University of Washington
Department of Civil and Environmental Engineering

INTERPRETATION OF HYDROLOGIC EFFECTS OF CLIMATE CHANGE IN THE SACRAMENTO-SAN JOAQUIN RIVER BASIN, CALIFORNIA

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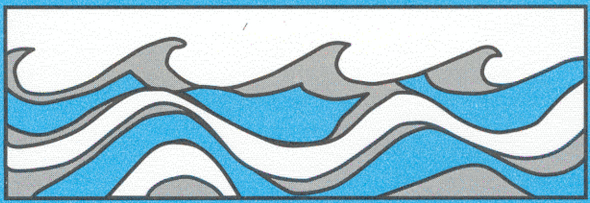

Water Resources Series
Technical Report No.110
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Prepared for: U.S. Environmental Protection Agency
Office of Policy, Planning, and Evaluation

Project Officer: Dr. Ronald P. Neilson
U.S. Environmental Protection Agency
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EXECUTIVE SUMMARY

<u>Objectives</u>: The objectives of the study were: 1) To develop a method to interpret the possible hydrologic impacts of global climate change for catchments on the order of tens to hundreds of square miles in mountainous regions; 2) To assess the interaction of the hydrologic diversity of medium sized catchments within a large river basin in California (the Sacramento-San Joaquin) with climate change predictions made using general circulation models (GCM's); 3) To assess differences in the hydrologic implications of different GCM's, with specific attention to the nature of predicted temperature and precipitation variations by month; and 4) To provide simulated hydrologic data at time and space scales suitable for an assessment of the possible water resource system impacts of climate change in the Sacramento-San Joaquin basin.

<u>Approach:</u> Four study catchments with area ranging from 203 to 358 square miles were selected in the headwaters of the Sacramento-San Joaquin basin. The study catchments were selected on the basis of their geographic and hydrologic diversity, the absence of major upstream diversions or flow regulation, and the availability of long-term hydrologic and meteorological records. Three of the study catchments, The McCloud River, the North Fork American River, and Thomes Creek, lie in the Sacramento River Basin; one, the Merced River, is in the San Joaquin basin.

Snow accumulation and ablation, and runoff were simulated under current (historical) conditions using the National Weather Service snowmelt and soil moisture accounting models. The snowmelt model operated on a six hourly time step, while the soil moisture accounting model operated on a daily time step. Once the models were calibrated to present conditions, simulations were performed under seven alternative climate scenarios. Four of these were initial cases, based on GCM climate scenarios corresponding to 1) Geophysical Fluid Dynamics Laboratory (GFDL) model results for CO2 doubling; 2) Goddard Institute for Space Studies (GISS) model results for CO2 doubling; 3) A transient climate predicted by the GISS model for CO2 changing from current concentrations to double current levels over an eighty year period; and 4) Oregon State University Meteorology Department (OSU) model results for CO2 doubling. Sensitivity analyses were performed using two additional climate scenarios: 1) the GISS model temperature predictions, with precipitation assumed to remain the same as present; and 2) a long-term climate similar to that experienced in the 1930's.

All simulations were performed using 100 years of daily temperature and precipitation data (disaggregated to a six hourly interval for the snowmelt model) consisting of the years 1951-80 supplemented by 70 additional years drawn at random from the 1951-80 record. For the alternative climate scenarios, the 100 year temperature and precipitation records were adjusted as follows: The long-term average GCM temperature and precipitation means were interpolated to 120°W, 40°N, which is approximately the centroid of the Sacramento-San Joaquin basin. For precipitation, the ratio of the GCM-predicted long-term monthly mean to the long-term mean for a base case (nominally, present conditions) for the same GCM was computed. This ratio was applied to all of the historic precipitation records. For temperature, the same approach was used, except that the difference between the long-term monthly mean temperature for a given climate alternative and the mean temperature for the same model's base case was used to adjust the historic precipitation. For the 1930's analog, the precipitation factors and temperature adjustments were based on an analysis of long-term historic data, rather than GCM results.

Results: All of the initial scenarios (based on steady state CO2 doubling, or a transient from present conditions to CO2 doubling) showed that the simulated hydrologic changes were dominated by a shift in the snow accumulation pattern. Specifically, under the warmer conditions predicted by the GCM's, snow would occur only rarely at lower elevations, and the snow accumulation would be reduced at the higher elevations. For all but the highest catchment (the Merced), this resulted in a change from a snow-dominated to a rainfall-dominated hydrologic regime. Long-term mean snow accumulations were greatly reduced, and the maximum mean runoff was shifted from the spring to the winter. Spring and summer runoff were greatly reduced. In addition, soil moisture in the winter months increased, and decreased in the spring and summer. Because of the reduction of summer soil moisture, and the increased potential evaporation in the spring, there was a shift in maximum evapotranspiration earlier in the season. These general shifts were observed for all of the alternative climates. They were most severe for the GFDL and GISS CO2 doubling scenarios, for which the temperature shifts were the greatest, and were least severe for the OSU model CO2 doubling, for which the predicted temperature increases were less than one-half those for the GISS and GFDL models for most months.

The sensitivity analyses were designed to assess the extent to which the simulated hydrologic changes resulted from GCM-predicted temperature, as opposed to precipitation, changes. Simulations based on input from the GISS model temperature changes, with present precipitation, showed that the simulated hydrologic changes were dominantly the result of the GCM-predicted warming, and not of the predicted precipitation changes. The simulations for the 1930's analog reflected a vastly different hydrologic regime than that predicted by the GCM warming scenarios: temperatures were about the same as present, but precipitation was reduced somewhat. Therefore, for this case, winter snow accumulations were slightly reduced (the reduction was much less than for CO2 doubling scenarios), but the seasonal flow distribution remained about the same, as did the seasonal distribution of soil moisture, and evapotranspiration.

Conclusions: The major conclusion of the study is that, for the snow-dominated hydrology of the Sacramento-San Joaquin basin, a general warming on the order of that predicted by all the GCM's would cause a major reduction in winter snow accumulation, and hence increases in winter runoff and reductions in spring and summer runoff. The simulated changes in annual runoff were minor, and from a practical standpoint, inconsequential in comparison to the change in the seasonal distribution of runoff. Attendant changes in the seasonal distribution of soil moisture, and evapotranspiration, would also occur. From a hydrologic perspective, GCM-predicted changes in precipitation, for which there is less consensus than temperature, would be less important than the predicted temperature changes.

This preliminary study suggests a number of aspects of the hydrologic cycle that require further study. These include: 1) The space-time distribution of precipitation under GCM-predicted altered climates; 2) The interaction of long-term shifts in vegetation, particularly as they would affect evapotranspiration and runoff; 3) Changes in the distribution of extreme floods, given the likely increased incidence of rain-on-snow events in the mid-winter period of maximum precipitation; and 4) Estimation of potential evaporation under the GCM predicted climates.

Review Comments: Four independent reviewers were identified by the funding agency (EPA). Many of the review comments have been incorporated in the final draft of the report. Some of the comments relate to the design of this study, and other companion studies commissioned by EPA. For this reason, the four reviewers' comments are included in their entirety in Appendix C, along with the authors' response.

ACKNOWLEDGEMENTS

The authors appreciate the assistance of a number of individuals who assisted in various aspects of the project. Dr. Richard H. Hawkins, then on leave with the EPA Environmental Research Laboratory, Corvallis, Oregon and now with the Watershed Management Program, University of Arizona, was instrumental in the initial planning of the study. Dr. Ronald Neilson of ERL, the Project Officer, participated in the project design and management, as did Dr. Robert Worrest of ERL, and Mr. Joel Smith of EPA's Office of Policy, Planning, and Evaluation. Mr. Wendell Tangborn of the HyMet Company graciously provided computer tapes of daily meteorological data for California. Mr. Roy Jenne, of the National Center for Atmospheric Research, assisted by Mr. Dennis Joseph of NCAR, provided additional meteorological data, as well as computerized summary output of the Global Climate Model results. Some of the computer simulations and preliminary analysis were performed by Dr. N. Davies Mtundu, a Postdoctoral Research Associate in the Department of Civil Engineering, University of Washington. The report was reviewed by Dr. Stephen J. Burges, of the Department of Civil Engineering, University. Notwithstanding the contributions of these individuals, the content of the report, and any opinions expressed, are the sole responsibility of the authors.

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CHAPTER 1: INTRODUCTION

1.1 Background

Modern civilizations depend critically on water for municipal and industrial supply, irrigated agriculture, natural resources recovery and other uses. Throughout history, water shortages have had dramatic cultural effects. Periods of below-normal flow persisting for months to years are a characteristic of the hydrologic cycle that must be recognized in water resource system planning. This is normally accomplished by constructing reservoirs, sometimes augmented by groundwater withdrawals, which act as a buffer to variations in streamflow.

The reliability of a water resource system depends on the withdrawals (demand), as well as the long-term statistics of the reservoir inflows, including their means, coefficients of variations, skew coefficients, and cross- and auto-correlations. Most water resource systems are designed and operated based on a requirement that the system must perform reliably during droughts similar to those experienced in the historic streamflow record. Statistically this is equivalent to an assumption that the inflows are stationary, that is, the streamflow statistics are not time-varying.

The possibility of permanent changes in streamflow, such as might result from long-term changes in climate, complicates the problem of water resources system design and operation considerably. Although changes in climate over periods of thousands of years are well documented, there has been less agreement among hydrologists as to whether changes within typical project planning periods (on the order of a hundred years or less) can be distinguished from the random variations that are to be expected in a stationary time series (see, for example, Klemes, 1974; Lettenmaier and Burges, 1978). This issue was the topic of extensive research by hydrologists in the 1960's and early 1970's, some of which is summarized in the overview to a 1977 National Research Council report (Wallis, 1977). The general conclusion of the NRC report was that, from a practical standpoint, evidence for climate change is not detectable in historic streamflow or meteorological records, which are typically of length less than 100 years.

The advent of general circulation models (GCMs), and some consensus regarding the likely direction of future global climate change places the problem in a somewhat different light. There is now a quasi-deterministic basis for assuming the form that future climate change might take, at least with respect to changes in temperature. A GCM simultaneously solves (numerically) equations representing the conservation of mass, energy, momentum and the equations of state on a global grid (Hansen et al., 1983, 1988). The spatial scale of the GCM results is, however, inadequate for hydrologic interpretation. GCM predictions are provided as spatial averages over areas on the order of hundreds of thousands of square kilometers. In addition, it is questionable if GCM predictions on time steps shorter than about one month reflect the observed natural variability, particularly given that they represent grid-cell averages (see, for example, Rind et al., 1988).

Interpretation of the effects of changes in meteorological inputs to a hydrologic system (and in turn, water resource developments) requires that those inputs be specified on a time scale appropriate for modeling river basin storm response. This is so because the rainfall-runoff process is highly nonlinear, and such subprocesses as infiltration and evapotranspiration, which play major roles in determining the runoff yield of a basin, depend strongly on the storage and movement of water within the soil column during storms, and the soil moisture condition at the onset of storms. For practical purposes, this implies a daily time scale for large basins (several hundreds of square kilometers and up) and hourly or less for smaller basins. While GCM's can provide grid cell average results for time steps on the order of a day or less, it is not clear whether the results at these short time scales properly reflect the short term dynamics of the atmospheric circulation process.

Therefore, while the GCM models predict long-term changes which could have substantial impacts on water resource systems, an appropriate interface between the GCM output (most importantly, precipitation, temperature, and potential evaporation) and hydrologic models has not been developed. It is unreasonable to use GCM results directly as input to a hydrological model to provide streamflow predictions which might be used in the same sense, for instance, as an estimate of the 100 year flood for flood plain mapping. In the absence of better space-time resolution, current hydrologic interpretations are limited to providing descriptive results which must be interpreted in an alternative scenarios, or sensitivity analysis context. There is no basis at present to predict the hydrologic effects of long-term climate change; all results presented in this document must, therefore, be interpreted in an alternative scenarios context.

1.2 Objectives

The objectives of this work are:

1. To develop a method to provide a descriptive interpretation of the hydrologic impacts of global climate change for medium sized catchments on the order of tens to hundreds of square miles in mountainous regions. The approach must account for the changes in

snowmelt hydrology that would result from long-term temperature increases, coupled with possible changes in precipitation and evapotranspiration;

2. To assess the interaction of the hydrologic diversity of medium sized catchments within a large river basin in California (the Sacramento-San Joaquin) with GCM predictions to interpret the modes through which climate change could be evidenced in catchment hydrology;
3. To assess differences in the hydrologic implications of different GCM's, with specific attention to the nature of predicted temperature and precipitation variations by month;
4. To use the methods and results developed in 1) and 2) to provide hydrologic input at time and space scales that allow descriptive interpretation of the water resource systems impacts of climate change on the Sacramento-San Joaquin basin;
5. To develop recommendations for research needed to improve the assessment methodology, particularly in light of the relative uncertainties in the GCM predictions, and spatial and temporal resolution incompatibilities between the GCM model output and hydrologic data requirements.

1.3 Relationship to Other Studies

The primary emphasis of this work is the interpretation of the implications of global climate change as predicted by three GCM's (the models of the Geophysical Fluid Dynamics Laboratory -- GFDL, the Goddard Institute for Space Studies -- GISS, and the Oregon State University Department of Meteorology -- OSU) on four medium sized catchments in the Sacramento-San Joaquin River basin of California. As part of this work, predictions of streamflows for larger subbasins of the Sacramento-

San Joaquin system were developed and used in a companion study of the implications of global climate change on the operation of the Sacramento-San Joaquin water resource system (Sheer and Randall, 1988). Sheer and Randall applied a model of the water resource system which uses as input monthly streamflow volumes for 13 subbasins. These subbasins have drainage areas much larger than the study catchments described in this report, for which detailed hydrologic models were implemented.

For several reasons relating to data availability and time and budget constraints, it was not possible to implement, or develop, a detailed hydrologic model of each of the 13 subbasins. Therefore, to provide the input required by the water resource systems model used by Sheer and Randall, a statistical model was developed to relate the subbasin (monthly) streamflows to streamflows in the four study catchments. These subbasin flows represent the interface between this study and Sheer and Randall's work, and (indirectly) with other studies which are based on Sheer and Randall's results. In this report, however, we emphasize the interpretation of the hydrologic implications of climate change on the four study catchments. Because the relationship between the study catchment and subbasin flows is statistical, there is no basis for a dynamical interpretation of the changed hydrologies at the subbasin level.

CHAPTER 2: STUDY DESIGN AND METHODOLOGY

2.1 Overview

The overall study design is shown schematically in Figure 2.1. The climatic inputs fall into two categories: historic data, also referred to as the base case (Case 0), and GCM climate alternatives, referred to as Cases 1-7, identified in Table 2.1. The Case 0 historic data, for the period 1951-1980, were augmented by randomly resampling (with replacement) from the years 1951-80 to provide a total record of length 100 years. The hydrologic outputs were either for one of four study catchments (with drainage areas ranging from 203 - 358 square miles), or for water resource system nodes, which are major subbasins of the Sacramento-San Joaquin of size up to several thousand square miles. The initial effort in the study was to implement hydrologic models, one for prediction of snow accumulation and ablation, and another for soil moisture accounting, which could predict the four study catchment outflows on a daily time scale, for precipitation and temperature maxima and minima on a daily time scale, and monthly average pan evaporation.

Table 2.1 General circulation model scenarios investigated

Case	Description
0	Historic conditions 1951-80
1	Geophysical Fluid Dynamics Laboratory (GFDL) 2xCO2 steady state
2	Goddard Institute for Space Studies (GISS) 2xCO2 steady state
3	GISS 80 year 2xCO2 transient
4	Oregon State University (OSU) 2xCO2 steady state
5	GISS 2xCO2 steady state with temperature change only (historic precipitation assumed)
6	GISS 2xCO2 steady state with differential GCM node input for southern and northern study catchments
7	1930's analog precipitation and temperature

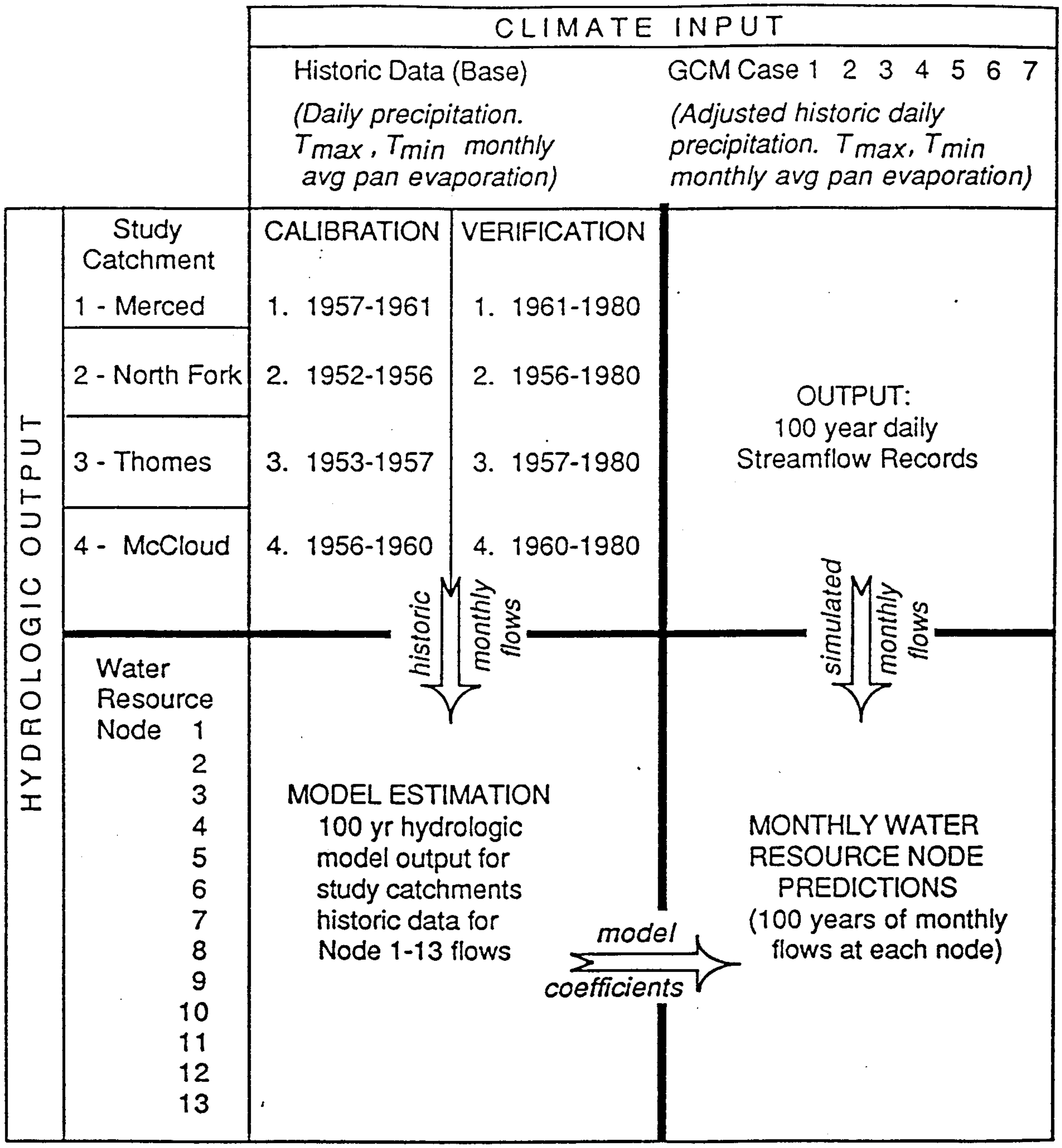


Figure 2.1 Schematic overview of study design

The implementation followed a standard procedure of model calibration, or parameter estimation, using a selected subset of the historic record, and an independent subset of the data for model verification. Section 2.5 gives details of the calibration and verification procedure. Once the hydrologic models were calibrated, they were run with the historic data altered by addition of a seasonal shift in the case of temperature, and by multiplication by a seasonally varying factor in the case of precipitation, to be consistent with predictions from each of seven long-term GCM predictions. For each climate alternative, study catchment outflows were predicted on a daily time step for the 100 year period indicated above.

This report focuses on the upper right quadrant of Figure 2.1, that is, on interpretation of the hydrologic model output which included soil moisture, snow accumulation, evaporation, and other variables, as well as streamflow. For the purposes of a companion study (Sheer and Randall, 1988) monthly streamflows at each of the 13 water resource system model nodes were predicted using a spatial disaggregation model applied to the study catchment monthly flows; a random noise term was included to assure that selected statistical properties of the disaggregated flows were preserved. The disaggregation model coefficients were estimated using the Case 0 study catchment predictions (summed daily flows to provide a 100 year monthly flow record) and the corresponding historic monthly flows at the water resource model nodes, as indicated in the lower left quadrant of Figure 2.1. Finally, as indicated in the lower right quadrant of Figure 2.1, the disaggregation model was used to simulate 100 year monthly streamflow sequences at the water resource system model nodes corresponding to each of the seven climate alternatives. The climatological, hydrologic, and geologic features of the Sacramento-San Joaquin basin, and the four study catchments, are described, and the study approach is expanded, in the next section.

2.2 Sacramento-San Joaquin Basin Description

The Sacramento-San Joaquin Basin (Fig. 2.2), or Central Valley, extends nearly 500 miles from north to south, with an average width of about 45 miles separating the Sierra Nevada from the Coast Range. The elevation of much of the valley floor is close to sea level. Beneath its silt and gravel cover is a thick sedimentary sequence. The Coast Range parallels the Pacific coast from the Oregon border to just north of the Los Angeles Basin. The mountains in the Coast Range rise abruptly from the narrow coastal plain to peak elevations of 8,000 feet. The Sierra Nevada, with peak elevations over 14,000 feet, form the eastern boundary of the basin. The Central Valley is terminated in the south by several transverse ranges, which are composed of many overlapping mountain blocks of nearly east-west trend. The basin terminates to the north near the Oregon-California border, where the Coast Range, the Sierra Nevada, and the Cascade range converge.

