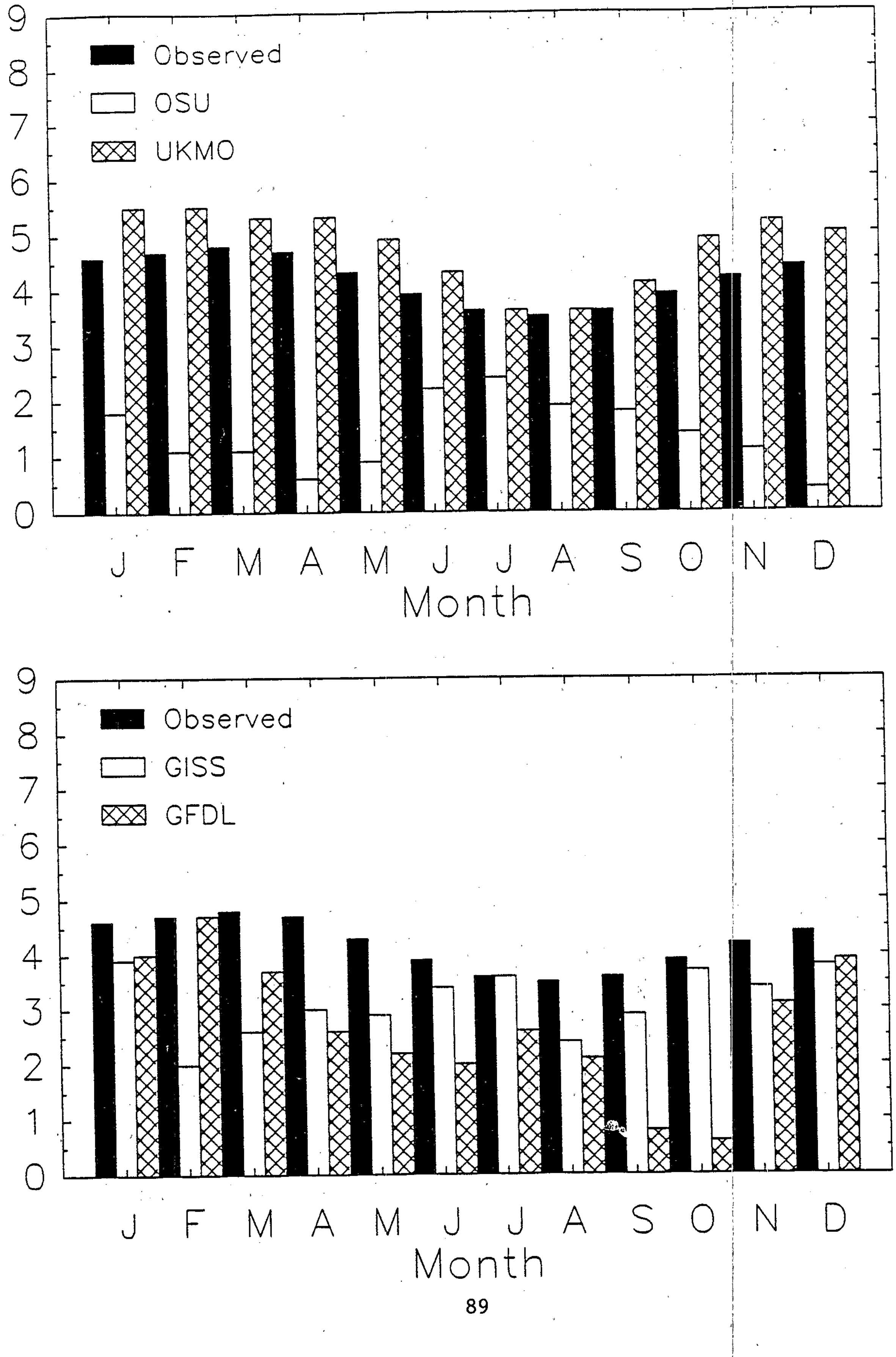


Figure A.3 