The Sierra Nevada protect the Sacramento-San Joaquin basin from the cold continental air masses that flow further east in winter. The Coast Range blocks the strong westerly air-flow, and accompanying cool summer temperatures that are experienced by the western slopes of the Coast Range. Most of the precipitation in the basin is derived from frontal storms originating in the North Pacific between the months of November and March. Precipitation is strongly orographic; it is heaviest on the west facing slopes of both the Coast Range and the Sierra Nevada. The valley floor is semi-arid, with average annual precipitation generally less than 15 inches.

Temperatures are influenced by prevailing air masses, elevation, and the drainage of cold dense air from the higher elevations into the Central Valley. Although the climate on the western side of the Coast Range is

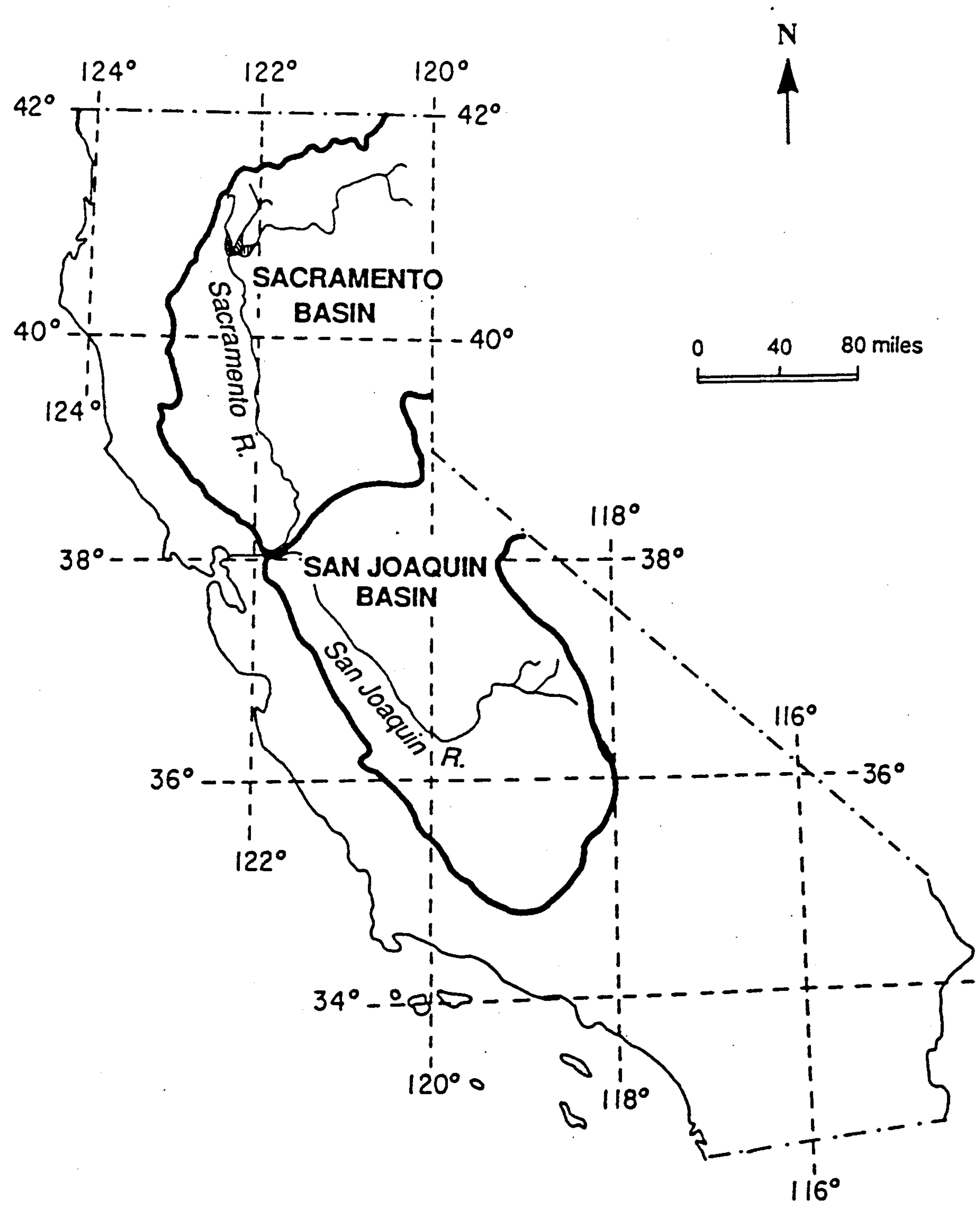


Figure 2.2 Location of the Sacramento - San Joaquin River Basin

dominated by the Pacific Ocean, with warm winters, cool summers, small daily and seasonal temperature ranges, and high relative humidities, the Sacramento-San Joaquin Basin experiences a more continental type of climate with colder winters, warmer summers, greater daily and seasonal temperature ranges and generally lower relative humidities than are common for the Coast Range.

2.3 Study Catchment Description

The four study catchments (Figs. A.1 to A.4) were selected to represent the geographic, climatic, and hydrologic diversity within the Sacramento-San Joaquin River basin, and to represent, via the spatial disaggregation model described in Section 2.4.3, the monthly streamflows at the water resource systems nodes. Initially, 26 candidate study catchments were identified that were upstream of all major reservoirs. Modeling of streamflow below reservoirs is complicated by the necessity to account for the effect of reservoir storage on stream flow; in practice, to implement a rainfall-runoff model successfully at a daily or shorter time scale requires streamflow data relatively unaffected by reservoirs or upstream diversions.

In addition to the requirement that upstream regulation be minimal, it was required that 1) the candidate study catchments be defined by U.S. Geological Survey stream gaging stations rated "good" or better (interpreted by the USGS to mean that the true flow can be expected to be within 10 percent of the recorded flow 95 percent of the time); an exception to this criteria was allowed during periods of ice cover;
2) that there be at most minor diversions above the stream gage; and 3) that the period of streamflow record include the years 1951-80. Further screening using these criteria reduced the number of candidate catchments to 19.

The remaining stations were then ranked based on the correlation of their annual flow with the summed annual flow over all the 13 water resource system node annual flows. The three most highly correlated basins, the North Fork of the American River at North Fork Dam (USGS 11-4270, drainage area 342 square miles), Thomes Creek at Paskenta (USGS 11-3820, 203 square miles), and the McCloud River near McCloud (USGS 11-3675, 358 square miles) were selected. Because of the desirability of representing the San Joaquin subbasin, the southern subcatchment, (the Merced River at Happy Isles Bridge, USGS 11-2645, 181 square miles), having the highest correlation to the total annual basin flow was selected as the fourth study catchment.

Figure 2.3 shows the locations of the index basins. Precipitation on two of the index basins, the American and the Merced River, is typical of that occurring on the west facing slopes of the Sierra Nevada; precipitation in the Thomes Creek Basin is characteristic of the east facing slopes of the Coast Range. The McCloud River, which drains the extreme northern part of the Sacramento River basin, has precipitation characteristics intermediate between those of the east facing slopes of the Coast Range and the west facing slopes of the Sierra Nevada. A brief summary of the particular characteristics of each of the study catchments is provided in the remainder of this section.

2.3.1 McCloud River

The annual precipitation, runoff, and temperature extremes (for January and July) are listed in Table 2.2. The McCloud Basin (358 mi^2 - Fig. A.1) has fairly warm summers, with mean annual temperature slightly below 70°F and cool winters (annual mean of 45°F). Snow and freezing temperatures are not common except at higher elevations. The basin has annual precipitation in excess of 70 inches but rain is light in summers and more frequent in late fall and in winter, with over 80 percent of the annual

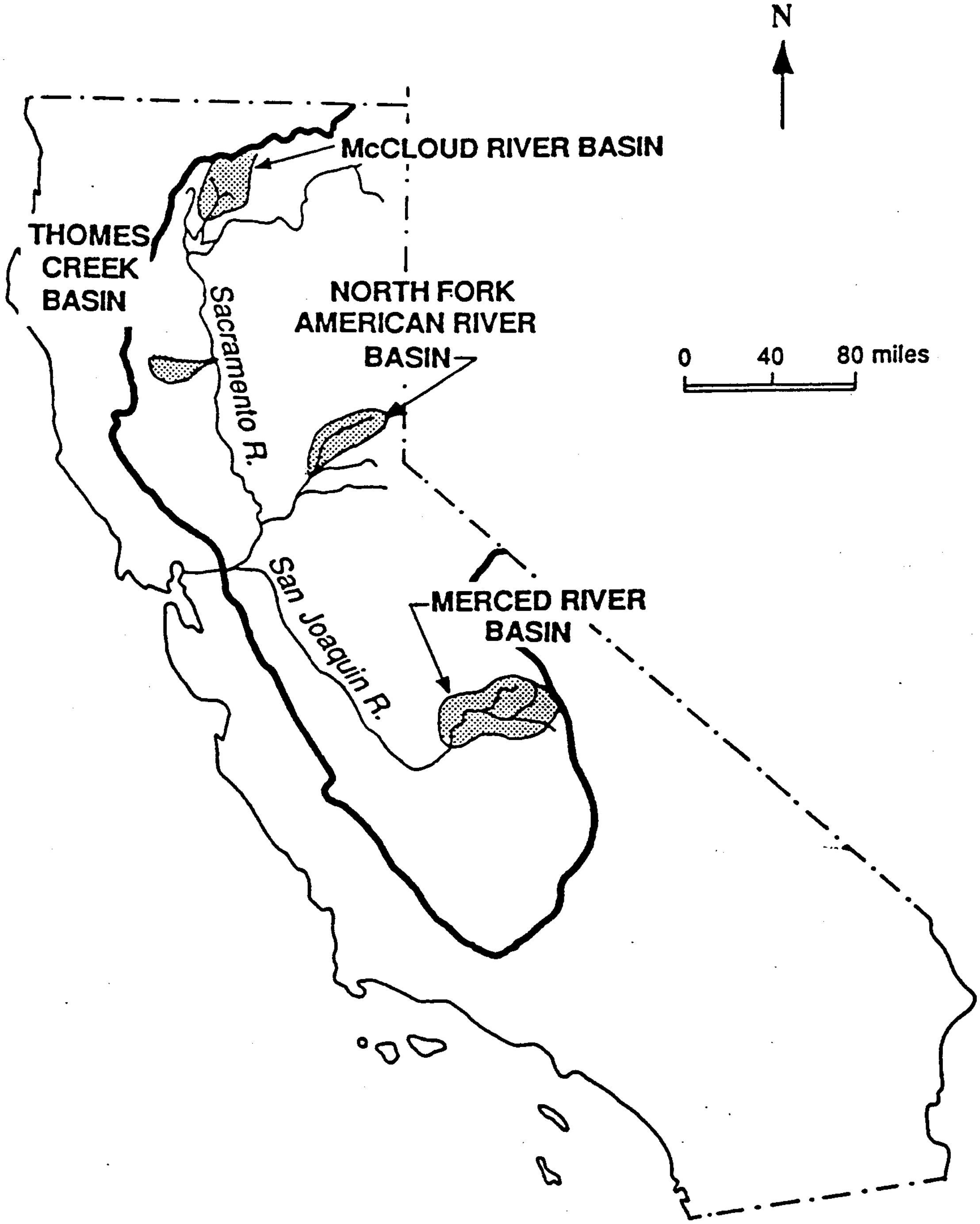


Figure 2.3 Study catchment locations

Table 2.2 Mean annual historical precipitation, runoff and temperature of McCloud River, Merced River, North Fork American River, and Thomes Creek study catchment

Basin	Mean Annual Runoff Inches cfs	Mean Annual Precipitation[a] (Inches)	Mean January Daily Temperature °F[a]			Mean July Daily Temperature °F[a]		
			Daily Average	Minimum	Maximum	Daily Average	Minimum	Maximum
McCloud	35.40 (933.6)	72.90	30.5	19.5	41.6	63.7	43.0	84.0
Merced	26.30 (621.9)	64.00	31.4	20.5	42.2	66.4	47.9	84.9
North Fork American	33.50 (844.0)	60.30	39.8	30.4	49.0	72.9	58.5	87.2
Thomes Creek	19.86 (297.0)	56.50	35.5	24.9	46.3	66.8	45.2	88.2

[a] Weighted average over elevation bands

total falling between November and May. Thunderstorms occur occasionally in summer, however they account for only a small percentage of the total annual precipitation.

The basin is located in an area with large, gently sloping volcanoes built by outpouring of basaltic and andesitic lava. Most of these rock formations are deeply weathered, resulting in deep, well-drained soils of extremely high permeability. Even where unweathered, the lavas are highly permeable, and generate little surface runoff. Consequently, the annual runoff hydrograph has extremely low variability with a peak to average flow ratio of only about 2.

2.3.2 Merced River

The climate in the Merced basin (321 mi^2 - Fig. A.2) is elevation-dependent, with hot summers and mild winters at low elevations and mild summers and cold winters at high elevations. Because of its relatively higher mean elevation, its hydrology is more controlled by snowfall and snowmelt than other study catchments.

Precipitation is less in the Merced basin than in the McCloud, with an annual mean of about 64 inches. It increases with elevation, from 36 inches at 4,000 feet elevation to a maximum of about 70 inches between 8,000 and 10,000 feet. Most of the precipitation falls in winter, with almost 90 percent of the annual total falling between November and April. Most precipitation falls as snow at the higher elevations.

The soils in the basin are varied, but are, in general, deep and permeable; some areas are clayey and have lower permeability. The slopes range from nearly level to very steep. Because of the high permeability of the soils the basin has a relatively dampened storm response, as evidenced by the ratio of the mean annual flood to mean annual flow of about 7.

2.3.3 North Fork American River

Figure A.3 shows the location of the North Fork American River Basin (342 mi^2) and the main stem of the American River. The North Fork American River has the lowest median elevation (4,000 ft) of any of the study catchments. Much of the annual precipitation (50-60 inches) falls in late autumn and winter. Precipitation in summer is light and generally limited to occasional convective storms.

The topography varies from nearly level to rolling old valley fill in the vicinity of the Sacramento Valley to predominantly steep dipping, faulted, and folded metamorphic rocks that have been intruded by several types of igneous rocks. Most soils in the mountainous uplands formed in place over metamorphic rock, granitic rock, or andesitic conglomerate, and are not as permeable as those in the Merced Basin. Consequently, the runoff response of the catchment is flashy, particularly in the upland mountains; the peak to average flow ratio is about 20.

2.3.4 Thomes Creek

As with the other study catchments most of the precipitation in the Thomes Creek basin (203 mi^2 - Fig. A.4) is derived from winter frontal storms. Thundershowers, most frequent in May and June, are generally of short duration but occasionally bring rainfall of high intensity.

Much of the western part of the basin which is above an altitude of 3,500 feet has moderately deep to deep steep soils underlaid by hard sedimentary and metamorphic (mainly fractured mica schist) rock. Permeability is low to moderate resulting in relatively flashy storm response; the peak to average flow ratio is about 22.

2.4 Model Description

The models selected for this study are a snowmelt model, a soil-moisture accounting (rainfall-runoff) model, and a spatial disaggregation model. Each of the models is described briefly in this Section.

2.4.1 Snowmelt Model

The snowmelt model was developed by Eric Anderson of the U.S. National Weather Service Hydrologic Research Laboratory (Anderson, 1973). The model consists of a set of equations which describe the change in storage of water and heat in the snowpack. The model inputs are ambient air temperature and precipitation at a six hourly time step. In this study, daily precipitation was interpolated to six hourly increments and six hourly temperature was estimated from daily temperature maxima and minima using equations given by Anderson (1973). The model input is limited to air temperature and precipitation because data other than temperature and precipitation needed for heat budgets are not normally available in mountainous environments.

The model can be summarized as follows. The heat exchange computations are separated into melt and non-melt periods. Melt periods are further separated into wet (precipitation) and dry periods. If precipitation occurs, the ground is bare, and the ambient air temperature is greater than 32°F, no computations are performed. If the ground is not bare, the heat exchange at the air-snow interface is computed. Two conditions are considered, warm air (air temperature (T_a) > 32°F), and cold air (T_a < 32°F). For T_a > 32°F, the following assumptions are made: a) there is no solar radiation; b) incoming longwave radiation is equivalent to blackbody longwave radiation at T_a; c) the snow surface temperature is 32°F; d) the dew point is T_a; and e) the rain temperature is T_a. On the basis of these assumptions, the heat balance is computed as melt heat loss = $Q_n + Q_e + Q_h + Q_p$, where Q_n = long wave radiation, Q_e = latent heat transfer due to condensation, Q_h = sensible heat transfer (Bowen ratio based on abc assumptions), and Q_p = heat transfer by rain water (based on assumed rainwater temperature). If T_a is less than 32°F, it is assumed that the precipitation is falling as snow, and that no melt occurs.

For melt during non-rain periods, the model first checks to determine whether the snowpack is isothermal at 32°F. If the snowpack is not isothermal, no melt occurs, and the net heat flux is added to the heat content of the snowpack. If the snowpack is isothermal, and the air temperature is greater than 32°F, melt is assumed to take place proportionate to a seasonally varying melt factor and the difference between the air temperature and 32°F (assumed isothermal temperature of the snowpack).

During non-melt periods (assumed by the model to be any time T_a is less than 32°F), an antecedent temperature index (ATI) is used as an index of the temperature of the surface layer of the snowpack. The ATI is similar to the antecedent precipitation index often used for storm hydrograph prediction (see, for example, Linsley et al., 1975). The net heat exchange at the surface of the snowpack is assumed proportional to the difference between the ATI and the current air temperature. The proportionality constant is a parameter termed the negative melt factor which varies seasonally in the same manner as does the melt factor used during non-rain periods.

Finally, the model accounts for the areal extent of snow cover. During periods of snow accumulation, this is assumed to be 100 percent. During periods of depletion, the model uses an areal depletion curve, which expresses the percent snow covered area as a function of the ratio of mean areal snow water equivalent to an index value, where the index value is the smaller of the maximum snow water equivalent since snow began to accumulate (e.g., the beginning of the snow season), or a preset maximum.

The most important parameters in the model are: a) the melt factor for non-rain period melt; b) the negative melt factor for the heat balance computation during non-melt periods; c) the recursion parameter in the antecedent temperature index; and d) the minimum index value in the snow covered area relationship. This brief description has omitted some details of the model: there is an expression to account for heat transfer at the base of the snowpack, and the retention of liquid water in the snowpack is also modeled. In addition, the model allows the rain-snow division to be made at other than 32°F, and also allows nonrain period melt to occur based on a threshold base air temperature which can be other than 32°F. These expressions and generalizations involve some additional parameters, however, they usually are not as important as the parameters indicated above for studies of the type being performed here. For a complete description of the algorithm, the reader is referred to Anderson (1973).

2.4.2 Soil Moisture Accounting Model

The Soil Moisture Accounting Model was developed by Burnash et al. (1973) and forms the basis of the U.S. National Weather Service's basic catchment hydrologic response model for operational forecasting. It is a deterministic, lumped parameter, conceptual model. The original model was designed for daily precipitation input but later versions allows finer time increments (6-hours or less). Input to the model is pseudo precipitation (snowmelt model output) and potential evaporation (actual, or long-term average).

The structure of the soil moisture-accounting model is shown schematically in Figure 2.4. When rainfall occurs it is considered to fall on two types of basin covers: (1) a permeable soil mantle, and (2) lakes,

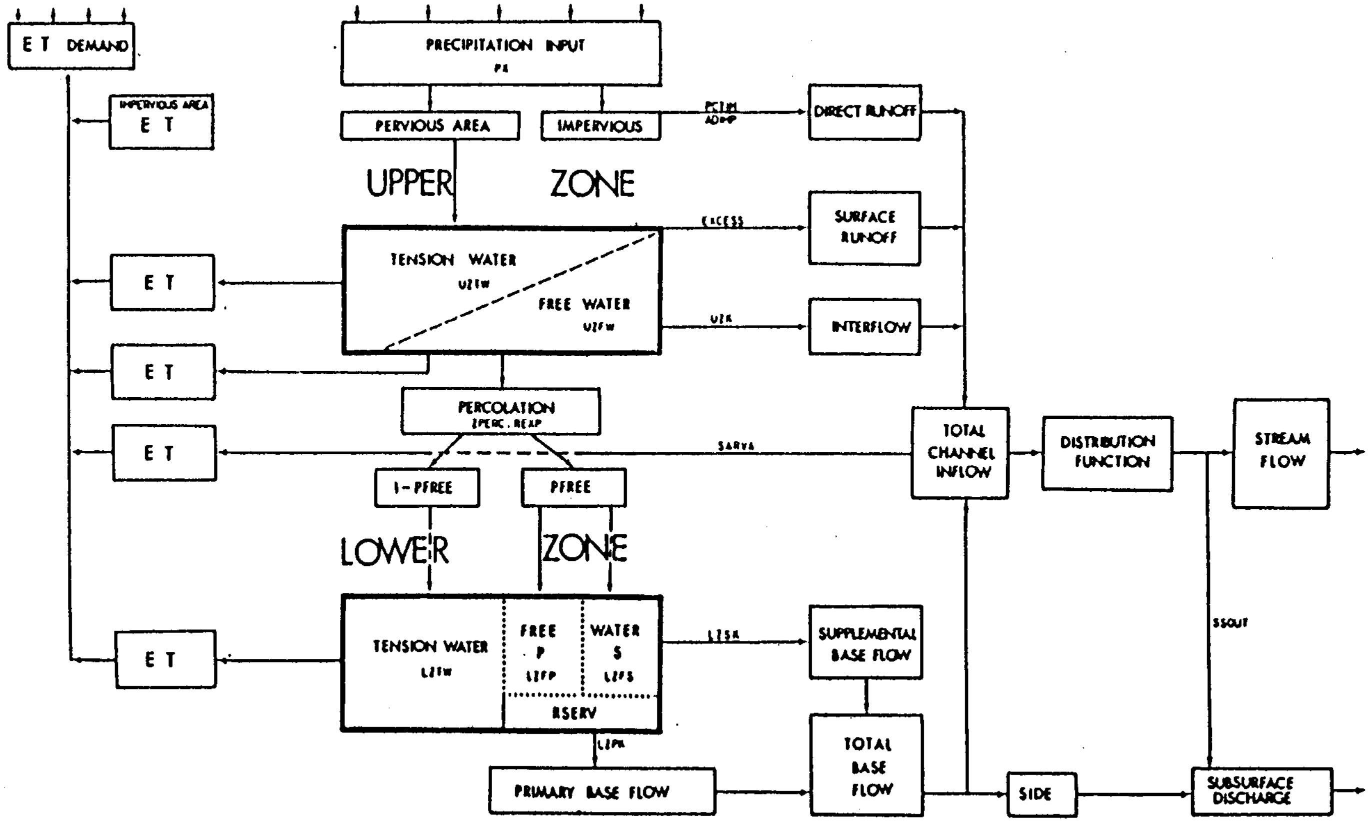


Figure 2.4 Soil-moisture accounting model schematic

channel networks, and impervious areas. Rain falling on impervious areas always becomes direct runoff, whereas that which falls on the permeable soil mantle undergoes a complicated sequence which represents the infiltration process. Below the permeable soil mantle, the soil moisture storage is conceptually made up of upper and lower zones (Fig. 2.4). Each zone stores moisture in two forms, tension moisture, and free moisture. Tension moisture denotes water closely bound to the soil particles while free moisture is the moisture that fills up the interstitial soil pores. For medium sized basins such as the four study basins, one set of lumped model parameters is sufficient to represent the basin hydrology.

The upper zone represents topsoils and the basin interception layer. Upper zone tension water, bound closely to the soil particles, must be filled before moisture can be stored as free water. Upper zone free water generates vertical drainage (percolation) to the lower zone and lateral drainage (interflow) to the channel. If the precipitation rate exceeds the sum of lateral and vertical drainage rates, and the upper zone free water capacity is completely filled, excess surface runoff will result. The actual percolation rate to the lower zone is governed by the interrelationship between soil drainage characteristics and the relative soil moisture conditions of the two zones.

The lower zone, which represents a groundwater reservoir, has a tension water storage zone and two free water storage zones (called primary and secondary). Water goes to the tension water zone first and then to the two free water zones, which generate primary and secondary baseflow. The reason for using three storage zones is to allow the nonlinear characteristics of baseflow recession to be represented.

Evapotranspiration (ET) extracts moisture from the upper and lower tension zones and from free water surfaces. For areas covered by surface water or phreatophyte vegetation, actual basin ET occurs at the daily potential rate. Over other areas of the soil layers, ET extraction depends on the demand and the volume and distribution of tension water storage. The upper tension zone provides ET before the lower zone. The sensitivity of ET changes to climate variations is discussed in Section 3.1.4.

Total runoff is the sum of direct runoff from impervious and water surfaces, surface runoff and interflow from the upper zone free water, and primary and secondary baseflows from the lower zone free waters. The model does not relate soil moisture explicitly to vegetation characteristics. The equations that describe the linkage between the tension zone contents, potential evapotranspiration, and actual evapotranspiration act as a surrogate for vegetation effects.

2.4.3 Spatial Disaggregation Model

The spatial disaggregation model consists of two stages. The first stage relates the monthly flows at the six water resource system model nodes (see Sheer and Randall (1988) for details) to the monthly flows at the four study catchments described in Section 2.3. These six nodes are termed primary sites. The second stage relates the remaining seven water resource system model nodes used by Sheer and Randall (termed secondary sites) to a selected primary site. Table 2.3 identifies the primary sites, the secondary sites, and, in the case of the secondary sites, the primary site to which they are indexed.

Monthly flow data were approximately log normally distributed so data were transformed logarithmically to the normal domain. The model used to relate the primary site monthly flows to the monthly flows for the four study catchments is of the form

$$Y_k = A_k X_k + \epsilon_k \tag{2.1}$$

Table 2.3 Primary and secondary sites for spatial disaggregation model

Site[a]	Name	Index Primary Site
1 (p)	Trinity River	--
2 (p)	Sacramento River at Red Bluff	--
3 (p)	American River	--
4 (p)	sum of Yuba and Bear Creeks	--
5 (p)	sum of San Joaquin basin inflow	--
6 (p)	Feather River	--
7 (s)	Sacramento Valley floor	3
8 (s)	Putah Creek	3
9 (s)	Cache Creek	3
10 (s)	Stony Creek	3
11 (s)	Sacramento Valley West Side	3
12 (s)	Sacramento Valley East Side	3
13 (s)	East Side Streams	4

[a] p = primary, s = secondary

where Y_k = 6xn matrix of n years of monthly streamflow logarithms for month k at the 6 primary sites, X_k = 4xn matrix of n years of monthly streamflow logarithms for month k at the 4 study catchments, A_k = 6x4 coefficient matrix, and ϵ_k = 6xn matrix of normally distributed residuals. The parameters of this model are the coefficient matrix A_k, and $G = E(\epsilon_k \epsilon_k^T)$, which is the covariance matrix of the (zero-mean) residuals ($E(\cdot)$ is the mathematical expectation operator).

The parameter matrices A_k and G_k can be expressed in terms of the covariances of the Y_k and X_k as

$$A_k = C_k \Sigma_{0k}^{-1} \tag{2.2a}$$

and

$$G = S_{0k} - A\Sigma_{0k}A_k^T \tag{2.2b}$$

where

$$S_{0k} = E(Y_k Y_k^T)$$

$$\Sigma_{0k} = E(X_k X_k^T)$$

$$C_k = E(\epsilon_k \epsilon_k^T)$$

Once the monthly streamflow logarithms at the four sites were disaggregated to the six primary sites, the disaggregated streamflow logarithms were exponentiated to provide the corresponding streamflow in real space. The disaggregation procedure explicitly preserves the means, variances, and covariances of the logarithms of streamflows (both between the primary sites, and between the study catchments and the primary basins) in each month. The model does not preserve these same statistics explicitly in real space, however it was verified using the historic flows that these moments were preserved quite well in real space as well (Table 2.4 gives historic and simulated correlation coefficients for the six primary sites for January and July). More importantly, the model does not preserve the lagged covariances in either real or log space (the correlation between the flows in month k and month k-1 are not preserved). A more complex model of the form

$$Y_k = A_k X_k + B_k X_{k-1} + \epsilon_k \qquad (2.3)$$

explicitly preserves the lagged correlations. This model was tested, and it was found that for some months, no feasible parameter matrices existed. The possibility of using the more complex model in months where parameter solutions could be found, and the simpler model (Eq. 2.1) in the remaining months, was considered. We concluded it was better that any distortions in the covariance structure of the simulated flows relative to the historical flows be consistent through all months, so the simpler model (Eq. 2.1) was used.

Once the primary site monthly flows were estimated, the secondary site monthly flows were estimated using a simple linear regression,

$$\ln(Q_{kij}) = \alpha_{ki} q_{k,L(i),j} + \beta_{ki} + \eta_{kij} \qquad (2.4)$$

Table 2.4 Simulated and historic correlation coefficients for the six primary sites (base case)

January Historic

1.000	.950	.817	.855	.740	.907
.950	1.000	.872	.918	.812	.949
.817	.872	1.000	.989	.944	.955
.855	.918	.989	1.000	.932	.978
.740	.812	.944	.932	1.000	.900
.907	.949	.955	.978	.900	1.000

July Historic

1.000	.827	.773	.826	.746	.875
.827	1.000	.727	.750	.672	.887
.773	.727	1.000	.949	.905	.897
.826	.750	.949	1.000	.833	.897
.746	.672	.905	.833	1.000	.832
.875	.887	.897	.897	.832	1.000

January Simulated

1.000	.918	.797	.836	.613	.905
.918	1.000	.844	.895	.729	.922
.797	.844	1.000	.984	.884	.936
.836	.895	.984	1.000	.852	.955
.613	.729	.884	.852	1.000	.785
.905	.922	.936	.955	.785	1.000

July Simulated

1.000	.824	.774	.787	.688	.884
.824	1.000	.698	.676	.566	.904
.774	.698	1.000	.916	.808	.865
.787	.676	.916	1.000	.719	.829
.688	.566	.808	.719	1.000	.737
.884	.904	.865	.829	.737	1.000

where Q_{kij} is the predicted flow in month k at site i in year j, α_{ki} and β_{ki} are coefficients estimated by ordinary least squares regression, and $q_{k,L(i),j}$ is the predicted primary site monthly streamflow logarithm at site L(i), which is specified as the index site for secondary site i. η_{kij} is a (normally distributed) random error term. This model explicitly preserves only the first two moments (mean and variance) of the historic flows; it does not explicitly preserve any of the off-diagonal covariances. The secondary sites were selected because their flows are much smaller than the primary sites, so failure to preserve statistics other than the mean and the variance at the secondary sites is of considerably less importance than at the primary sites.

2.5 Model Implementation

This section describes the selection of precipitation-temperature stations to provide representative climatic data for the four study catchments as well as the method used to subdivide each study catchment, into elevation zones. In addition, the procedure used for calibration (parameter estimation) of the Snowmelt and Soil-Moisture Accounting models is described. Characteristics of the selected precipitation-temperature stations, as well as final parameter estimates for each study catchment are given.

2.5.1 Precipitation-Temperature Stations and Data Quality

Since precipitation input errors are among the most important source of runoff simulation errors, selection of meteorological stations is an important step in the modeling process. Few records are available for mountainous areas. For this reason, most of the meteorological stations used lie at relatively low elevations. The selection criteria used were data record length, quality of record (in terms of missing data), geographical locations of stations with reference to the basin topography, and distance of the stations from the study catchments. The precipitation-temperature stations selected for each of the study catchments are given in Table 2.5.

Table 2.5 Precipitation/temperature gage stations selected for McCloud River, Merced River, North Fork American River, and Thomes Creek study catchments

Basin	Station ID	Station Name	Elevation (feet)	Years of Record	
				Temp	Precip
McCloud	4-5449	McCloud	3280	76	76
Merced	4-9855	Yosemite Park HQ	3966	81	81
~~North~~ Fork American	4-1912	Colfax	2410	114	117
Thomes	4-2081	Covela	1430	46	68

To reduce the data handling effort, only one precipitation-temperature gage station was chosen for each basin. In mountainous basins, orographic effects, which generally cause precipitation to increase with elevation, dominate the local climatology. Establishing the proper precipitation-elevation relationships is made difficult by the paucity of high elevation meteorological stations and their susceptibility to recording errors. The approach we used was to define an elevation-dependent adjustment factor to relate precipitation at a given elevation (e.g. the midpoint of a snowmelt model elevation band) to gage precipitation as follows:

$$P_e = [1 + P_f(e-e_g)/100]P_g \qquad (2.5a)$$

where P_e is precipitation at elevation e, P_g is gage precipitation at gage elevation e_g. The (nonlinear) form of the factor $P_f(e-e_g)$ was determined by trial and error based on annual water balance considerations. In general,

P_f is a monotonic function of $e-e_g$, but its second derivative is negative, reflecting the fact that the rate of increase of mean precipitation with elevation decreases at high elevations.

The relationship of temperature to elevation was described by a constant lapse rate. In fact the lapse rate is a function of meteorological conditions, eg wet or dry day, storm type, and other factors. However, the available data were insufficient to support more complex relationships.

2.5.2 Snowmelt Model Parameter Estimation

It is essential that mountainous catchments be divided into elevation zones, and that the snowmelt model be applied to each zone separately because low elevations might be receiving rain while higher elevations receive snow from the same storm. The weighted mean of the pseudo-precipitation from all zones was treated as the mean areal precipitation, which is the input to the Soil-Moisture Accounting Model. In general, the weighting factors used were equal to the radios of the elevation zone subareas to the total basin area.

The elevation bands were delineated as follows. First, hypsometric curves (elevations versus area fractions) were developed. Each basin was then divided into three or four zones of equal area, depending on the elevation range, and the elevation of the midpoint of each band was identified. The McCloud and North Fork American River catchments were divided into three zones while the Merced River and Thomes Creek catchments were divided into four zones (Table 2.6).

Initial values for the precipitation-elevation adjustment factors $P_f(\cdot)$ for each elevation band were estimated from the change in mean annual precipitation with elevation of selected nearby precipitation stations. Initially, $P_f(\cdot)$ was assumed to be a linear function of the elevation

Table 2.6 Elevation zones for McCloud River, Merced River, North Fork American River and, Thomes Creek study catchments

Basin	Zone	Elevation Range (ft)	Median Elv. (ft)	Percent Basin Area	Basin Area (Square Miles)
McCloud	1	2800-4300	3900	50	358
	2	4300-5300	4600	30	
	3	5300-12000	6500	20	
Merced	1	3900-7500	5750	25	321
	2	7500-8350	7900	25	
	3	8350-9400	8800	25	
	4	9400-12000	10050	25	
North Fork American	1	750-3350	2550	34	342
	2	3350-5250	4100	32	
	3	5250-8600	6300	34	
Thomes	1	900-3100	2000	25	203
	2	3100-4200	3750	25	
	3	4200-5500	4700	25	
	4	5500-9500	6350	25	

difference. Subsequently, refinements were made through a trial and error approach, which was carried out concurrently with the calibration of the soil-moisture accounting model. The final precipitation-elevation adjustment factors are given in Table 2.7.

The snowmelt model was manually calibrated for all the elevation zones. Ideally, observed snow course data could be used for calibration but in practice snow course observations are sparse in time and space, and they represent point realizations which usually are not representative of the elevation band average snow water equivalent predicted by the model. In practice, the calibration procedure involves adjusting the most important parameters to ensure that the model predicts the initiation of snow accumulation in the fall and the gradual melting of the snowpack in the late

Table 2.7 Precipitation adjustment factors by elevation zone for McCloud River, Merced River, North Fork American River, and Thomes Creek study catchments

Basin	Precipitation Adjustment Factors			
	Zone 1	Zone 2	Zone 3	Zone 4
McCloud	0.304	0.443	0.786	
Merced	0.544	0.839	0.884	0.927
North Fork American	0.025	0.283	0.474	
Thomes	0.123	0.357	0.402	0.450

winter, and spring. The other parameters were assigned nominal values which have been used in previous studies.

The lapse rate, or rate of temperature decreases with elevation, is a critical parameter. As with the function $P_f(\cdot)$, the lapse rate is usually nonlinear. It was found that average lapse rates for four periods (each of length 6 hours) of each day for all basins vary from -0.5°C/100m to -0.8°C/100m. Together with the P_f function, lapse rates were estimated concurrently with the calibration of the Soil-Moisture Accounting Model (see Section 2.5.3).

Seasonal melt factors were interpolated between MFMAX (maximum non-rain melt factor which occurs on June 21) and MFMIN (minimum non-rain melt factor which occurs on Dec 21) and were estimated to vary between 0.9 to 1.2 and 0.2 to 0.5 mm/°C/6 hours, respectively. PXTEMP, the temperature above which precipitation was assumed to be rain (°F) was taken to be 32°F. SI, the mean areal water-equivalent above which 100 percent areal snow cover always exists was assumed to vary between 75 and 150mm. Tables 2.8 and 2.9 give descriptions and calibrated values of the snowmelt model parameters

2.5.3 Soil Moisture Accounting Model Parameter Estimation

Parameter estimation for the soil moisture accounting model was based on a process of initial parameter estimation suggested by Peck (1976), sensitivity analysis to determine those parameters deserving further attention, followed by automated parameter estimation using a simplex search procedure (Nelder and Mead, 1965) for the most sensitive parameters. The objective function in the search procedure was the sum of the squared difference between the logarithms of the predicted and observed (daily) streamflow over the calibration period.

The parameters estimated using the search procedure were LZFPM, LZFSM, LZPK, LZSK, UZK, UZFWM, ZPERC, REXP, UZTWM, LZTWM, and PXADJ (parameters are

Table 2.8 Snowmelt model parameter description

Parameter	Description
DAYGM	Average daily ground melt at the snow-soil interface in mm
EFC	Area over which evapotranspiration can take place when there is complete areal snow cover
ELEV	Mean height of the basin elevation band
MBASE	Melt factor base temperature (assumed to be 0°C)
MFMAX(MFMIN)	Maximum and mimimum non-rain melt factors which occur on June 21 and Dec. 21 respectively
NMF	Maximum negative melt factor
PLWHC	Percent liquid-water holding capacity of ripe snow
PXTEMP	Temperature in °C to divide rain from snow
SCF	A multiplying factor to correct for gage catch deficiency in the case of snowfall
SI	Areal water quivalent in mm above which there is always complete areal snow cover
TALR	Lapse rate (°C/100m)
TIPM	Antecedent snow temperature index parameter
UDAJ	Mean wind function value during rain-on-snow periods

Table 2.9 Calibrated values of snowmelt model parameters

	McCloud River	Merced River	North Fork American River	Thomes Creek
PAYGM	0.4	0.4	0.4	0.4
EFC	0.9	0.9	0.9	0.9
MBASE	0.0	0.0	0.0	0.0
MFMAX	0.90	1.10	1.10	1.20
MFMIN	0.40	0.40	0.20	0.20
NMF	0.12	0.12	0.12	0.12
PLWHC	0.07	0.07	0.07	0.07
PXTEMP	0.5	0.5	0.5	0.5
SCF	1.03	1.03	1.03	1.03
SI	200	150	100	120
TALR	-0.5	-0.7	-0.8	-0.7
TIPM	0.3	0.3	0.3	0.3
UDAJ	0.10	0.10	0.10	0.10

defined in Table 2.10). The parameters which were assigned nominal values were PCTIM, SSOUT, ADIMP, SIDE, IMPRT and SARVA.

All parameter estimates were based on calibration periods of length four years. The calibration periods were selected to include dry, medium and wet years so that during calibration, the model was subjected to a broad range of changes in conceptual storages.

Because of its deep and highly permeable soils, the McCloud River catchment is dominated by subsurface flow, even during intense storms. For this reason, the McCloud River catchment was calibrated manually. Calibrations for all catchments were complicated by errors in the rain and melt data produced by the snowmelt model which itself was calibrated through trial and error. The initial and optimized values, upper and lower bounds for the sensitive parameters are reported in Table 2.11. To test whether the model had been overfit, that is, whether the simulation errors were consistent between the calibration periods and an independent verification period consisting of those years in the period 1951-80 not used for calibration, a seasonal Wilcoxon test (see Hirsch, 1988; Hettmansperger, 1984) was applied to the monthly sum of log flow differences squared. The results for all four study catchments fell within the 95 percent critical region for a two-tailed test, which confirmed that the performance of the model in the calibration and verification periods was comparable.

2.6 Model Input Characterization

This section describes the relationship between the upper left and right quadrants of Figure 2.1, that is, the relationship between the historic input data for the hydrologic model, and the input corresponding to the GCM alternatives. The historic input data were adjusted to reflect the altered climate predicted by each of the seven alternatives. This approach was taken in preference to using the GCM output directly, or attempting to

Table 2.10 Soil moisture accounting model parameter description

Soil Moisture Phase	No	Parameters	Description
Direct runoff	1	PCTIM	Minimum impervious area (percent)
	2	ADIMP	Additional impervious area (percent)
	3	RIVA	Riparian vegetation area (percent)
	4	EFC	Effective forest cover (percent)
Upper zone	5	UZTWM	Upper zone tension water capacity (inch)
	6	UZFWM	Upper zone free water capacity (inch)
	7	UZK	Daily upper zone free water withdrawal rate
Percolation	8	ZPERC	(ZPERC+1)xPBASE is the maximum percolation rate
	9	REXP	Exponent for the percolation equation
Lower zone	10	LZTWM	Lower zone tension water capacity (inch)
	11	LZFSM	Lower zone supplemental freewater capacity (inch)
	12	LZFPM	Lower zone primary freewater capacity (inch)
	13	LZSK	Daily supplemental withdrawal rate
	14	LZPK	Daily primary withdrawal rate
	15	PFREE	Fraction of percolation water passing directly to LZFM storages
	16	RSERV	Fraction of lower zone free water cannot be transferred to LZTW
	17	SIDE	Ratio of non-channel baseflow to channel baseflow
Initial water	18	UZTWC	Upper zone tension water content (inch)
	19	UZFWC	Upper zone freewater content (inch)
	20	LZTWC	Lower zone tension water content (inch)
	21	LZFSC	Lower zone supplemental free water content (inch)
	22	LZFPC	Lower zone primary free water content (inch)
	23	ADIMC	Tension water contents of the ASIMP area (inch)
Climatic Index	24	PXADJ	Precipitation adjustment factor
	25	PEADJ	ET-demand adjustment factor

Table 2.11 Initial and optimized final values and upper and lower bounds for the soil-moisture accounting model parameters

Thomes Creek

	LZFPM	LZFSM	LZPK	LZSK	UZK	UZFWM	ZPERC	REXP	ZTWM	LZTWM	PXAD
Initial	6	4	.009	.02	.10	2.0	20	1.80	3	4	0.008
Optimized	1.75	1.75	.005	.053	.09	1.67	33.4	1.55	2.7	7.10	.006
Upper Bound	7.0	5.0	.03	.08	.3	3.5	43	3.0	7.0	11.0	.02
Lower Bound	1.1	1.0	.005	.01	.05	.05	10.0	1.1	1.5	2.0	.004

McCloud River Basin

	LZFPM	LZFSM	LZPK	LZSK	UZK	UZFWM	ZPERC	REXP	UZTWM	LZTWM	PXAD
Initial	20	5.6	.003	.026	0.06	3.0	43.3	1.60	4.0	5.0	1.1
Optimized	53.0	14.7	.0022	.004	.07	2.0	81.3	1.03	5.2	6.4	0.86
Upper Bound	77.0	25.0	.03	.08	.3	9.5	98	3.0	11.0	21	1.7
Lower Bound	1.1	1.0	.0005	.003	.05	.05	10.0	1.01	1.0	2.0	0.6

Merced River Basin

	LZFPM	LZFSM	LZPK	LZSK	UZK	UZFWM	ZPERC	REXP	UZTWM	LZTWM	PXAD
Initial	6.0	2.9	.006	.01	.11	1.9	34	1.8	4.8	7.2	0.90
Optimized	3.7	3.0	.016	.05	.08	2.80	49.5	2.30	1.2	8.1	0.98
Upper Bound	27.0	10.0	.03	.08	.3	9.5	68	3.0	11.0	21.0	1.7
Lower Bound	1.1	1.0	.0005	.004	.05	.05	10.0	1.01	1.0	2.0	.05

American River Basin

	LZFPM	LZFSM	LZPK	LZSK	UZK	UZFWM	ZPERC	REXP	UZTWM	LZTWM	PXAD
Initial	2.17	1.88	.009	.055	0.09	1.60	36	1.10	1.68	7.27	.91
Optimized	2.70	2.6	.006	.056	.13	1.4	24.3	1.11	1.47	6.03	.92
UpperBound		7.0	.03	.08	.3	3.5	43	3.0	7.0	11.0	1.7
Lower Bound	1.1	1.0	.005	.01	.05	.05	10	1.1	1.0	2.0	0.5

develop a stochastic model to predict the space-time meteorological structure associated with the GCM output. The reasons for using adjustments to the historic record as input to the hydrologic models were first, in terms of the project time constraint, that it was a straightforward approach that required no new model development, and second, that the sequences might be considered a feasible realization of the (present) natural process since the historic record has actually occurred. In the remainder of this section, the specific approach used to provide the precipitation, temperature, and potential evaporation inputs is described.