Cloud Cover Comparison

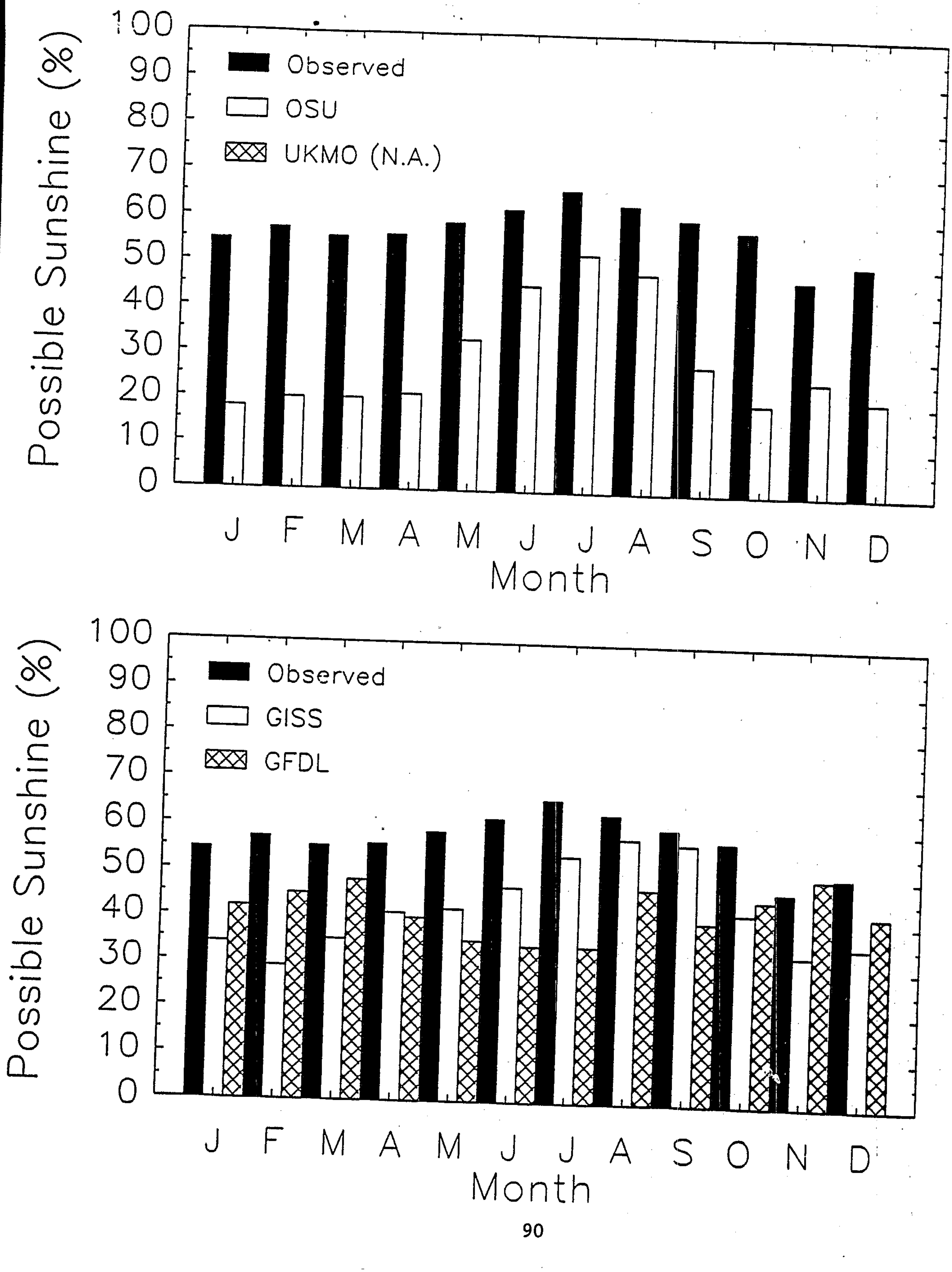