2.6.1 Precipitation

For each GCM alternative, the National Center for Atmospheric Research (NCAR) provided a disk file of the output corresponding to the center of each grid cell used by the given model, along with a program to read and print the output. This program provided, among other variables, the predicted GCM precipitation corresponding to a base case (nominally, present conditions) and the alternative climate. For all cases except Case 3 (GISS transient), the base cases and alternative climates were represented as long-term monthly averages. NCAR computed the ratio of the GCM alternative long-term precipitation to the base case long-term precipitation (or, in the case of the GISS transient, the ratio was computed for each decade over the 80 year transient run). The NCAR program was modified slightly to interpolate the results to longitude 120°W, latitude 40°N, which is approximately the centroid of that part of the Sacramento-San Joaquin basin that contributes most of the runoff. For all but the transient run, the computed precipitation ratio was then applied to all the raw input precipitation records.

In the case of the transient run, a statistical test (Spearman's rho; see for example, Conover, 1971) was applied to the 80 year sequence of decadal precipitation factors to determine whether there was a statistically significant trend. For those cases (four months) where the trend was significant, a linear regression was fit to the decadal precipitation factors, and the resulting "ramp" was used to adjust the historical precipitation records. In those cases (eight months) where the trend was not significant, the average precipitation factor (over the eight decades) was computed, and this average precipitation adjustment was used in the same way as were the NCAR-computed factors for the steady state runs.

2.6.2 Temperature

For the steady state runs, a temperature shift was computed as the difference between the 2xCO2 and base condition. These monthly differences were then applied directly to the historic data. In the case of the GISS transient run, the sequences of eight decadal shifts were tested for trend, in the same manner as were the precipitation factors. All months were found to have statistically significant uptrends, so a linear regression was fit to all months, and the resulting ramps were used as input to the hydrologic models.

2.6.3 Potential Evapotranspiration

Potential evapotranspiration (PET) was computed from the Penman equation, which is given in Veihmeyer (1964). Penman's equation is based on a theoretical energy balance approach. It predicts PET as a function of temperature, average wind speed, humidity, mean solar radiation, and the ratio of duration of bright sunshine to maximum possible duration of bright sunshine.

Penman's equation was applied on a monthly basis, using average values of the input variables. Some of the input variables (wind speed) are not well known, so they were adjusted to obtain a total annual evaporation estimate that was roughly consistent with observed pan evaporation at stations throughout the Central Valley (usually on the order of 55-65 inches of pan evaporation on the valley floor).

Once an adequate "fit" was obtained, the input values were compared with selected station values to make sure they were physically realistic. The most sensitive input value was wind speed, which can be strongly affected by local factors, so the trial and error approach seemed justified. Nonetheless, the assumed (seasonally constant) value of 200 miles per day that was used was remarkably close to the observed long-term mean at Red Bluff, which has one of the longest records in the Central Valley.

The Penman PET was then recomputed for each GCM using two sets of temperature data: the base condition for that GCM, and the predicted temperature corresponding to the CO2 doubling. The monthly differences in the Penman PET were computed, and these differences were then applied to the historic data as input to the hydrologic models. In the GISS transient case, the differences corresponding to the base and altered climate temperatures at the beginning and end of the temperature "ramp" were computed, and the resulting Penman PET differences were used to define a PET "ramp".

CHAPTER 3: RESULTS

As described in Chapter 2, the long-term hydrologic response of the study catchments was simulated for climates associated with a base case (nominally, present conditions) as well as three sets of GCM predictions (Cases 1,2, and 4) that were based on steady state climate following a doubling of current atmospheric CO2 concentrations. In addition, the hydrologies of the study catchments associated with a transient climate resulting from doubling of atmospheric CO2 over an 80 year period (Case 3) were also evaluated.

Three alternative climates (Cases 5-7) were used to test the sensitivity of the hydrologies of the study catchments to selected aspects of the GCM climate predictions. These included a scenario (Case 5) designed to explore the relative effect of predicted precipitation and temperature change, a scenario (Case 6) designed to explore the effect of different interpretations of the predicted geographic distribution of temperature and precipitation changes, and a scenario (Case 7) in which the long-term climate was assumed to be similar to that experienced in the 1930's. Cases 0-4 are referred to as initial scenarios, and are discussed in Section 3.1. Cases 5-7 are referred to as sensitivity scenarios, and are discussed in Section 3.2. The temperature shifts and precipitation scaling factors associated with Cases 1-7 are given in Tables 3.1 and 3.2, respectively.

Because the snowmelt and soil moisture accounting models operate on daily or shorter time steps, and all cases involved running the snowmelt and soil moisture accounting models for 100 years, large amounts of computer output were generated. To simplify the analysis of the results, we selected the following model (simulated) variables to summarize the alternative hydrologies: 1) average snow water equivalent over each study catchment;

Table 3.1 Temperature shifts in °C for GCM cases 1-7

Case	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
1	3.5	4.35	4.5	4.55	5.70	6.10	4.35	3.90	4.90	4.30	4.10	3.45
2	5.9	4.6	4.6	5.4	3.1	4.1	3.9	5.50	7.20	5.3	3.4	4.4
3[a]	-.02	.33	.10	-.03	-.33	-.05	-.02	-.65	.87	-.46	.48	-1.61
	4.13	3.35	3.0	4.22	2.29	2.68	4.10	3.28	4.55	4.14	4.72	3.26
4	0.55	2.03	1.31	2.08	1.97	2.68	2.12	3.12	2.39	1.58	3.08	2.57
5	5.9	4.6	4.6	5.4	3.1	4.1	3.9	5.50	7.20	5.3	3.4	4.4
6[b]	6.60	5.06	4.78	5.15	3.14	4.0	3.31	5.98	8.55	5.33	3.47	4.69
	4.82	3.84	4.24	5.77	3.18	4.15	4.80	4.88	5.17	5.19	3.24	4.00
7	-0.16	-0.54	0.97	0.98	0.43	0.04	0.36	0.90	0.65	0.53	0.62	0.66

[a] The upper and lower entries represent the beginning and end transient temperature shifts for the 80-year period ramp used for Case 3.

[b] The first row represents temperature shifts for the 3 northern catchments and the second row the southern catchment (Merced River).

Table 3.2 Precipitation scaling factors for GCM cases 1-7

Case	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
1	.936	1.13	.924	.911	.710	.947	.11	.889	.818	1.084	1.189	1.096
2	1.21	1.06	1.34	.764	.976	1.28	.655	1.26	.765	1.30	1.24	1.15
3[a]	.954 1.171	1.082	1.123	.836	1.112 1.383	.864 1.564	.908	1.542	2.157	1.096	1.182	.783 1.070
4	1.03	1.13	1.04	1.36	.93	1.05	1.01	.88	1.07	0.89	0.76	0.89
5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
6[b]	1.227 1.181	1.156 0.911	1.525 1.045	1.019 .363	1.106 .771	1.439 1.038	1.061 .017	1.289 1.220	0.615 0.999	1.369 1.184	1.397 .989	1.110 1.216
7	0.854	0.994	0.845	0.934	0.879	1.15	0.622	0.249	0.67	0.807	.593	.949

[a] Only months with an upper and lower entry had a statistically significant transient. For months with a significant transient, the upper and lower entries represent the beginning and end precipitation scaling factors used in the 80-year ramp for Case 3.

[b] The upper entries represent precipitation scaling factors for the three northern catchments and the lower entries represent the southern catchment (Merced River).

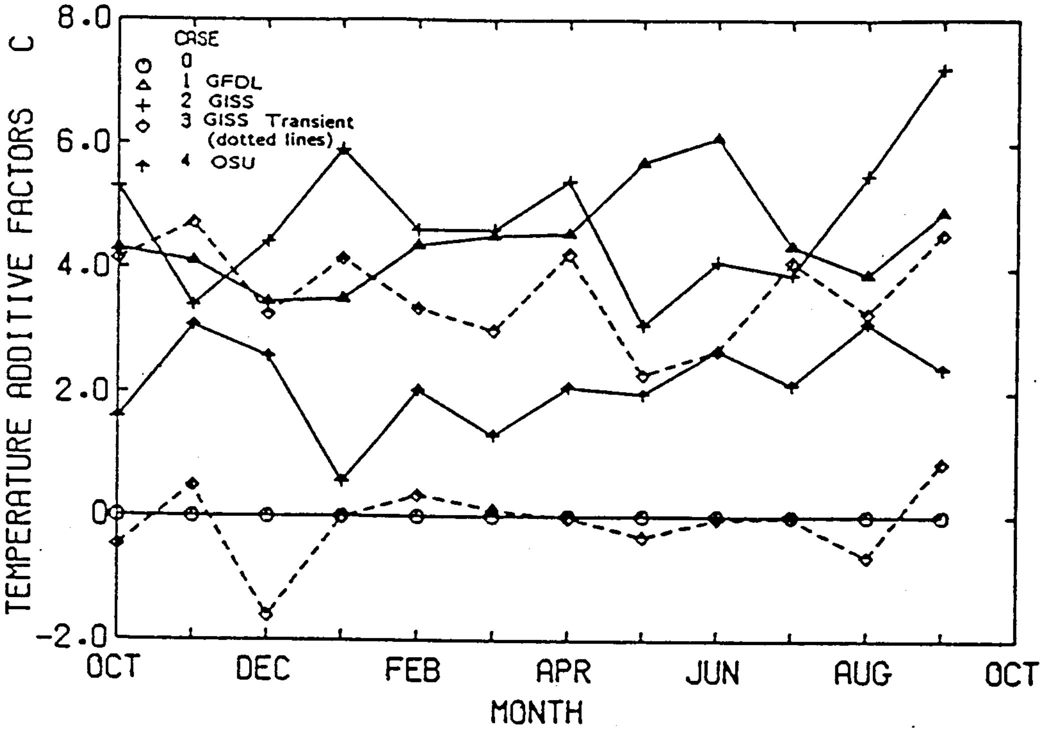
2) monthly average study catchment runoff; 3) monthly average study catchment evapotranspiration; 4) average end of month study catchment soil moisture storage in selected zones (see Section 2.4.2 for description of the model soil moisture zones); 5) predicted (disaggregation model) monthly primary node streamflow; and 6) predicted (linearly regressed) monthly secondary node streamflow. In all cases, the mean of each variable was computed for the 100 year simulation period, as well as the standard deviation (expressed as a coefficient of variation in some cases). In the interest of brevity, only selected mean values are reported in this chapter; Appendix B contains a complete graphical summary of the results.

3.1 Study Catchment Results for Initial Scenarios

The hydrology of the Sacramento-San Joaquin basin in general, and the study catchments in particular, is dominated by high elevation snow accumulation in the winter, and snowmelt in the spring and early summer months. Snow water storage is especially important because of the disproportionate amount of precipitation that occurs at high elevations, and because snow water storage shifts the peak of the annual runoff hydrograph from the high precipitation winter months toward the spring and summer. Increasing winter temperature decreases the amount of precipitation falling as snow, and causes any snow that accumulates in the winter to melt earlier. This is the principal mechanism by which the alternate climates affect the hydrology of the Sacramento-San Joaquin basin. For this reason, the order of presentation of the results is: predicted average snow water equivalents, monthly average runoff, monthly average evapotranspiration, and monthly average soil moisture. Before presenting the results, however, a brief discussion of the climate alternatives is in order.

All four of the initial scenarios (Case 1: GFDL 2xCO2, Case 2: GISS 2xCO2, Case 3: GISS transient, and Case 4: OSU 2xCO2) predicted increasing average temperature for all months (see Fig. 3.1). Generally, the largest temperature changes were predicted by the GFDL and GISS models, and the smallest by the OSU model. Figure 3.1 also shows the beginning and ending values of the "ramp" fit to the Case 3 temperature transients. In general, the final values in the transient case are slightly less than the Case 1 and Case 2 steady state values, but are larger than Case 4. Figure 3.1 shows that there was no consistency in the predicted long-term precipitation changes. The GISS model (Case 2) generally predicted an increase in precipitation in the winter months. Because the precipitation regime is highly seasonal, summer precipitation changes for the catchments are of much less importance hydrologically. The GFDL model predicted increased fall precipitation, and generally decreased winter and spring precipitation. The GISS transient and the OSU model had less obvious patterns, with predicted increases in some months and decreases in others.

Figures 3.2a-d show long term study catchment-average snow water equivalent, runoff, evapotranspiration, and soil moisture storage, respectively, by month for Cases 0-4. Figure 3.3a shows the predicted average annual runoff by decades while Figure 3.3b shows the catchment monthly mean flows of four successive 25-year periods for the transient case (Case 3). The results for Case 3 shown in Figures 3.2a-d represent averages over the 100 year simulation period, and do not represent the transient nature of the Case 3 response. In Figure 3.2d, the soil moisture zone to which the model performance was most sensitive is indicated. Because of the differences in the geologic and hydrologic characteristics of the catchments, the particular subsurface zone varies by catchment. For this



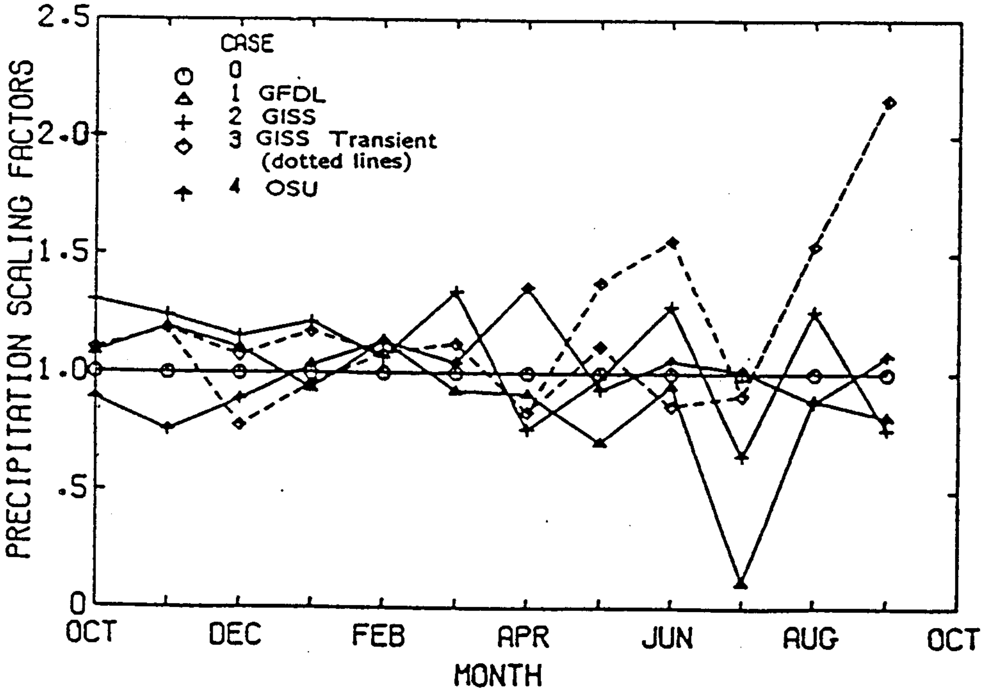


Figure 3.1 Monthly temperature shifts (1) and precipitation scaling factors (2) predicted by general circulation models for climate scenario Cases 0-4

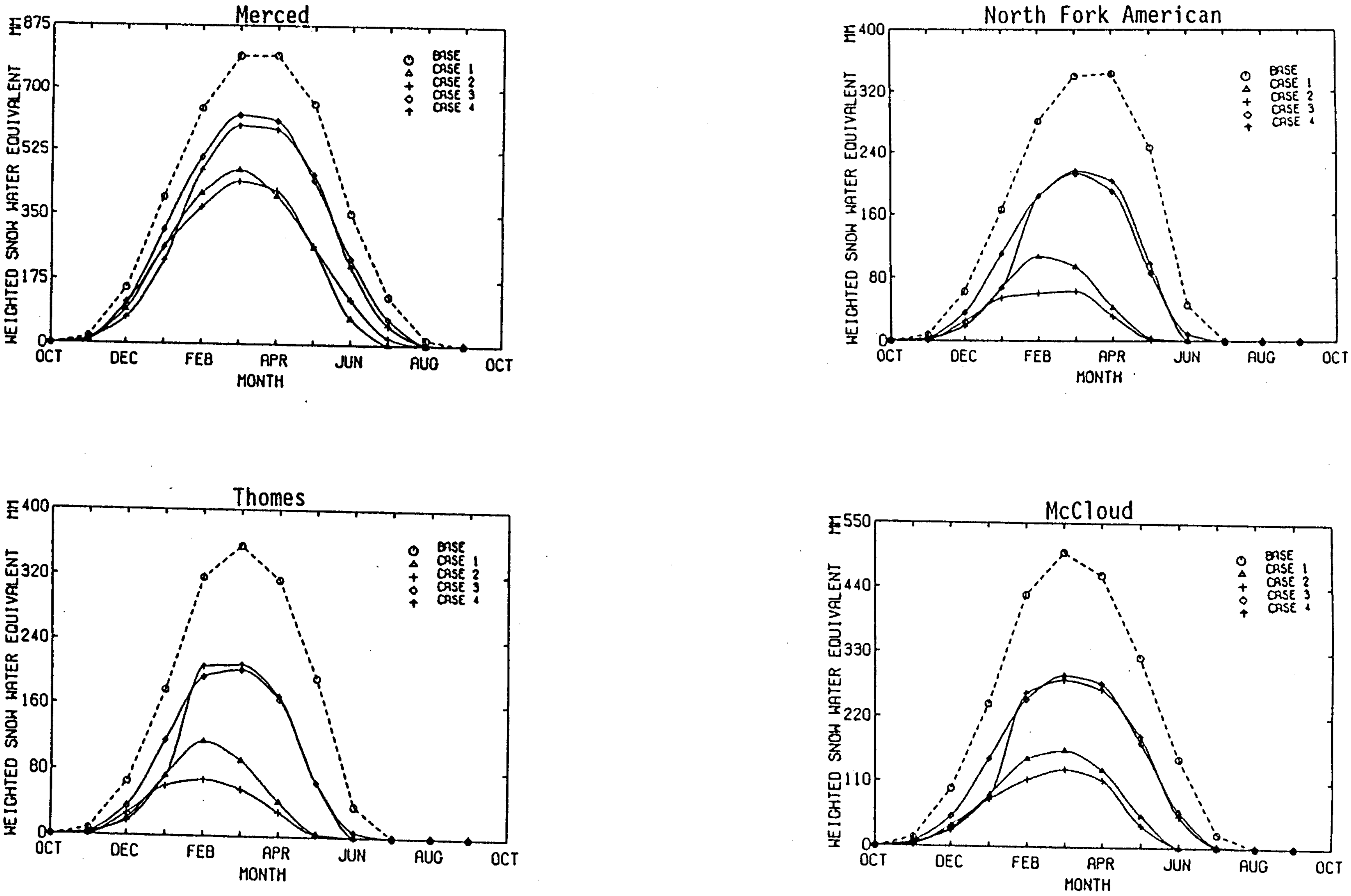


Figure 3.2a Study catchment monthly mean weighted snow water equivalent for climate scenario Cases 0-4