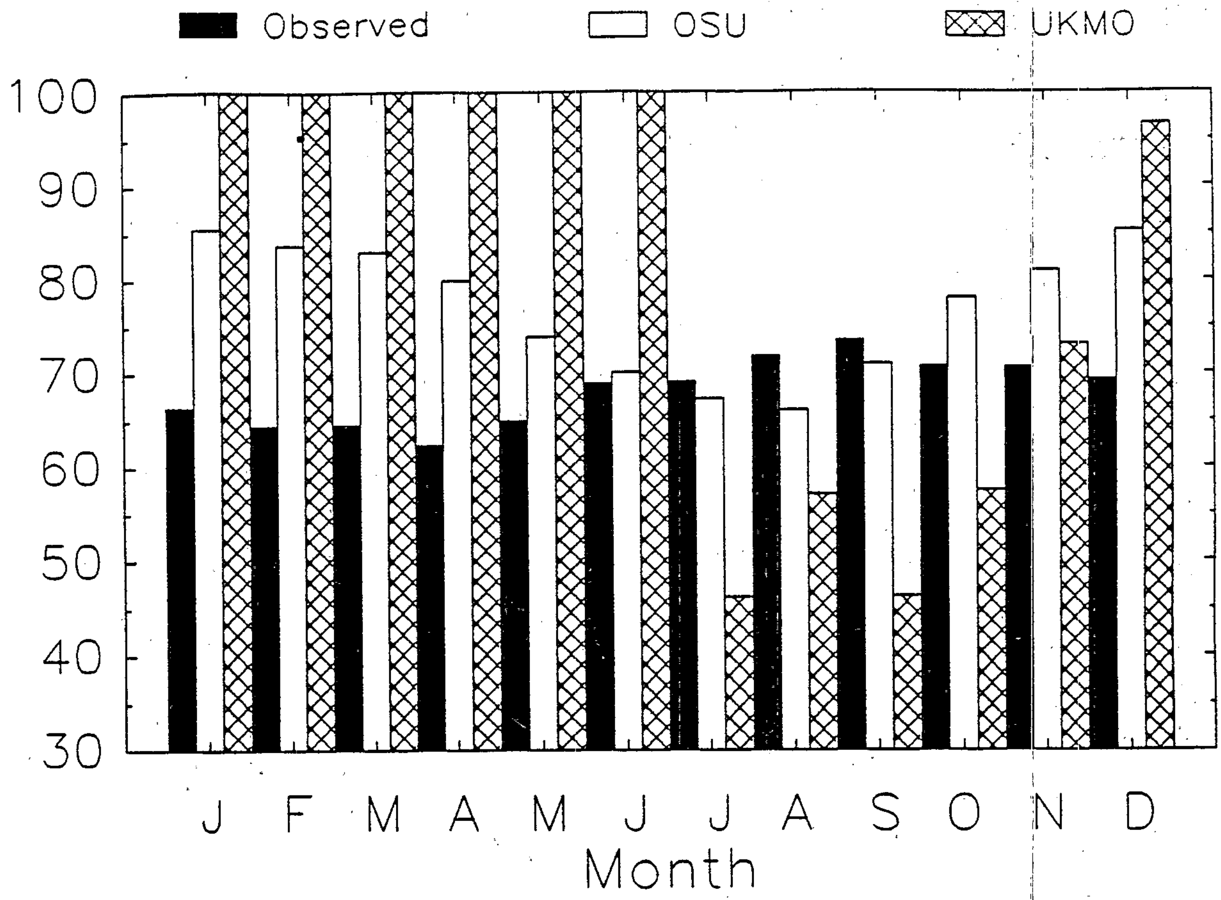