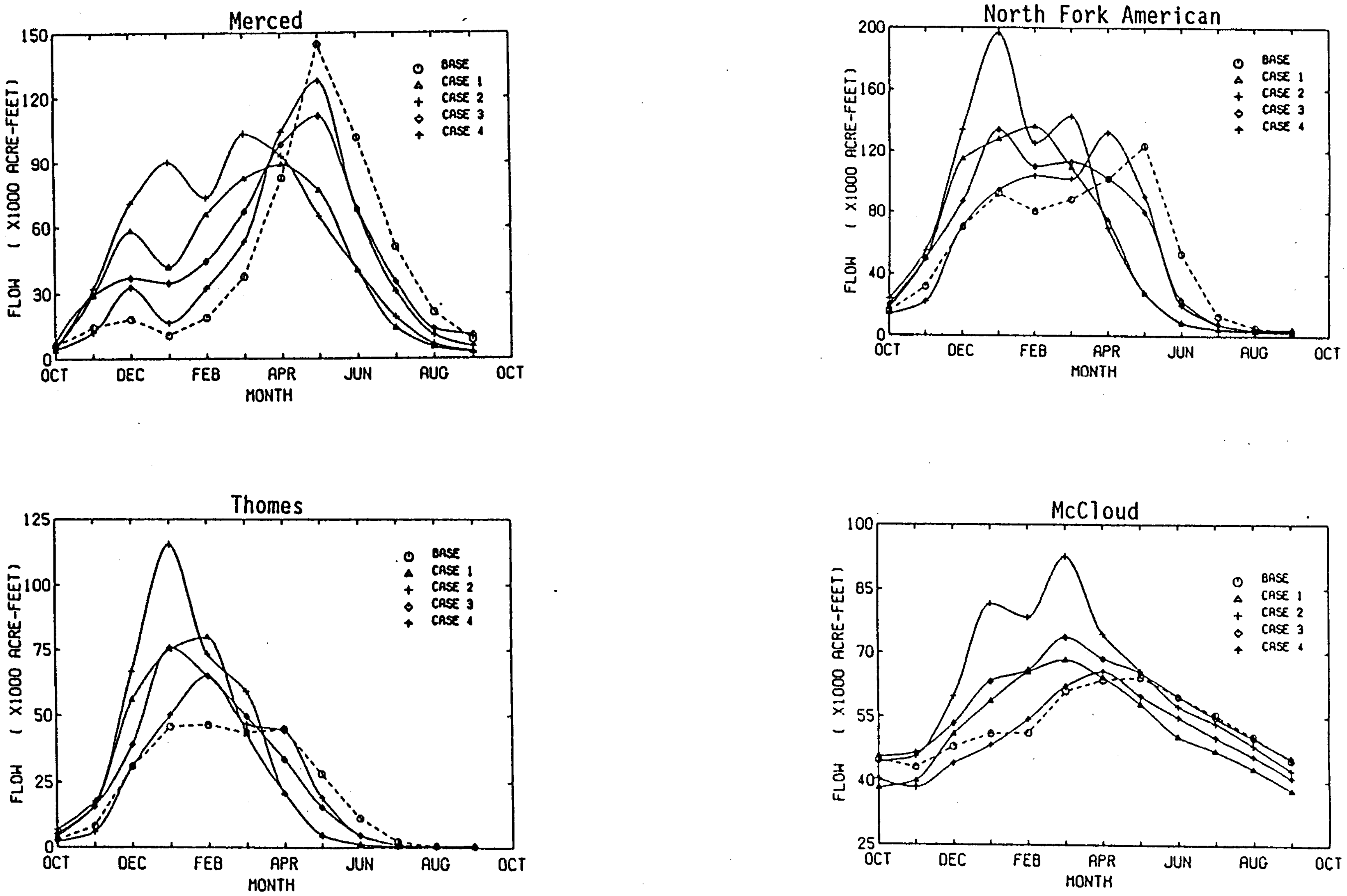
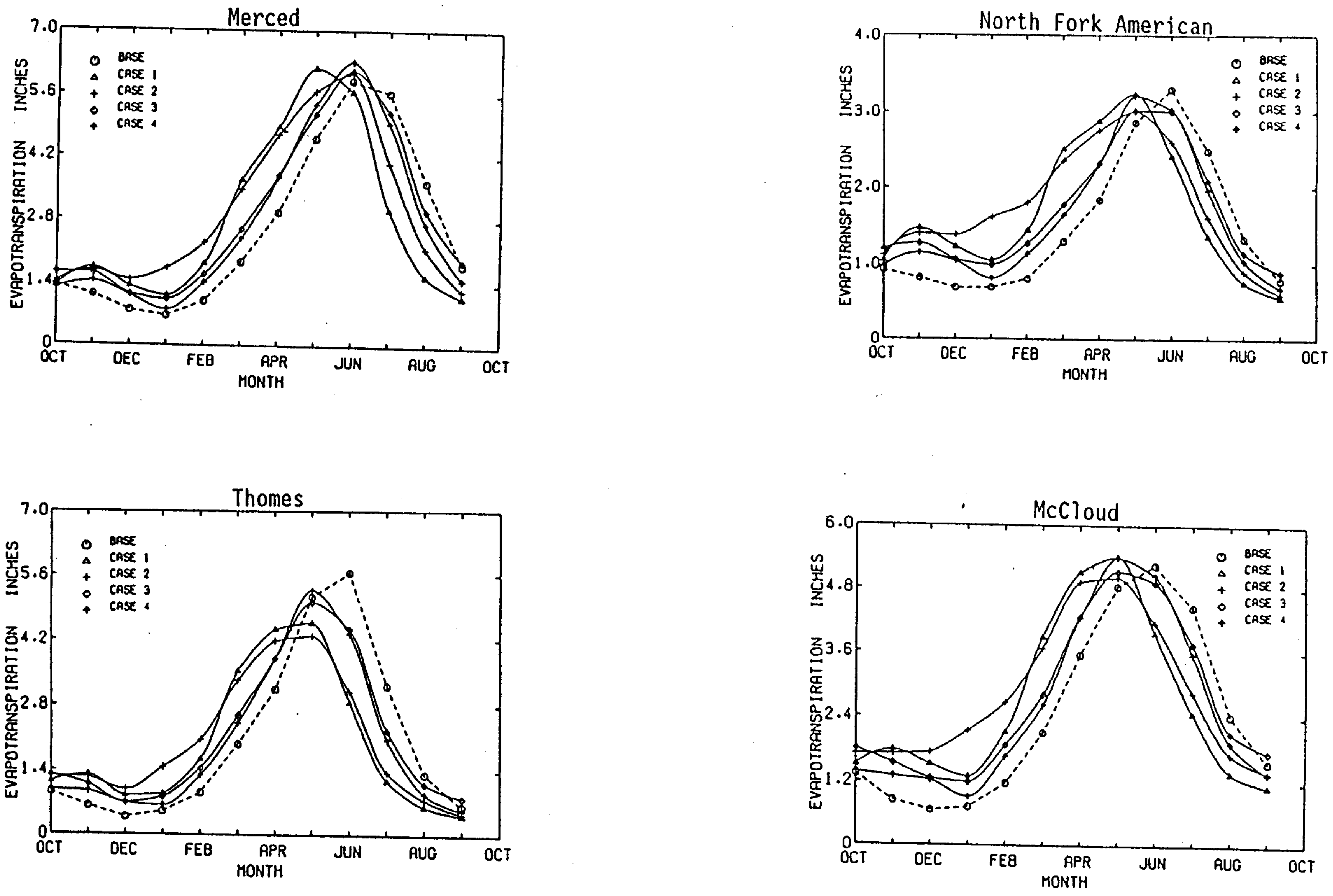


Figure 3.2b Study catchment monthly mean streamflow for climate scenario Cases 0-4


Merced

North Fork American

Thomes

McCloud

Figure 3.2c Study catchment monthly mean evapotranspiration for climate scenario Cases 0-4

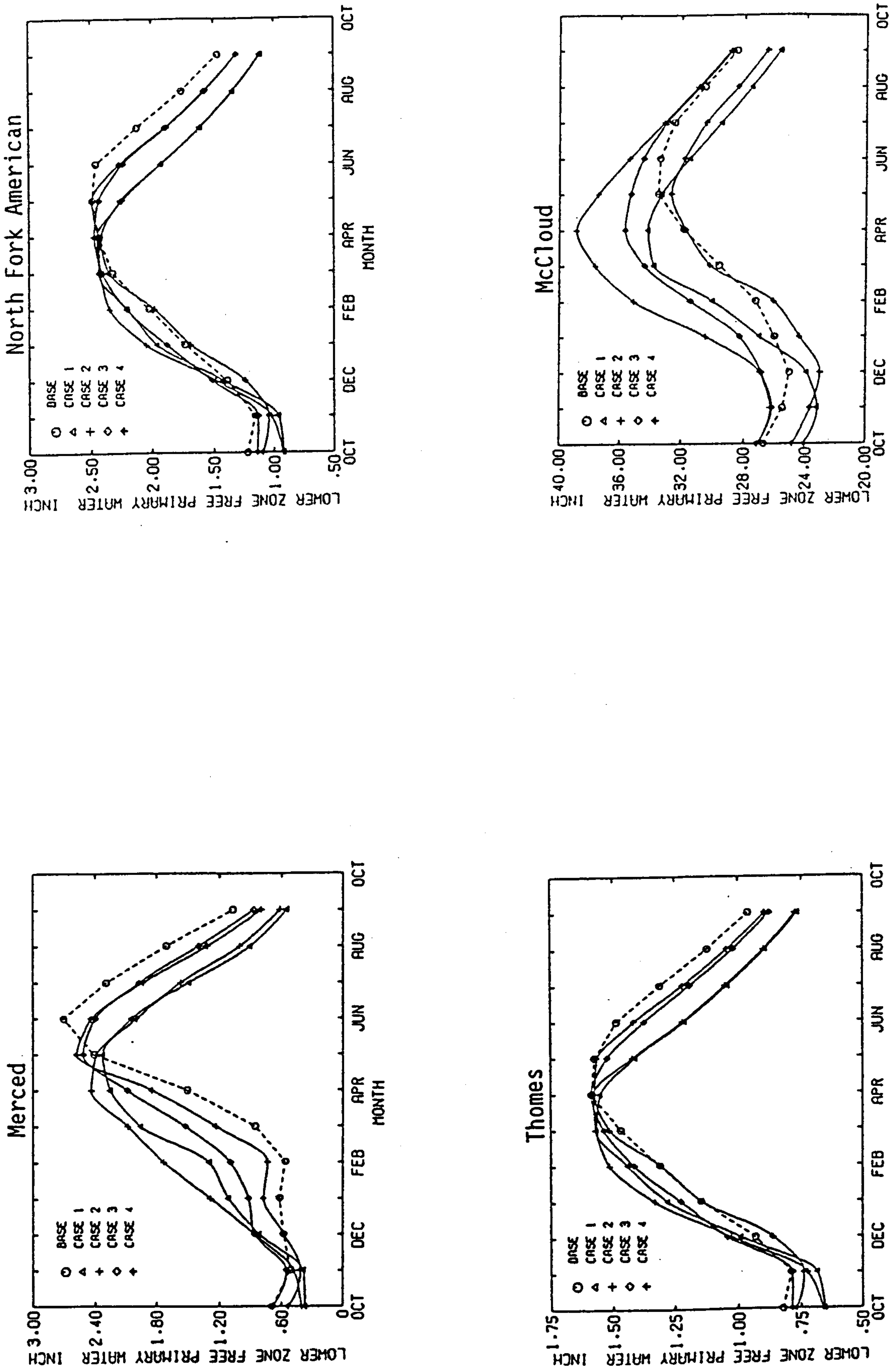


Figure 3.2d Study catchment monthly mean soil moisture for climate scenario Cases 0-4

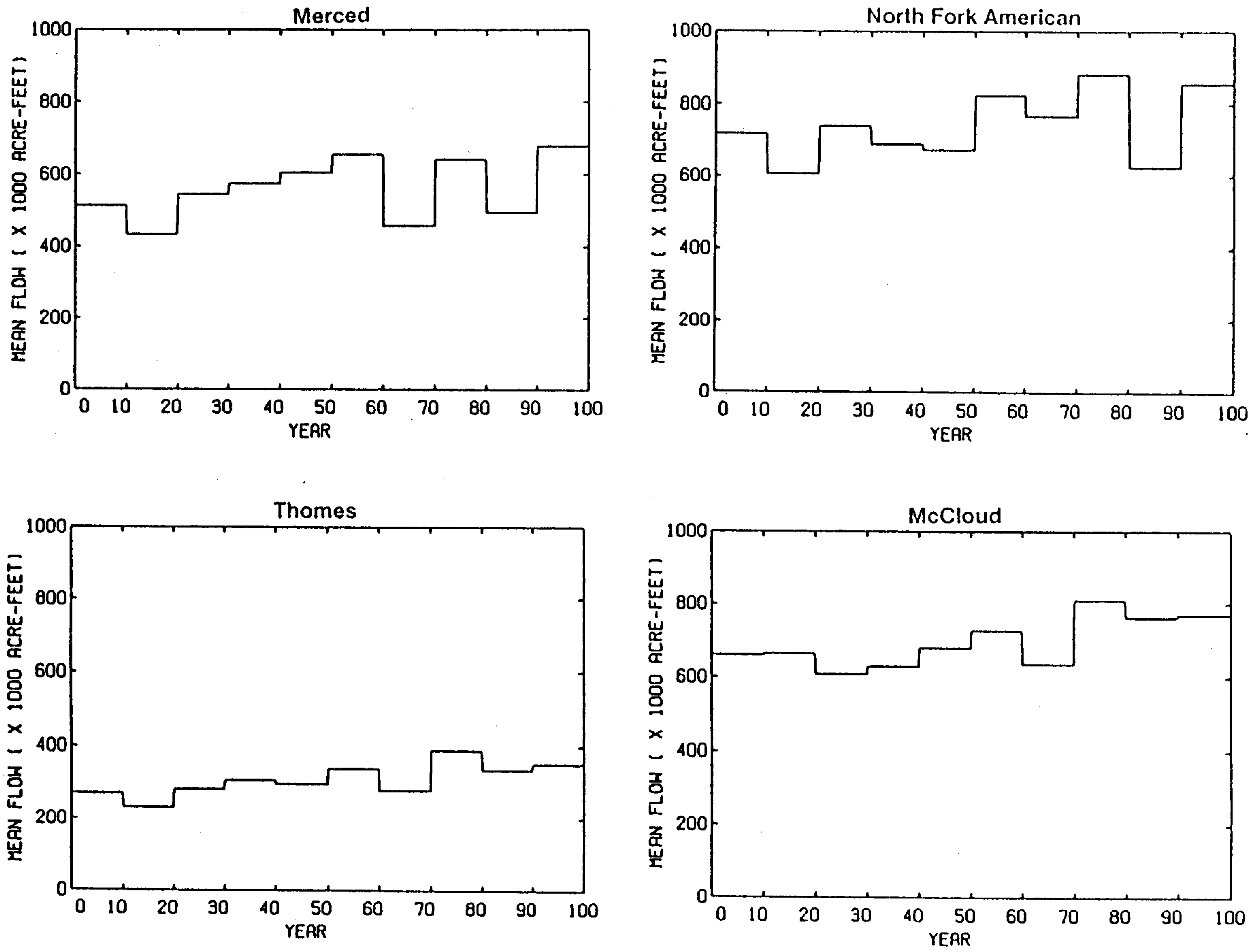


Figure 3.3a Study catchment decade mean flows for transient climate scenario (Case 3)

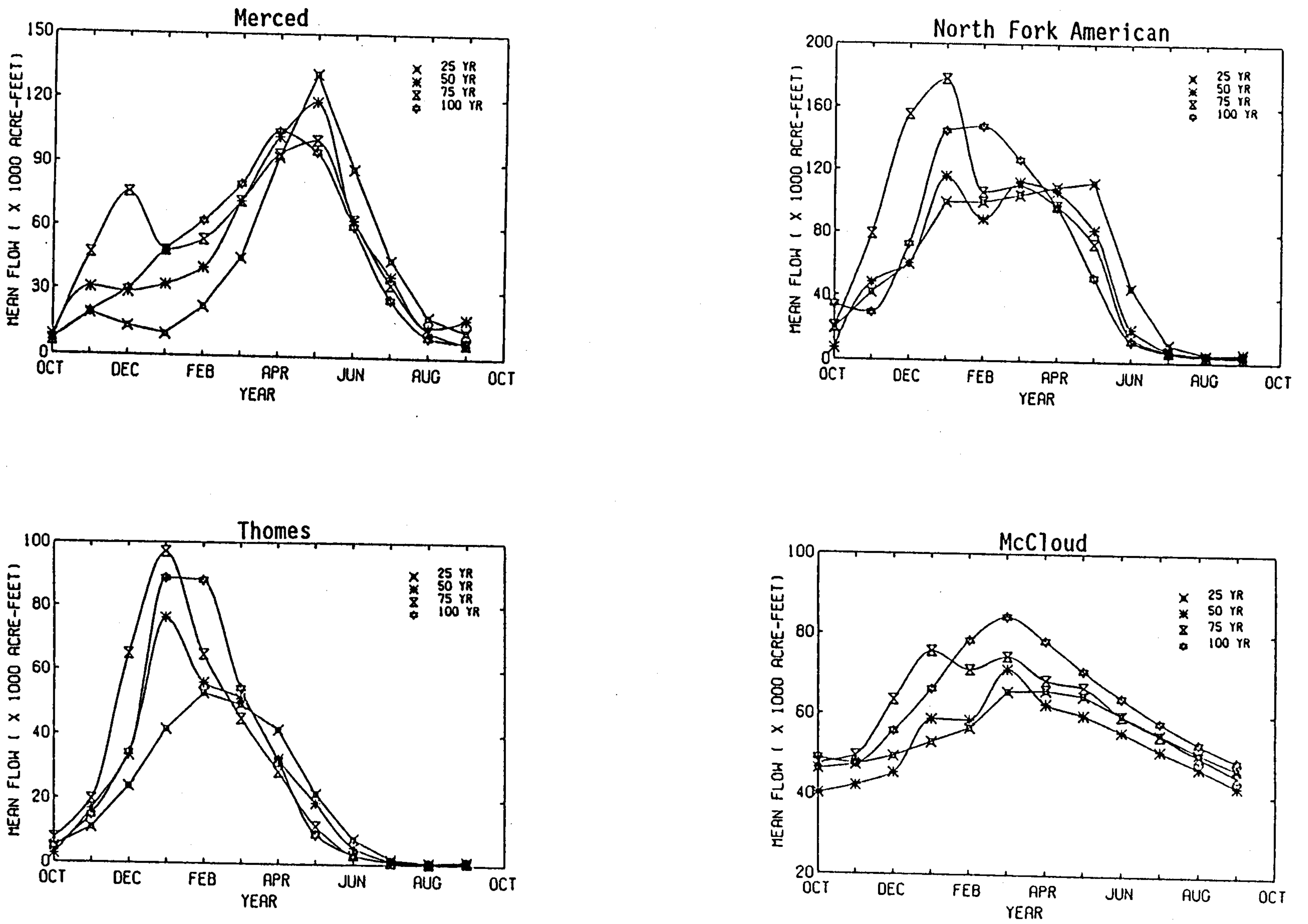


Figure 3.3b Study catchment monthly mean flows of four successive 25-year periods for transient climate scenario (Case 3)

reason, the relative values are of greater importance than the numerical values of the predicted storages.

The results of the simulations are reported in the remainder of this chapter and in Appendix B. In most cases, the results are reported as averages over the 100 year simulation period described in Chapter 2. For selected model variables, standard deviations over the 100 year simulation period were computed, and are reported in Appendix B. Brief interpretations of the results for snow water equivalent, runoff, evapotranspiration, and soil moisture are given in Sections 3.1.1-3.1.4, respectively.

3.1.1 Snow Water Equivalent

Figure 3.2a shows long term study catchment-average snow water equivalent by month for Cases 0-4. There was a marked reduction in average snow water equivalent for all of the study catchments for all of the alternative climates (Cases 1-4). The predicted changes, when expressed as a proportion of the base case average snow water equivalent, were the greatest for the North Fork American River, which has the lowest mean elevation, and the least for the Merced River, which is the highest basin. In Cases 1 and 2, snow storage is virtually eliminated in the lower elevation study catchments.

Although the proportionate reduction in mean snow water equivalent was the least for the Merced River, because it is influenced more by snowfall and snowmelt than the other basins, the magnitude of the reduction in snow water equivalent was larger than for any of the other study catchments. The Merced lost more snow water equivalent than the North Fork American River or Thomes Creek had in the base case. The Case 1 and 2 temperature increases are large enough to eliminate almost all the influence of snow water storage from all study catchments but the Merced.

3.1.2 Runoff

Figure 3.2b shows the predicted changes in the seasonal distribution of study catchment runoff. The effect of reduced snow storage is immediately apparent; in all cases, the annual hydrograph peak shifted earlier in the year because of a decrease in the amount of snowfall in relation to rainfall. Runoff increased markedly in all cases for the winter months, and decreased substantially in the late spring and summer. The predicted changes in annual runoff relative to the base case are reported in Table 3.3. Table 3.4 summarizes the months in which predicted runoff is reduced from present conditions.

Table 3.3 Simulated mean annual study catchment runoff for GCM cases 0-4

	Annual Runoff in Thousands of Acre-feet			
Case	Merced River	North Fork American River	Thomes Creek	McCloud River
0	518.0	679.0	267.7	448.2
1	509.3	680.0	304.4	427.7
2	596.5	795.1	367.7	591.6
3	551.2	733.3	297.1	521.7
4	500.6	669.1	269.1	406.0

Although the general shift in the annual streamflow hydrograph was consistent in all of the catchments, site-specific effects were observed as well. For instance, for the Merced River, which has high snowmelt-runoff between March and July, the effect of increased precipitation in Case 2 was overshadowed by the temperature increase. The North Fork American River has a mixed rainfall-runoff and snowmelt-runoff regime for the base case. This changes to a complete rainfall-runoff situation for Cases 1 and 2. The phase shift is less for Case 4 because the temperature increase is more modest. Because the North Fork American River has a large rainfall-runoff component for the base case, the increase in winter flows was not proportionally as large as for the Merced, which is snow-dominated in the base case. For Thomes Creek there was relatively less snowmelt, and the base flow in the summer approached zero for all cases including the Base Case. Case 2 resulted in the largest runoff changes, doubling the December and January mean flows and increasing February by about two-thirds. Although the mean flow and standard deviation increased (see Fig. B.1a), the coefficient of variation for the Thomes Creek runoff was generally reduced (Fig. B.1b).

The importance of groundwater for the McCloud River is shown in Figure 3.2b. Although all scenarios shifted the flows earlier, only Case 2 overwhelmed the soil moisture storage capacity of the model. Case 2 produced peaks in January and March, with slightly lower flows in February, but the entire winter had a predominance of rainfall runoff. The standard deviation of flows generally increased also (see Fig. B.1a), as did the coefficient of variation (Fig. B.1b).

The shift in the annual distribution of runoff is critical for water resources management; the seasonal distribution of runoff, and its variability, are more important than the annual runoff change. The implications of these changes in seasonal runoff distribution, and variability, are addressed in detail by Sheer and Randall (1988). Figure B.1b shows that for most of the catchments and climate change scenarios, runoff variability was substantially increased in the winter months, and reduced slightly in the summer months.

Table 3.4 Months with predicted reduction in streamflow, based on the climate change predicted by the GCMs.

Basin	Case	Months
Merced	1	May to September
	2	May to September
	3	May to August
	4	May to November
NF American	1	April to September
	2	April to September
	3	May to September
	4	May to November
Thomes	1	April to August
	2	April to August
	3	April to August
	4	May to November
McCloud	1	May to November
	2	June to September
	3	None or negligible
	4	May to January

3.1.3 Evapotranspiration

As described in Chapter 2, potential evapotranspiration (PET) was estimated for the alternative climate scenarios using the Penman equation with the GCM-predicted temperature changes. In all cases for all basins, the maximum actual evapotranspiration simulated by the soil moisture accounting model occurred earlier in the year (See Fig. 3.2c). Case 1 generally resulted in a flatter crest for the monthly mean ET than was predicted for the base case. For Thomes Creek, Cases 1 and 2 were flatter, lower, and peaked earlier than Cases 3 and 4. ET depends on soil moisture as well as PET, therefore, although PET increased for all months for Cases 1-4 because of the increased temperature, the direction of changes in actual ET varied by month.

The soil moisture-accounting model assumes that ET depends on the moisture contents of the conceptual tension zones. The rate of ET declines as the soil dries. Therefore, the shift of the flow from spring to winter shifts the ET similarly. ET also depends upon temperature, so that wet winter soils do not yield as much ET as similarly wet spring soils. The net result, despite the change in seasonal distribution, was relatively little change in annual total ET. Although the changes in seasonal distribution of ET were similar over all the study catchments, there were differences among the cases. Cases 1 and 2 have the greatest increase in mean temperature, and they show the greatest shift in timing of ET. Case 4 predicts the least temperature change, and it shows the least change in ET. The variability of the ET increased more or less in proportion to the mean. The increased spring ET suggests that agricultural irrigation demand might be increased over the present situation.

3.1.4 Soil Moisture Storage

Figure 3.2d shows long term catchment-average soil moisture storage by month for Cases 0-4. As described in Chapter 2, the soil moisture accounting model has five conceptual storage zones. The capacity of the soil moisture zones strongly affects the response of the model to altered inputs. The soil moisture zone capacities were estimated through the automated calibration process described in Chapter 2. While neither their capacities nor contents are measurable physical quantities as are, for instance, snow water equivalent or runoff, the soil moisture storages do reflect, in a general sense, the physical soil moisture storage capacities of the catchments.

Figure 3.2d summarizes the results for the soil moisture zone to which the model performance was most sensitive in each study catchment. Because of the differences in the geologic and hydrologic characteristics of the study catchments, the particular subsurface zone varies by catchment. For this reason, for comparisons between catchments, emphasis is placed on the relative values.

There are few distinctive trends observed between the basins, but some general climate-related changes in most of the catchments can be seen. Some of the generalizations that follow do not apply to the McCloud catchment, which behaves differently than the others because of its extremely large soil moisture storage capacity. The warmer and generally wetter climates predicted by the GCMs cause increased rainfall relative to snowfall, making more moisture available during winter and early spring, at the expense of late spring and summer. Therefore, there is a definite phase shift in practically all storages (see Figs. 3.2d and A.2a-d). This trend is stronger among the free water zones than the tension zones, and during summers than winters. In addition, Cases 1 and 2 exhibit larger phase shifts than Cases 3 and 4 since temperature and precipitation changes for the former are higher.

The moisture content of the upper tension zone (Fig. B.2b) is virtually unaffected by climate change during the wet October-March period because it has the first priority to absorb moisture and has small capacity (usually less than 2 inches). It is filled in all the climate scenarios. During the spring and early summer, the decrease in snowmelt gives rise to more severe moisture shortages, which are reflected in reduction of tension water storage. Because Cases 1 and 2 reflect the greatest warming, they result in larger phase shifts than Cases 3 and 4. The lower tension zone (Fig. B.2c), which is supplied after its upper counterpart, shows larger phase shifts than the upper tension zones, in particular during the October-March period. This is partly because after supplying the upper zone, the net moisture available is reduced. Moreover, partly due to the generally larger capacities of the lower tension zones in all the catchments, the lower tension zones are more affected by the availability of moisture.

The free water zones' contents are influenced by climate change. Not only do they exhibit larger phase shifts, but the changes are also more erratic between basins and among the various cases. The upper free water zone (Fig. B.2a) shows larger fluctuations in moisture content than the lower zones (Figs. 3.2d and B.2d). The upper free water zones are comparatively more sensitive to modest changes in precipitation than are the other zones (Fig. 3.1), especially for Case 2 in the McCloud River catchment.

3.2 Sensitivity Scenarios

The sensitivity scenarios were undertaken for three purposes: 1) To determine the extent to which precipitation (as opposed to temperature) change drives the simulations for the various climate scenarios (Case 5); 2) to determine the relative effect of an interpretation of the GCM predictions that provides differential input to the southern (Merced) study catchment relative to the three northern study catchments (Case 6); and 3) to evaluate the general character of the hydrologic scenarios associated with the GCM predictions relative to the historic 1930's drought (Case 7). The first issue was addressed by using the GISS GCM predictions (Case 2) with the precipitation adjustment factors set to 1.0, but with the Case 2 temperature shifts retained (this formed the new Case 5). The second issue was addressed by assigning temperature shifts and precipitation factors associated with the GISS 2xCO2 model cell (Case 2) centered at 35.22°N, 120°W to the Merced River study catchment, and the GISS grid cell centered at 43.04°N, 120°W to the three northern study catchments (as opposed to an interpolated grid cell centered at 40.0°N, 120°W which was assigned to all study catchments in Cases 1-4). This formed the new Case 6. Case 7 was formed by computing the ratio of the average monthly precipitation for selected Northern California stations for the period 1931-40 to the long-term (1890-1980) precipitation at the same stations. Temperature shifts for the 1931-40 decade relative to the 1890-1980 means at the same stations were also computed. For each month, the median precipitation ratio, and temperature shift, were computed. These medians were used to define a climate scenario (Case 7) which was analogous to the GCM scenarios.

The figures that summarize the sensitivity scenarios have been placed in Appendix B (Figs. B.1c to B.1g). The interpretation of these results is summarized in Sections 3.2.1-3.2.4.

The Case 6 (geographic sensitivity to inputs) results showed that the hydrologic simulations were qualitatively the same (at least for the GISS model) regardless of whether the grid cells were interpolated as described in Chapter 2, or a nearest cell center approach was used. This result held for all variables (snow water equivalent, runoff, evapotranspiration, and soil moisture), as shown in Figures B.1c-B.1g. Therefore, Sections 3.2.2-3.2.4 are devoted to a discussion of the temperature sensitivity (Case 5) and 1930's analog (Case 7).

3.2.1 Snow Water Equivalent

The difference between Case 2 and Case 5 indicates the sensitivity of the snow water equivalent to GCM-predicted temperature changes only. There was relatively little difference in this respect between Case 2 and Case 5. This confirms the earlier interpretation of cases 1-4 that changes in winter snow accumulation were primarily temperature dependent. The Case 2 predicted temperature changes were quite large, hence there would be relatively little snow in any of the study catchments except the Merced River under the CO_2 doubling scenarios.

The Case 7 (1930's analog) results emphasize how different the 1930's conditions were from the GCM predictions; under these conditions the simulated snow water equivalents were slightly less than the base case, but were much larger than any of the GCM climate scenarios. This reflects the fact that the 1930's drought was caused primarily by a reduction in precipitation; winter temperatures were relatively little changed from the base case.

3.2.2 Runoff

For the precipitation sensitivity scenario (Case 5), the Merced River had lower mean monthly flows and standard deviations (Figs. B.1d and B.1e) due to the reduction in winter rainfall relative to Case 2, but the phase shift in runoff was more or less the same. This is no surprise because temperature, which determines whether precipitation occurred as rainfall or as snowfall, was the same as in Case 2. Case 7 represents the precipitation and temperature analog of the relatively dry decade of 1930's. For Case 7, the temperature change was minor relative to the base case, an increase of less than 1°C. Therefore, the seasonal distribution of runoff was comparable to the base case. However, all the months had lower flows and standard deviations (Fig. B.1e). This reflects the dry conditions (most precipitation factors less than 1.0) experienced in the 1930's.

For the North Fork American River, the November to March flows (mean and standard deviations) were significantly lower in Case 5 than in Case 2. Due to minimal changes in temperature, Case 7 had a similar mix of rainfall runoff and snowmelt runoff as the base case. Comparisons between Figures B.1d and B.1e show that the changes in runoff variability (standard deviations) were generally larger than the changes in runoff volumes for the 1930's analog.

The Thomes Creek responses for Cases 5 and 7 showed qualitatively similar patterns to those observed for the North Fork of the American River. This is to be expected because the hydrologies of these catchments are somewhat similar.

The McCloud River simulations showed more marked impact of the reduced precipitation in Case 5 relative to Case 2. On average, runoff occurred earlier, with increased ET and reduced soil moisture contents. The groundwater recession began about two months earlier. The change in standard deviation for these cases is shown in Figure B.1e. Again, the McCloud catchment behaved somewhat differently than the other four catchments; the Case 5 results show that the interaction of changed temperature and precipitation was stronger in this catchment than in the other three. This is primarily a result of the damped storm response, which heightened the importance of between-storm dynamics.

3.2.3 Evapotranspiration

The Merced River (Fig. B.1g) is the only catchment for which there was any substantial change in ET for Case 5 compared to Case 2. This can be traced to the greater importance of snow water storage in this catchment under the alternative (warmer) climates. Reduction of precipitation in Case 5, relative to Case 2, reduced the average snowpack, and in consequence the spring and summer soil moisture. The amount of moisture available for meeting the daily ET demands was relatively unaffected by reductions in moisture supply, until the tension water storages were reduced to near zero. This was the case only for the Merced catchment. For the three catchments which are rainfall-driven in the warmer climate scenarios, ET was relatively little affected by the Case 5 reduction in winter precipitation.

For Case 7 (1930's analog) there was a slight phase shift in Case 7 ET for all the basins relative to the base case. The shift patterns was similar for all the study catchments. The 1930's analog climate had little effect on the mean ET except during summers (June to September) when the soil moisture contents of tension zones are reduced to near zero.

3.2.4 Soil Moisture Storage

Comparisons of Figures B.2a, B.2d, B.2e and B.2h show that the more of the soil moisture reduction associated with the reduced precipitation in Cases 5 and 7 came from the upper free water zone than the lower free water zones in both Cases 5 and 7. The McCloud catchment, however, had a much larger secondary free water capacity in the lower zone than the other study catchments (about ten inches storage capacity) to maintain its high baseflow. Therefore the reduction in precipitation in both Cases 5 and 7, gave rise to relatively higher reductions in moisture storages in the McCloud River than in the other catchments (Fig. B.2h).

Generally, the lower free primary zone had larger capacities than the secondary zone. The moisture content of the McCloud catchment was as high as forty inches, while the maxima for the other catchments were in the vicinity of only three inches. For both lower free zones, the phase shifts during summers and early autumns were more consistent than the other seasons because these seasons experience larger changes in moisture supply.

3.3 Spatial Disaggregation: Primary Nodes

Section 2.4.3 described the spatial disaggregation model used to generate monthly streamflows at the six primary sites given in Table 2.2. For the base case, the disaggregation model explicitly preserved the mean and variance of the flows at the primary nodes. Higher moments (e.g., skewness) were not preserved. The model also explicitly preserved the correlation between the sites in each month, but not the lagged correlation at a given site or between sites (for instance, the January correlations between node 1 and node 2 were preserved, but the January-February correlations at node 1 was not preserved). The model implicitly assumes that the statistical structure (moments) of the node flows relative to the catchment flows would remain the same under the alternative climates scenarios.

Figures 3.4a and B.3a show the monthly mean simulated flows for each of the six primary sites for Cases 0-4, and 5-7, respectively. These figures confirm that the disaggregated (primary node) flows were qualitatively consistent with those of the catchments (Figs. 3.2b). The phase shifts between various cases, as well as the high flows and low flows at the primary nodes, were generally comparable to those of the catchments. There was, of course, a substantial difference in runoff volumes, because the nodes represent much larger drainage areas than the catchments. For example, Site 2 (Sacramento River at Red bluff) had monthly runoff as high as 2.5×10^6 acre-feet, which is ten times higher than the highest study catchment mean flow. On a relative basis, however, the primary site annual runoff hydrographs were similar to those of the catchments.

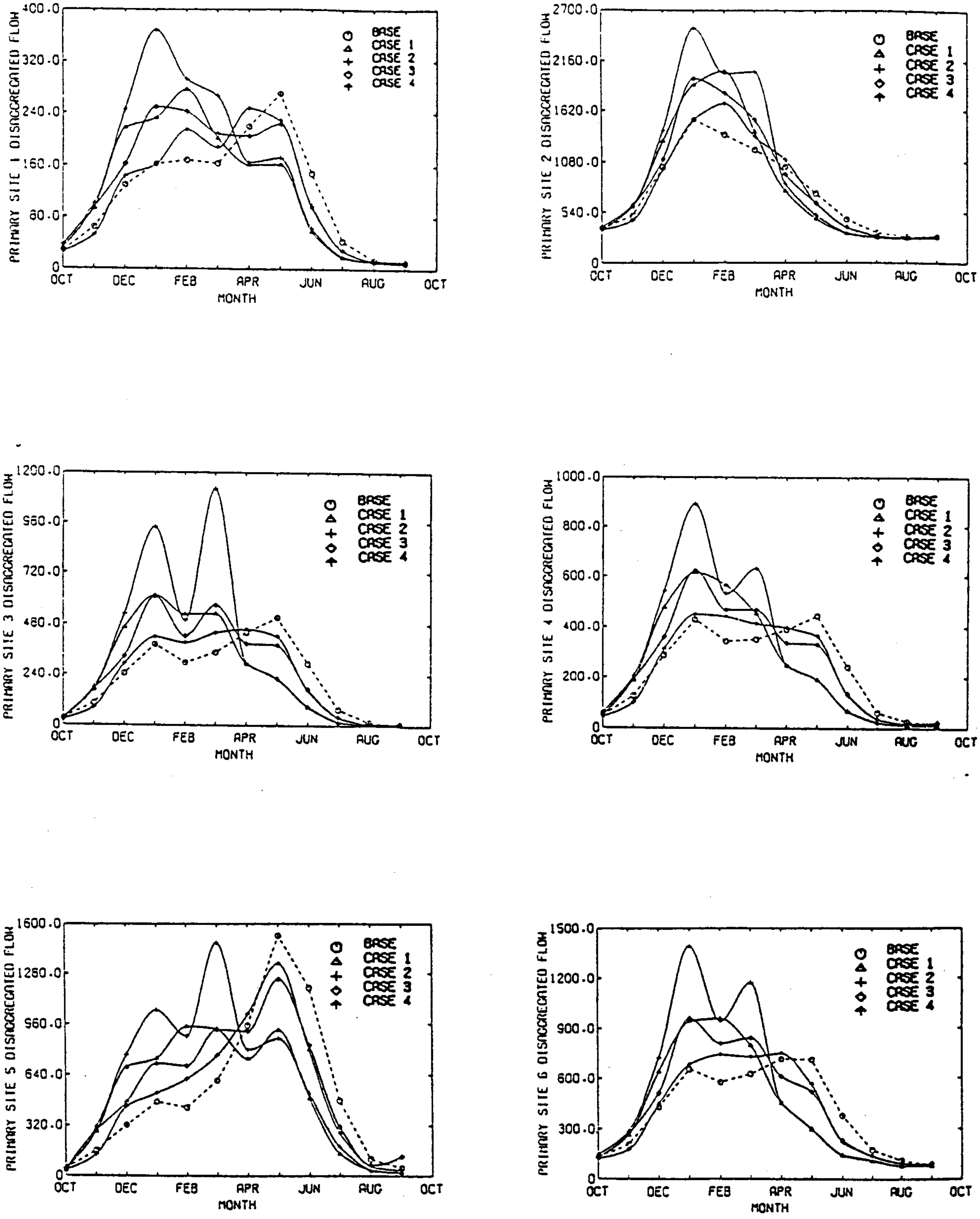


Figure 3.4a Water resource system primary node mean monthly flows for climate scenario Cases 0-4

3.4 Spatial Disaggregation: Secondary Nodes

The seven secondary nodes selected for this study are listed in Table 2.1. The secondary nodes generally represent smaller, lower elevation drainages than do the primary nodes. Because they lie at lower elevations, some of the secondary nodes have a large number of zero flows (and in some cases zero mean flow) in the historic record for the summer and fall months. Generally, the influence of the secondary site flows on the water resources management model described by Sheer and Randall (1988) is considerably less than that of the primary nodes. This consideration supported use of the simple regression model to simulate the secondary site flows conditioned on the (simulated) flow at a specified primary node (Eq. 2.4).

Figure 3.4b shows the mean simulated flows at the secondary sites for Cases 0-4. For those nodes where summer flows were nearly zero under the base condition, the net effect of the warmer climates was to increase the runoff in nearly every month. Because summer runoff was zero under the base case, no reduction was possible. Site 1 provides a good example of this effect. For those sites (for example, site 7) where there was some summer runoff for the base case, the change in the annual runoff hydrograph was more similar to those of the study catchments and the primary nodes. In Cases 1-4, the simulated increase in winter runoff exceeded the decrease in summer and fall. Figure B.3b shows similar results for Cases 5-7. Case 7 (1930's analog) showed the expected reduction in the mean flows during the winter months. This is the only case in which there was a significant reduction in the secondary site flows.

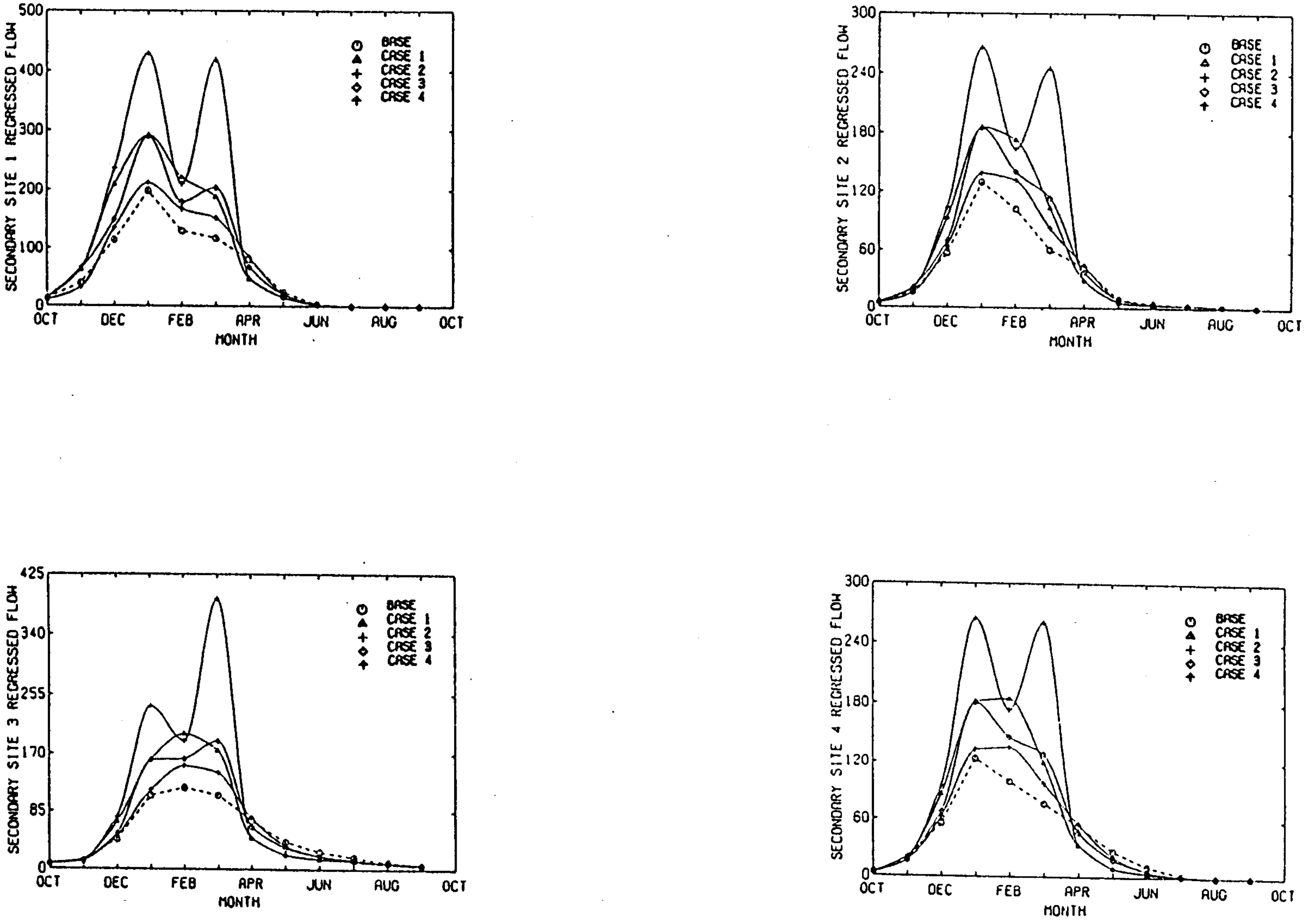


Figure 3.4b   Water resource system secondary node mean monthly streamflow for climate scenario Cases 0-4