Figure A.4 Relative Humidity Comparison



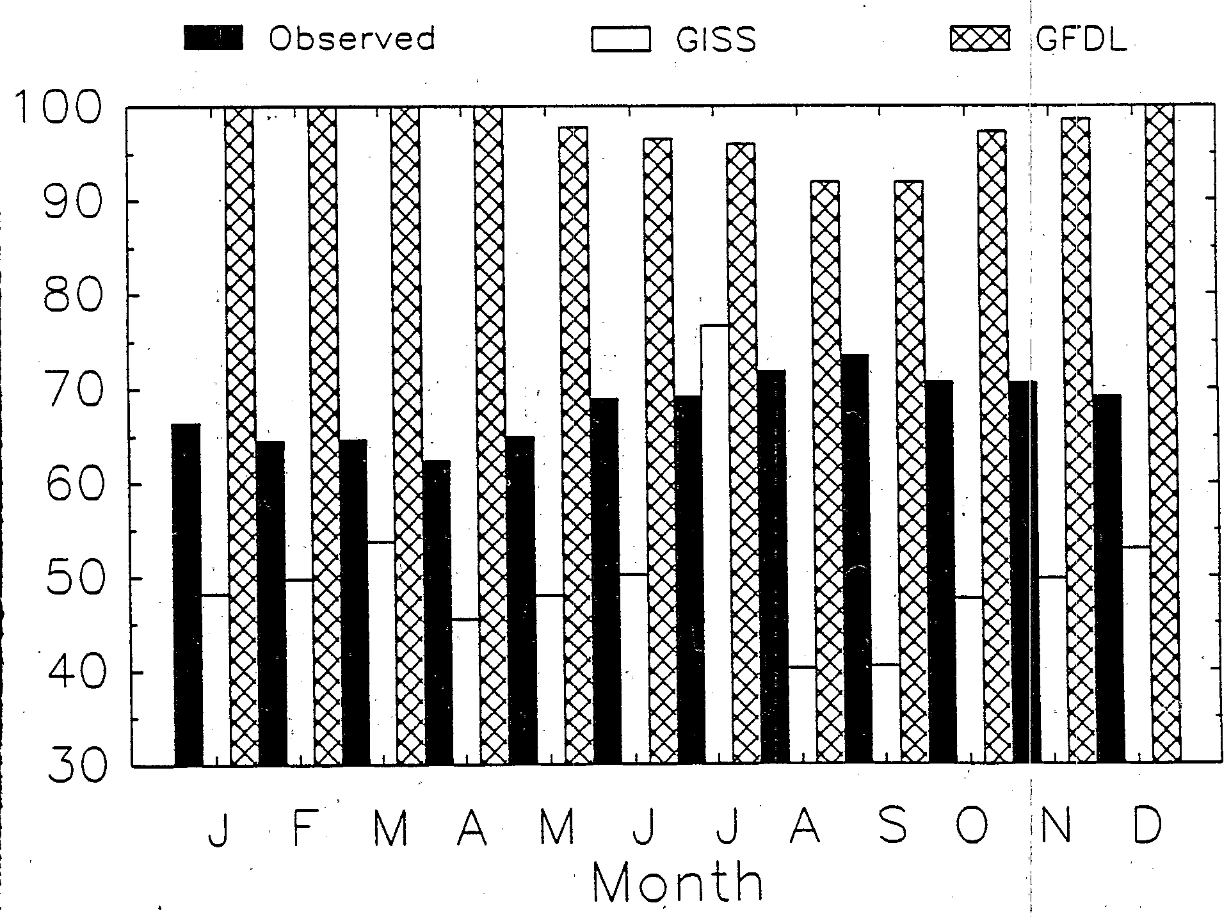
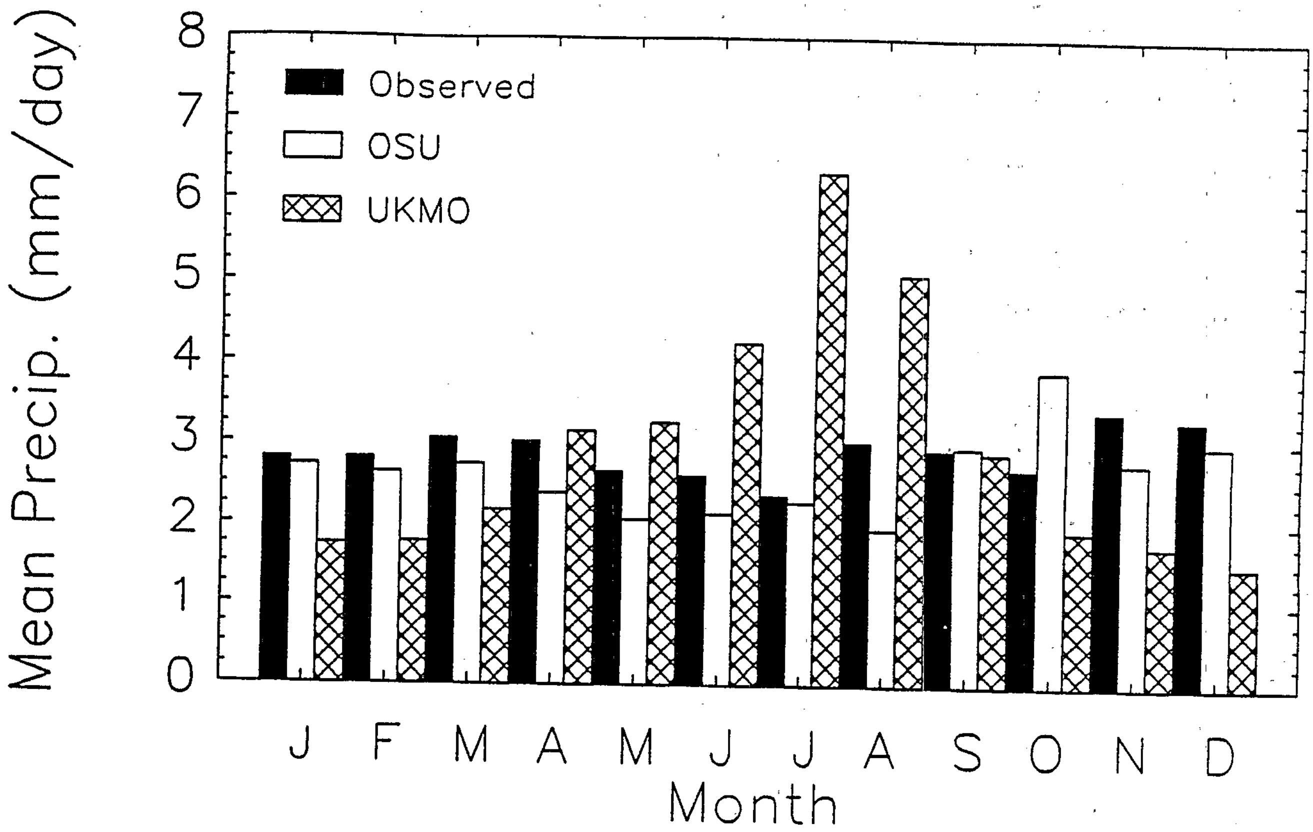
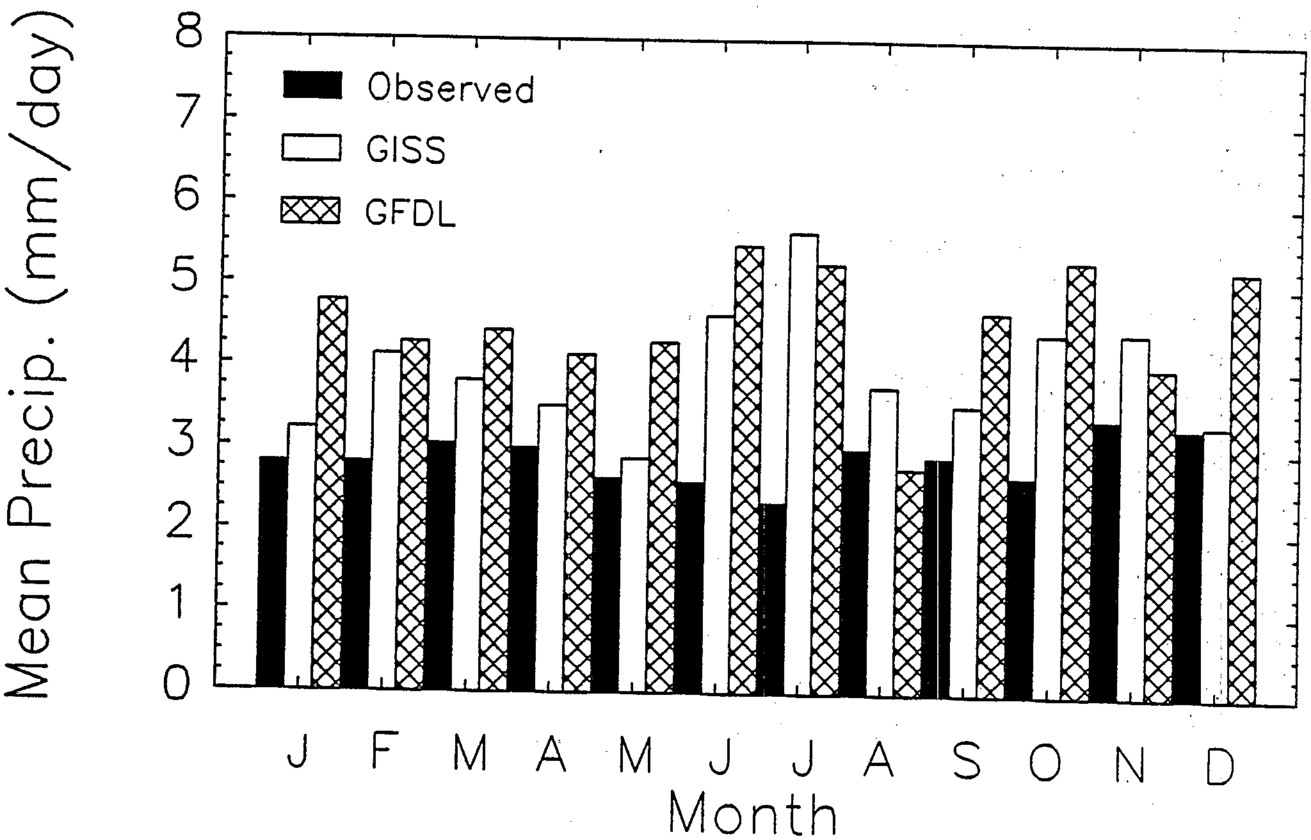


Figure A.5 Precipitation Comparison





APPENDIX B: NOTATION

CaM: low level drag coefficient (dimensionless)

Cp: specific heat of the air at constant pressure (kJ/kg-°K)

e°: saturated vapor pressure of air (kPa)

e: vapor pressure of air (kPa)

Ep: potential evaporation (mm/day)

Et: potential evapotranspiration (mm/day)

Et': actual evapotranspiration (mm/day)

G: soil heat flux (MJ/meter^2-day)

G': reservoir heat flux (MJ/meter^2-day)

Pa: air pressure (kg/meter^2)

P: air pressure (kg/meter^2)

qh: specific humidity (dimensionless)

Rb: longwave backscatter radiation (MJ/meter^2-day)

Rn: net radiation (MJ/Meter^2-day)

ra: atmospheric vapor resistance (seconds/meter)

rc: vegetation canopy vapor resistance (seconds/meter)

rs: stomatal vapor resistance (seconds/meter)

S: relative humidity (percent)

Ta: air temperature (°C)

U: windspeed (meters/second)

U*: friction velocity (meters/second)

1995-621-995/82126