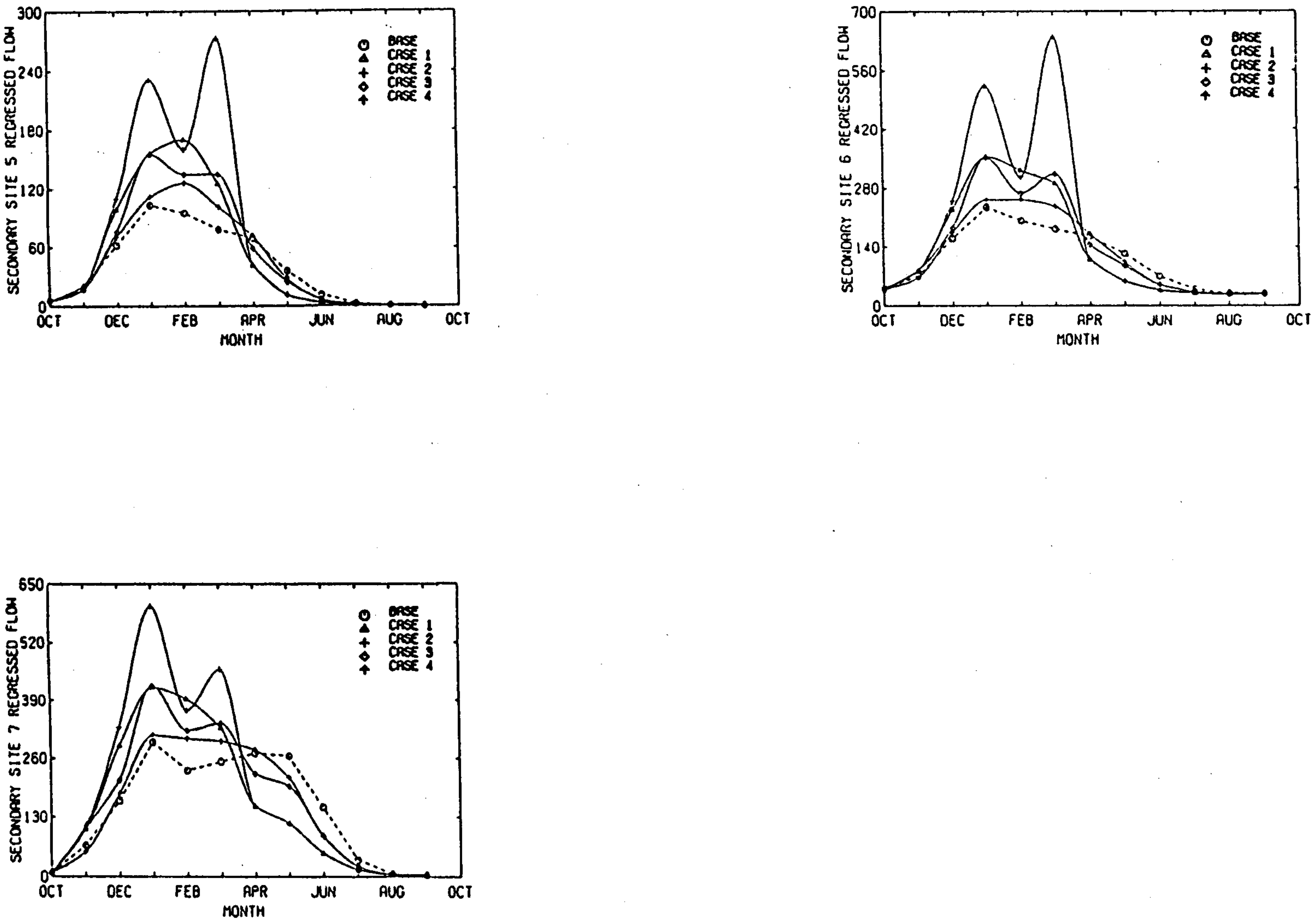


Figure 3.4b (Continued)

CHAPTER 4: SUMMARY AND CONCLUSIONS

The primary objectives of this work were to develop a methodology to provide a descriptive interpretation of the hydrologic effects of global climate change as predicted by selected GCM's, and to apply the methodology to the Sacramento-San Joaquin basin as a case study. This study is preliminary; the simulation results discussed in Chapter 3 should be interpreted in a "what if?" and not a predictive sense. Furthermore, existing hydrologic models (in particular, the National Weather Service snowmelt and soil moisture accounting models) were used, and the assumptions and simplifications incorporated in the models are reflected in the results. The following assumptions were made either implicitly or explicitly:

1) The altered climate scenarios were identical to current climate except that all precipitation was adjusted by a factor equal to the ratio of the selected GCM average monthly precipitation to the base case average monthly precipitation, and temperatures were shifted by an amount equal to the difference between the selected GCM scenario and the base case. This has the following implications for the hydrologic simulations:

   - Hydrologic systems are strongly affected by the variability of the driving variables, as well as their mean. In the case of precipitation, adjustment by a fixed factor implies that the coefficient of variation (standard deviation divided by the mean) is the same for the altered climate scenarios as for the base case. For precipitation factors greater than one (as for Cases 1-4 in most of the winter months) this means that the standard deviation of the inputs will increase. This particular assumption regarding the form of the altered input affects the stochastic structure of the output, which may well have significant implications for water resources management.

   - The spatial variability of the inputs was assumed to be exactly the same as in the base case. The performance of large multiple site water resource systems, such as the California State Water Project and the Central Valley Project, can be strongly affected by the spatial correlation of streamflows. If streamflows at the different sites (rivers) are highly correlated, droughts are likely to occur simultaneously at all, or many sites. If the spatial correlation is less, and the storage locations are dispersed, the required storage will be smaller. It is unlikely that the spatial correlation of the inputs would remain the same under substantially warmer climates, but the GCM grid spacing is too coarse to allow alternative inferences to be made at present.

- The precipitation arrival process (that is, the probabilistic structure of wet and dry day sequences) was assumed to be unchanged from the historic record. While the GCM's provide precipitation predictions at time scales of one day or less, the interpretation of these predictions in terms of point precipitation (as recorded at a precipitation gage) is difficult. The GCM's provide grid cell average values, but spatial averaging over an area the size of a grid cell removes most of the information regarding the point arrival processes. Further work is needed to verify the relationship of GCM predicted short-term precipitation to observable quantities (e.g., gage or gage-averaged precipitation corresponding to the base case). Changes in the precipitation arrival process affects catchment runoff response, even in the absence of changes in the longer term (e.g., monthly) statistics. For example, fewer storms of increased rainfall intensity, are likely to lead to increased runoff, reduced soil moisture, and decreased ET in the long run.

2) The hydrologic models provide an adequate description of the catchment dynamics under the altered climate.

Two major issues arise in this respect. The first regards the appropriateness of the hydrologic models to the base case. The National Weather Service River Forecast System, of which both the soil moisture accounting model and snowmelt model are part, has been widely used and verified operationally for a range of hydrologies. The soil moisture accounting model, in particular, was originally developed for use in the Sacramento basin. Although other hydrologic models might have been used, we believe the NWS models contain about the right level of detail for medium sized catchments, and can be expected to capture the essential elements of the long-term (as opposed to event) hydrologic response. The issue of applicability under alternative climate scenarios is more difficult to address. One major problem is that the soil moisture model cannot explicitly account for long-term changes in vegetation. At a minimum, the implicit assumption that the model relationship between PET and ET will hold in warmer climates needs to be verified. In the longer term, hydrologic models capable of simulating long-term runoff need to be explored.

3) The spatial disaggregation model provides an adequate description of the relationship between the study catchment flows and the flows at the water resource system nodes. Two key limitation related to the spatial disaggregation model must be considered:

- As described in Chapter 2, the spatial disaggregation model is unable to preserve the lagged correlations in the primary basin flows. Generally, the simulated primary basin flows for the alternative climate scenarios (including the base case) were found to have lower lag-one correlations, especially during the high runoff winter months, than the historic flows. This result is of concern because correlations affect the estimated reliability of the water resource system. These correlations do not affect any conclusions regarding the hydrologic response of the study catchments to the climate alternatives. The undersimulation of the lagged correlations is the result, in part, of groundwater inflow to the water resources system nodes that is not present in the higher elevation study catchments. Selection of a different set of catchments might allow use of a more complex disaggregation model (see Chapter 2), that could resolve this problem. However, it appears likely that none of the potential catchments would be strongly enough affected by groundwater in the winter months to allow feasible parameter estimates for this model. An alternative would be to model the groundwater effect directly. This would likely be a time-consuming undertaking. In terms of the relative importance of this problem, it is probably less than changes in the stochastic structure discussed below, or any of the issues relating to the hydrologic model discussed above. One reason for this is that the study design provided that comparisons be made with a base case, rather than historic streamflows; therefore the reduced winter correlations are evidenced in the base case, as well as the alternative climate scenarios.

- The structure of the stochastic relationship between the primary water resource system node streamflows and the study catchment flows is constant under the climate alternatives. One problem with this assumption is that the study catchments lie at high elevations and are affected by changes in snow accumulation patterns. Some of the contributing areas to the water resources system nodes lie at lower elevation, and are rain-affected under present conditions. Therefore, the effect on the water resources system nodes of a general warming would be different than in the catchments, resulting in a likely overestimation of the effect of the altered climate scenarios. Again, this problem affects only the water resource system node runoff predictions, and not the interpretation of the catchment results (Chapter 3). In addition, because the Sacramento-San Joaquin hydrology is snow-affected, the nodes that contribute most of the inflow to the water resource system will not be much affected by this problem. The problem is likely to be greatest for the low-lying secondary nodes, whose flows under the climate alternatives will likely be somewhat overestimated. Each of these assumptions, and the related limitations imposed, suggests a direction for future research.

Recognizing the preliminary nature of the work and the limitations imposed by the assumptions, the following general conclusions can be made:

- The general warming associated with all the GCM's would result in substantial decreases in average snow accumulations in all four of the study catchments;
- Reduction in the amount of precipitation occurring as snow would increase winter runoff, and decrease spring and summer runoff;
- Increased precipitation occurring as rainfall in the winter months would increase winter soil moisture storage, and would make more moisture available for ET in the early spring. Increased temperatures would increase spring ET;
- The reduction in moisture supply as snowmelt in the spring, coupled with increased spring ET, would reduce late spring, summer, and fall soil moisture, which would in turn reduce runoff during those periods;
- Although the above points suggest the general character of the changes that would occur under a general global warming, for any given catchment, the specific nature of the hydrologic change would depend on physiographic characteristics (notably, the area-elevation distribution) of the catchment, as well as the geologic and topographic features which control the precipitation-runoff response. Substantial hydrologic diversity existed between catchments, especially the McCloud River, which drains an area of deep volcanic ash in the vicinity of Mount Shasta, and has exceptionally persistent baseflow.

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APPENDIX A: STUDY CATCHMENT MAPS

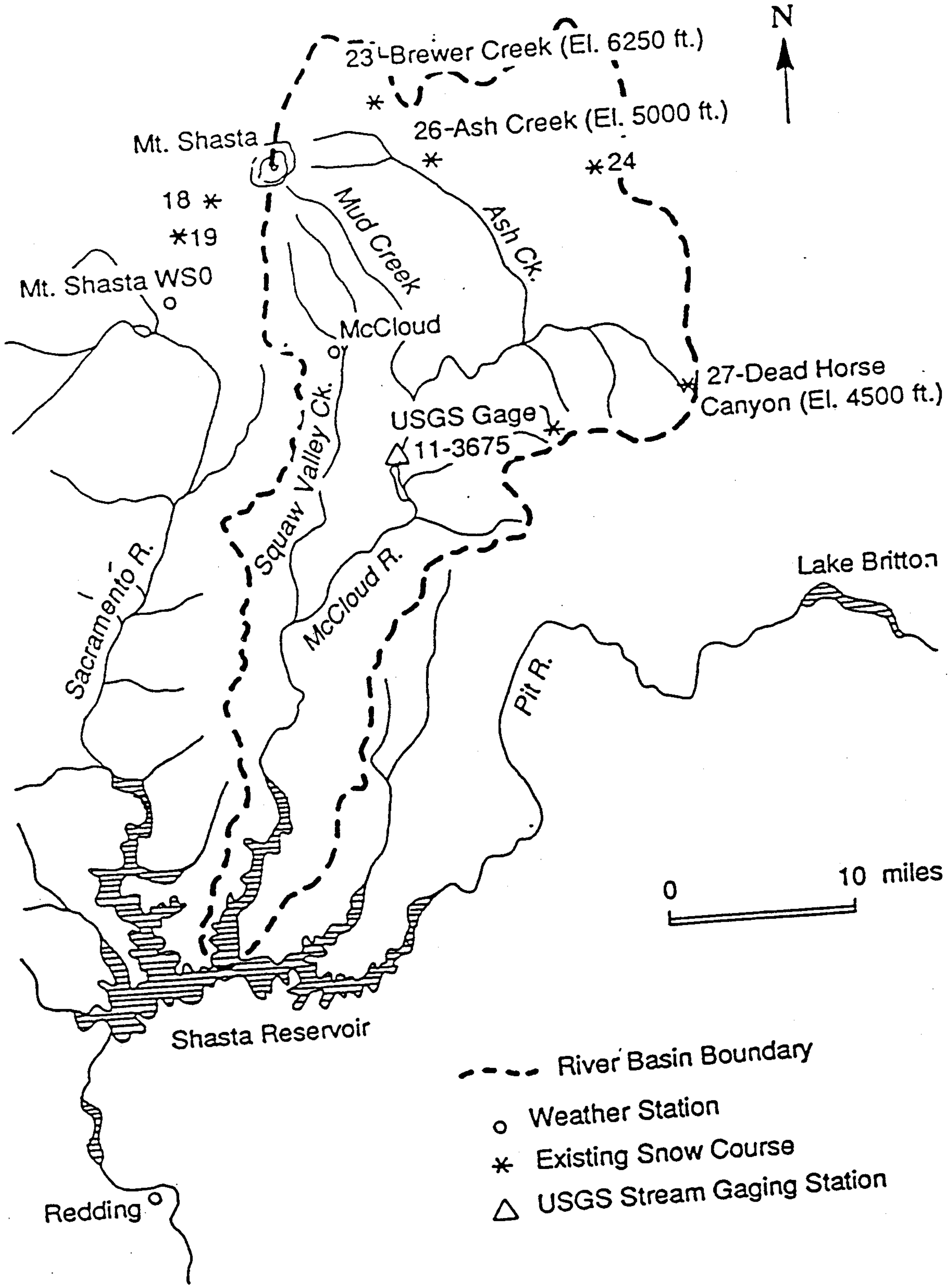


Figure A.1 McCloud River Basin study catchment

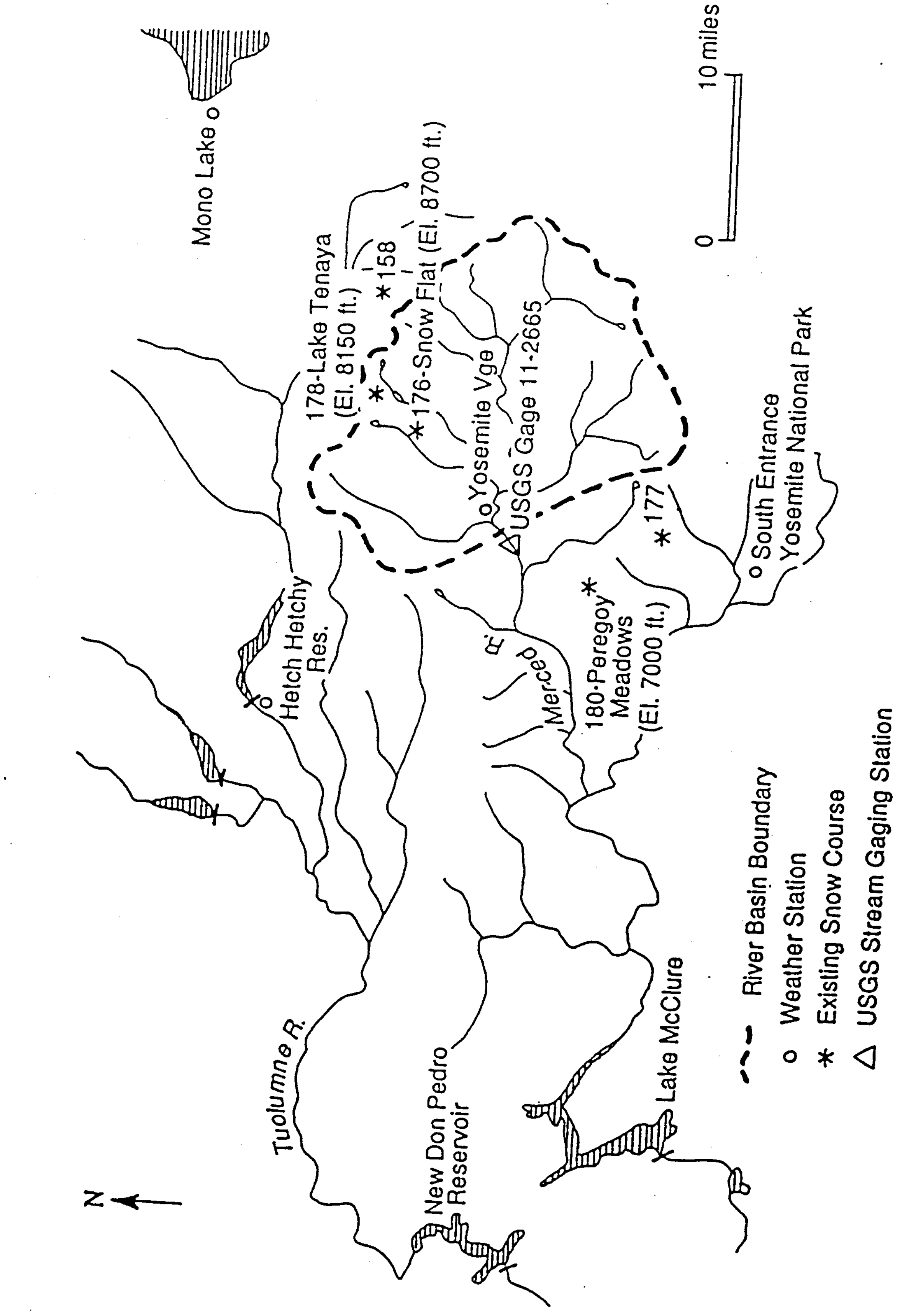


Figure A.2 Merced River Basin study catchment

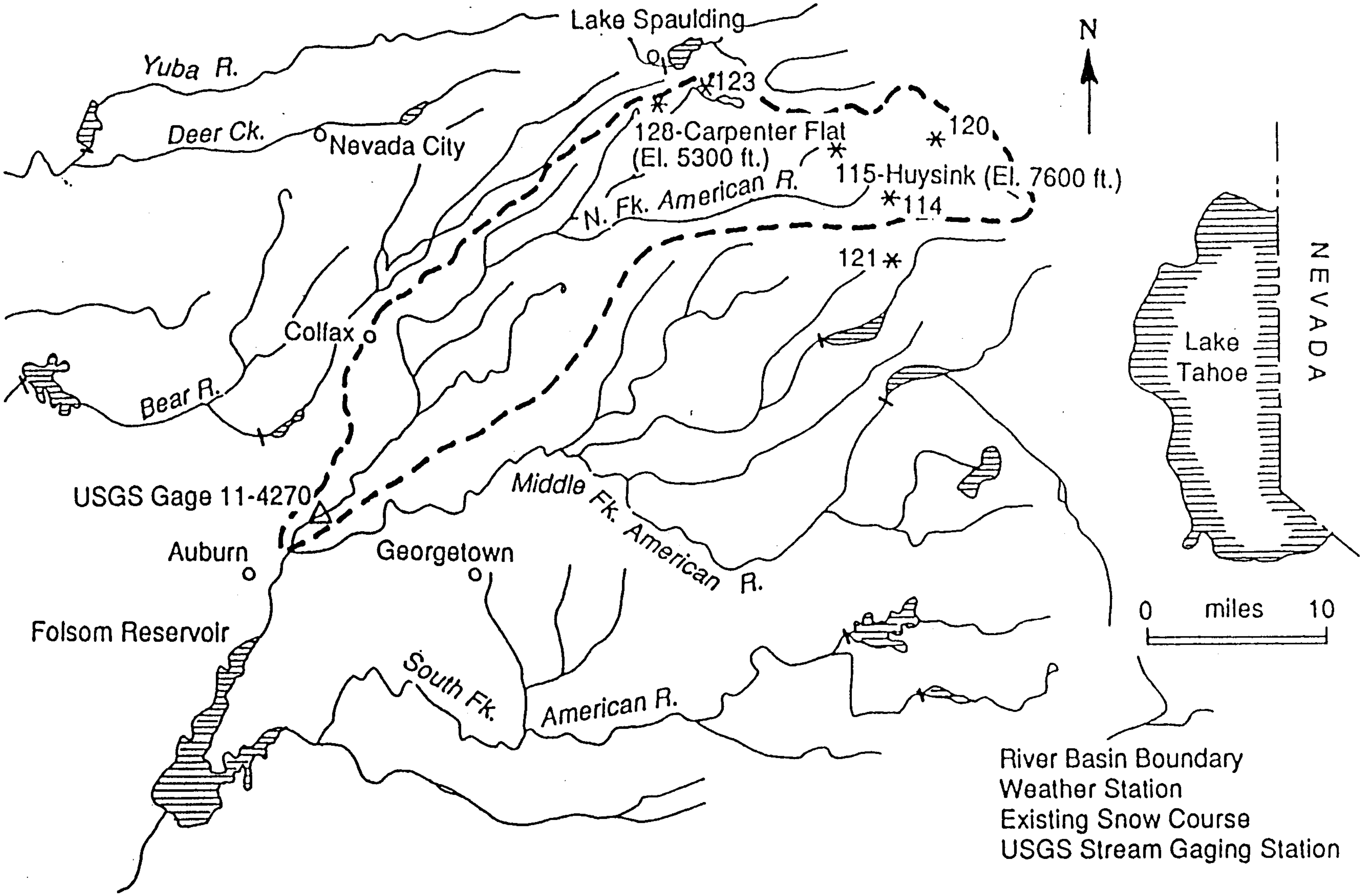


Figure A.3 American River Basin study catchment

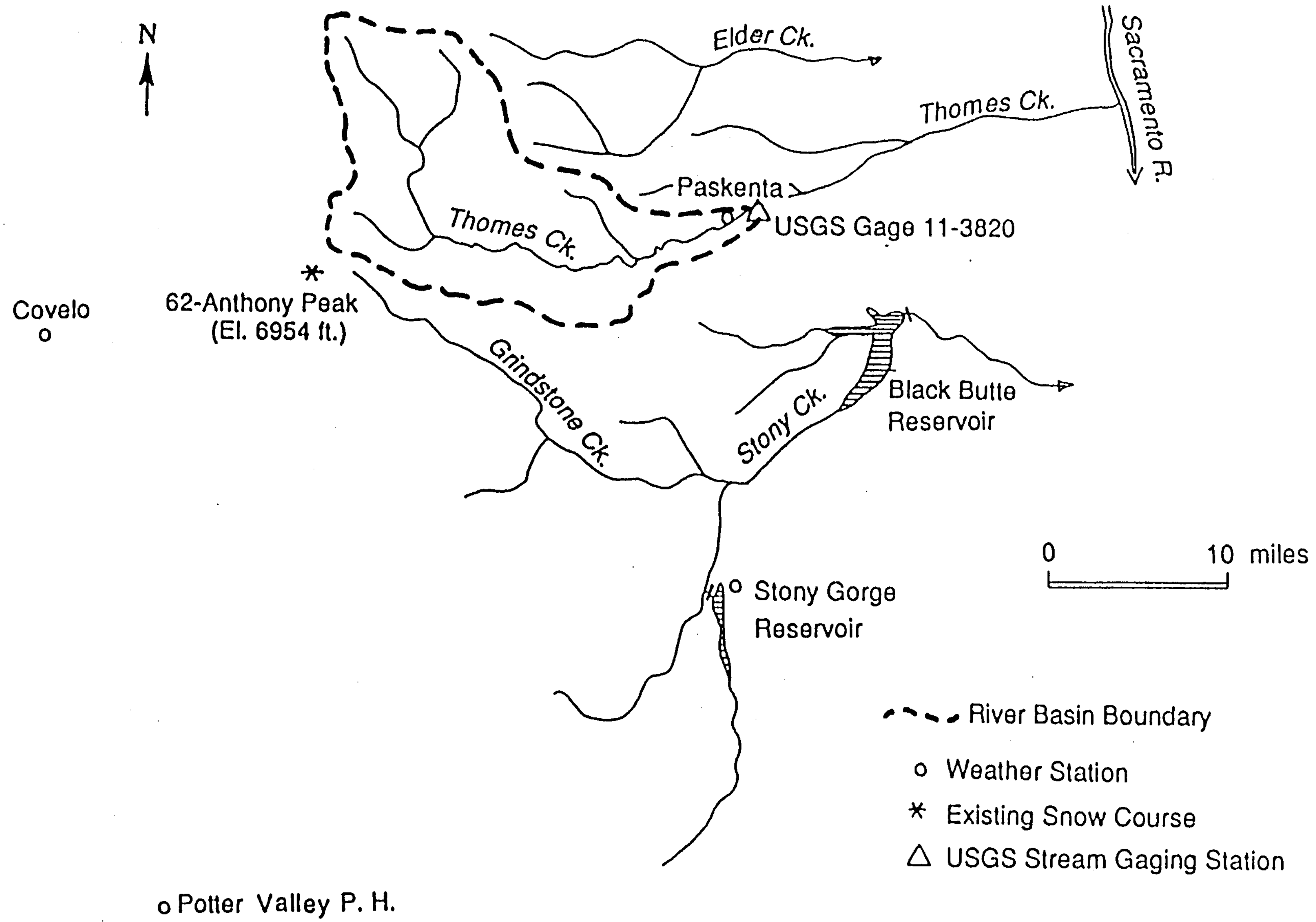


Figure A.4 Thomes Creek Basin study catchment

APPENDIX B: SUPPLEMENTAL RESULTS

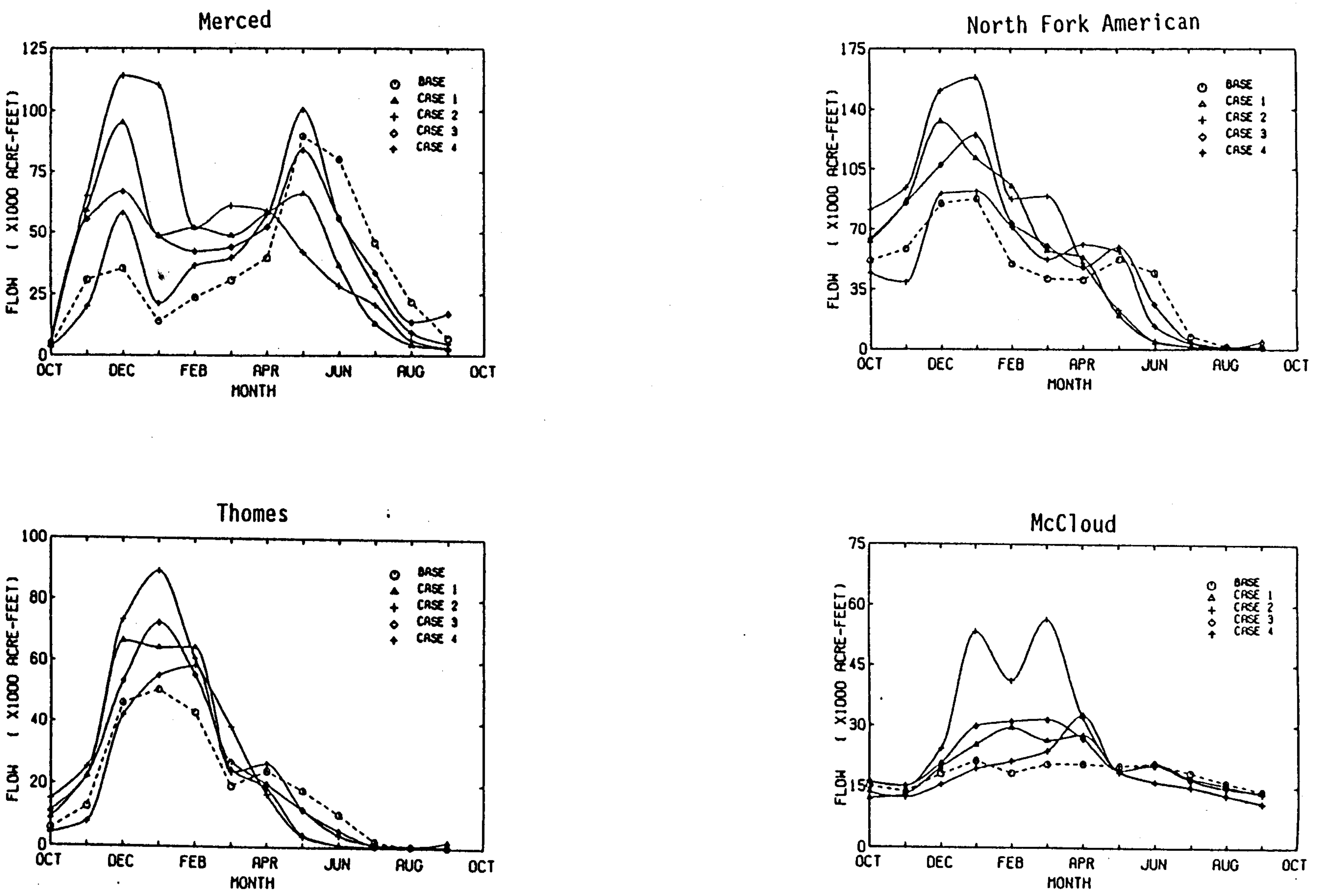


Figure B.1a Study catchment streamflow standard deviations for climate scenario Cases 0-4

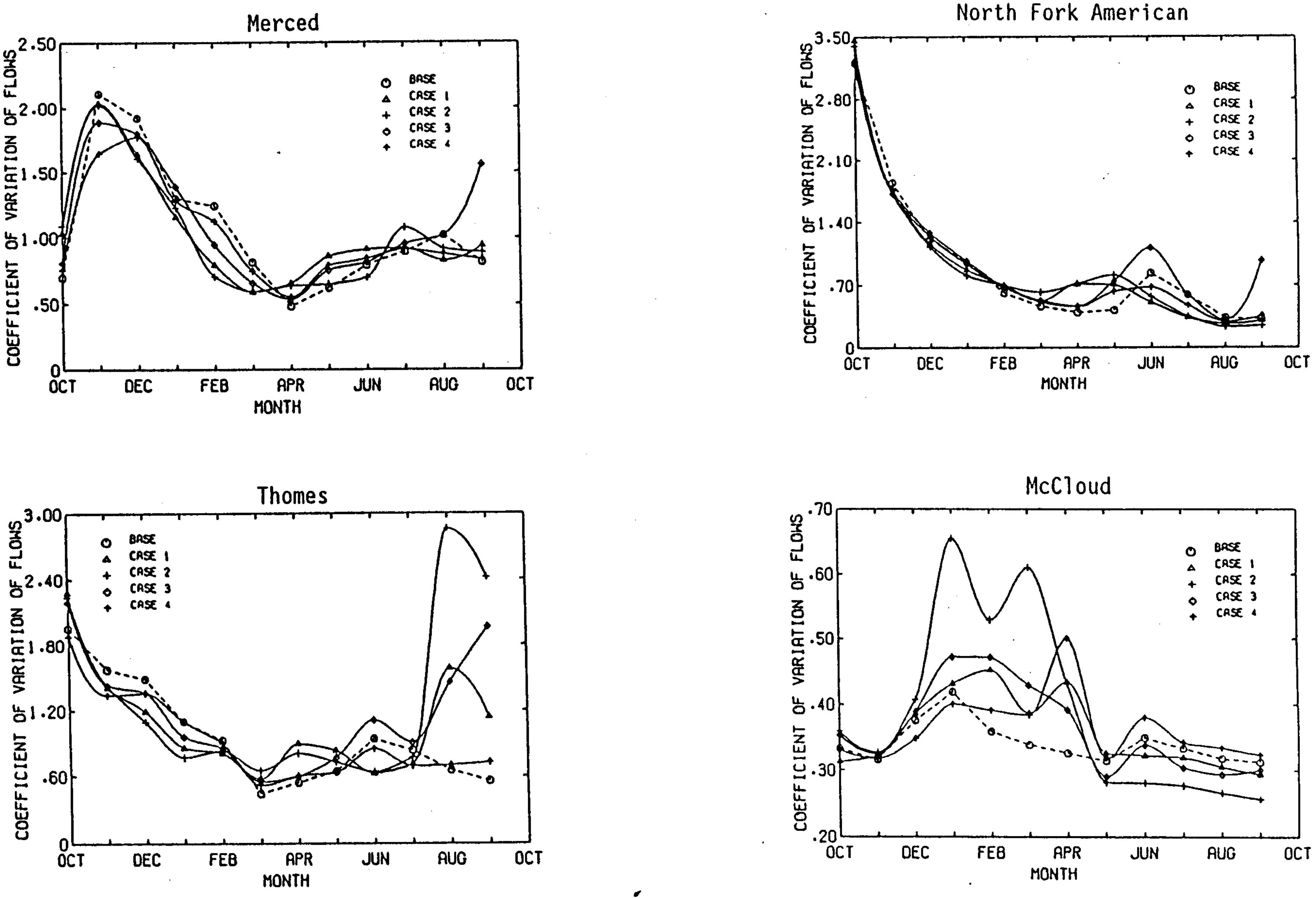


Figure B.1b Study catchment streamflow coefficients of variation for climate scenario Cases 0-4

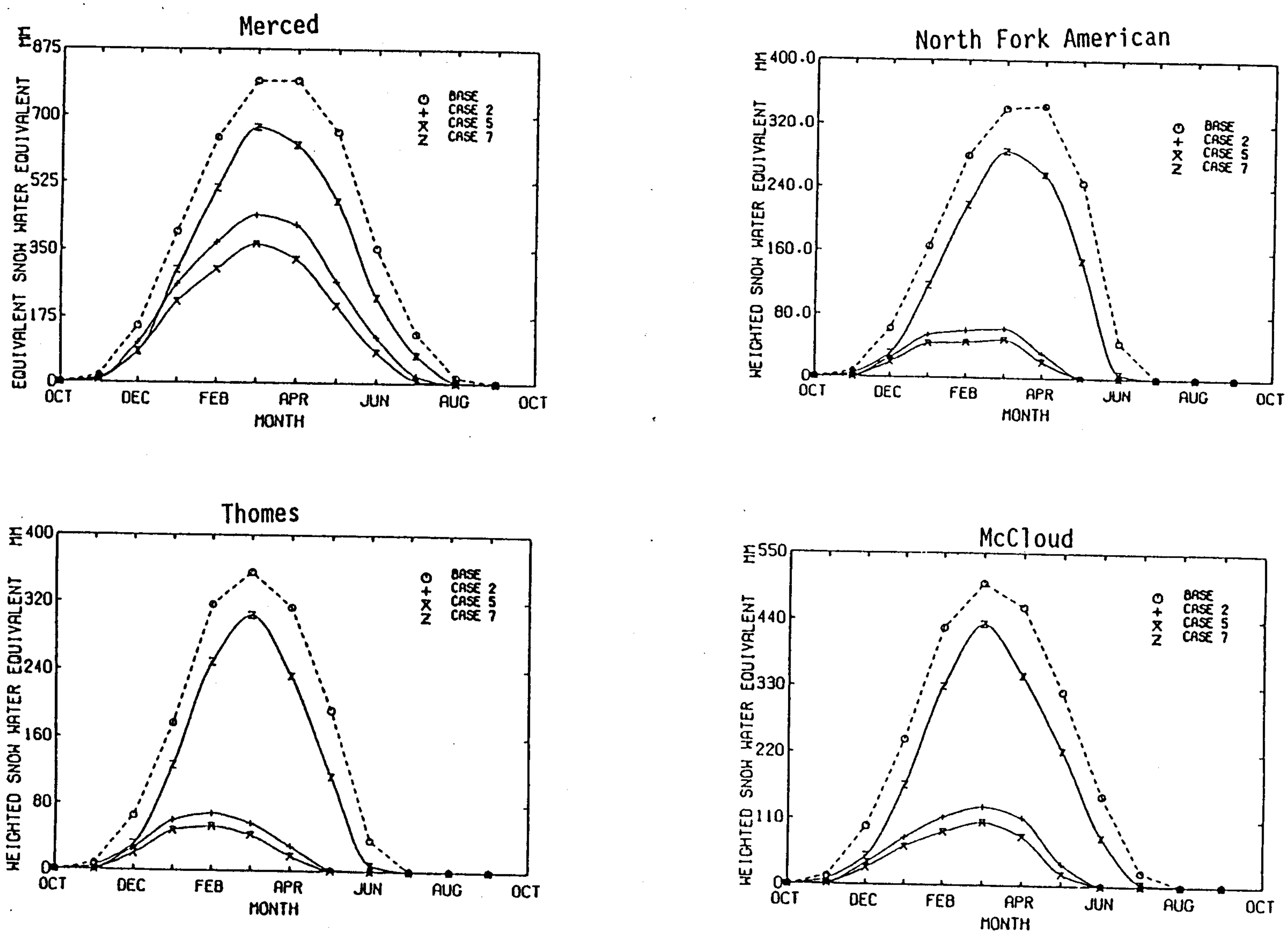


Figure B.1c Study catchment monthly mean weighted snow water equivalents for climate scenario Cases 5-7

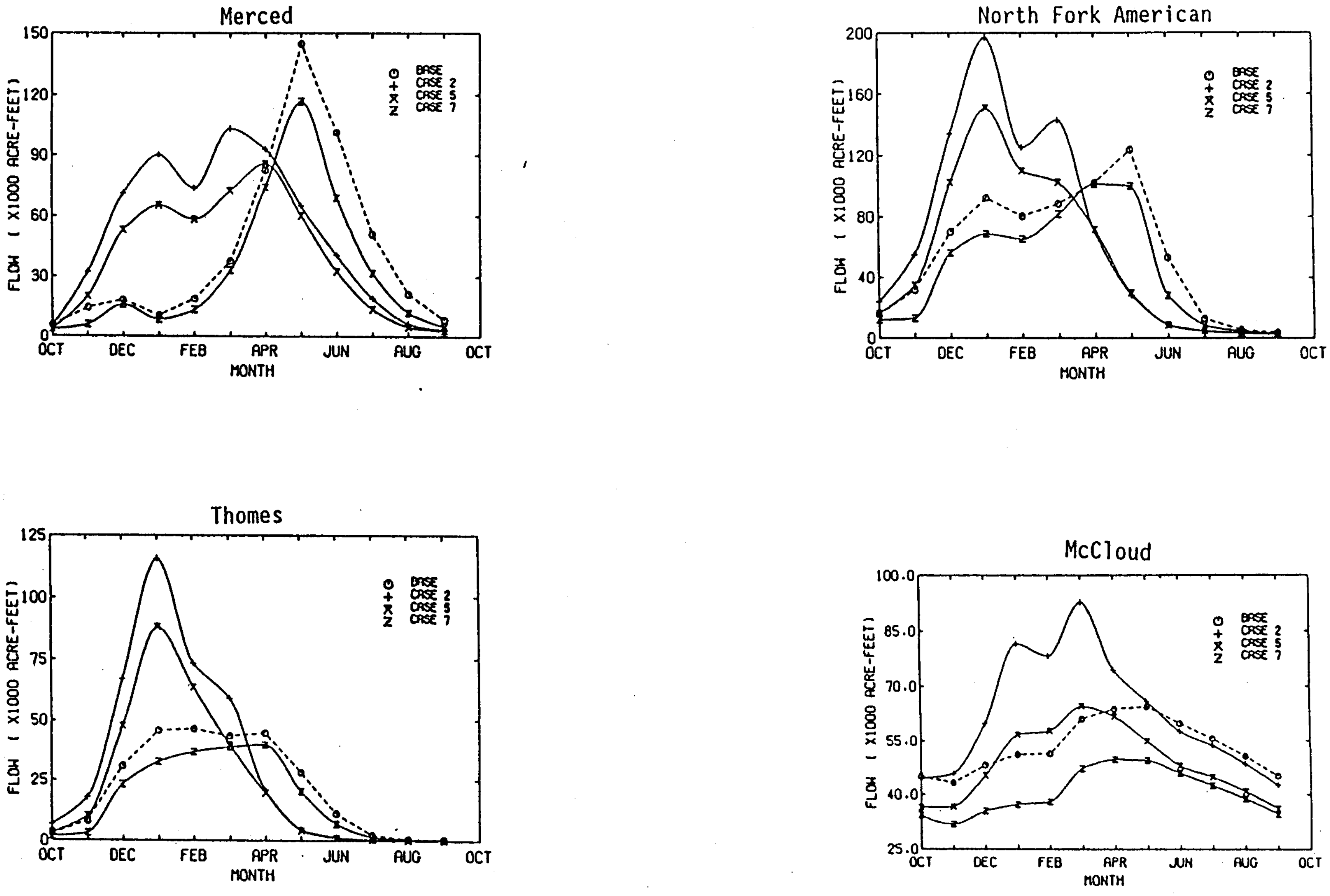


Figure B.1d Study catchment mean monthly streamflow for climate scenario Cases 5-7

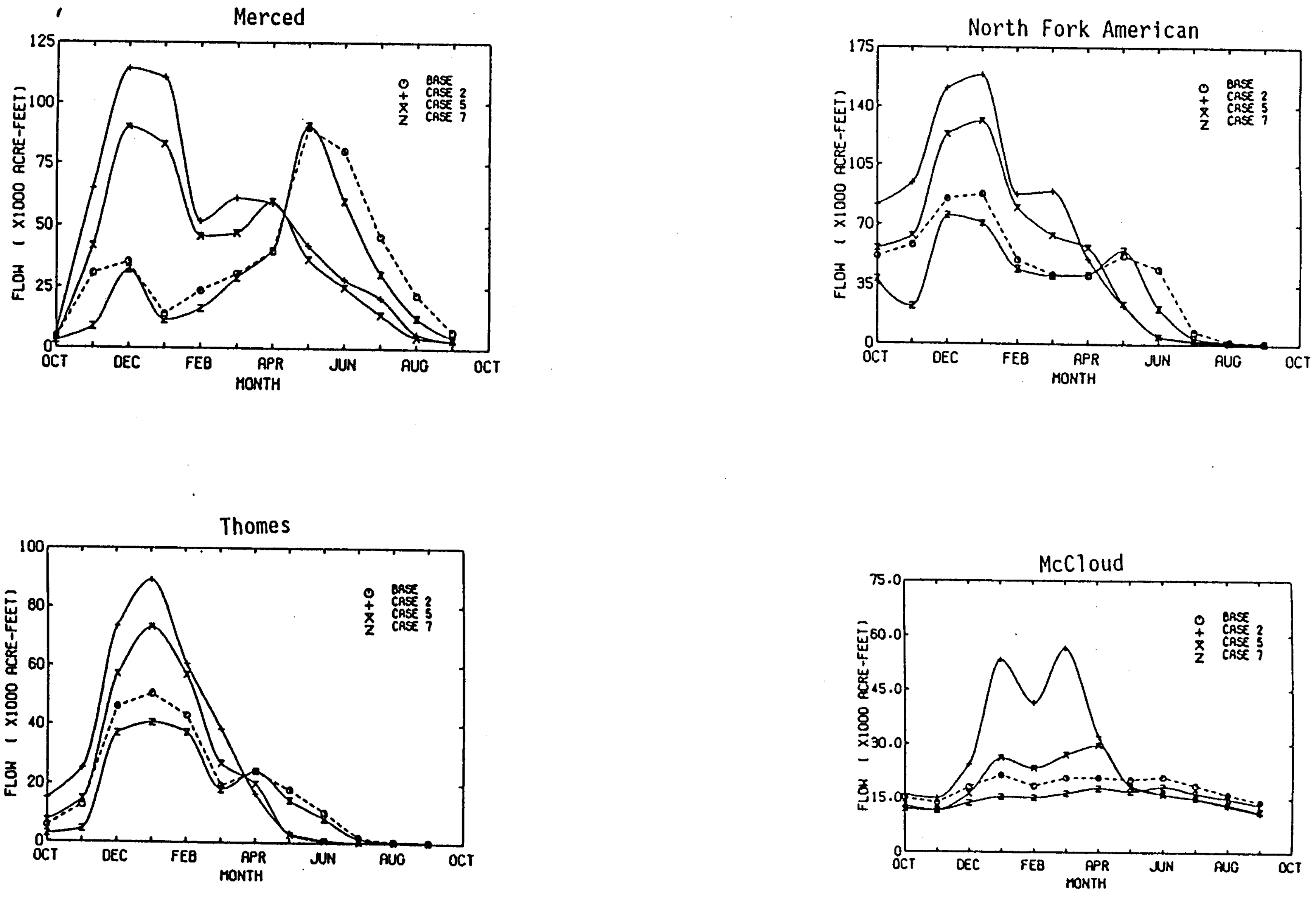


Figure B.1e Study catchment monthly streamflow standard deviation for climate scenario Cases 5-7

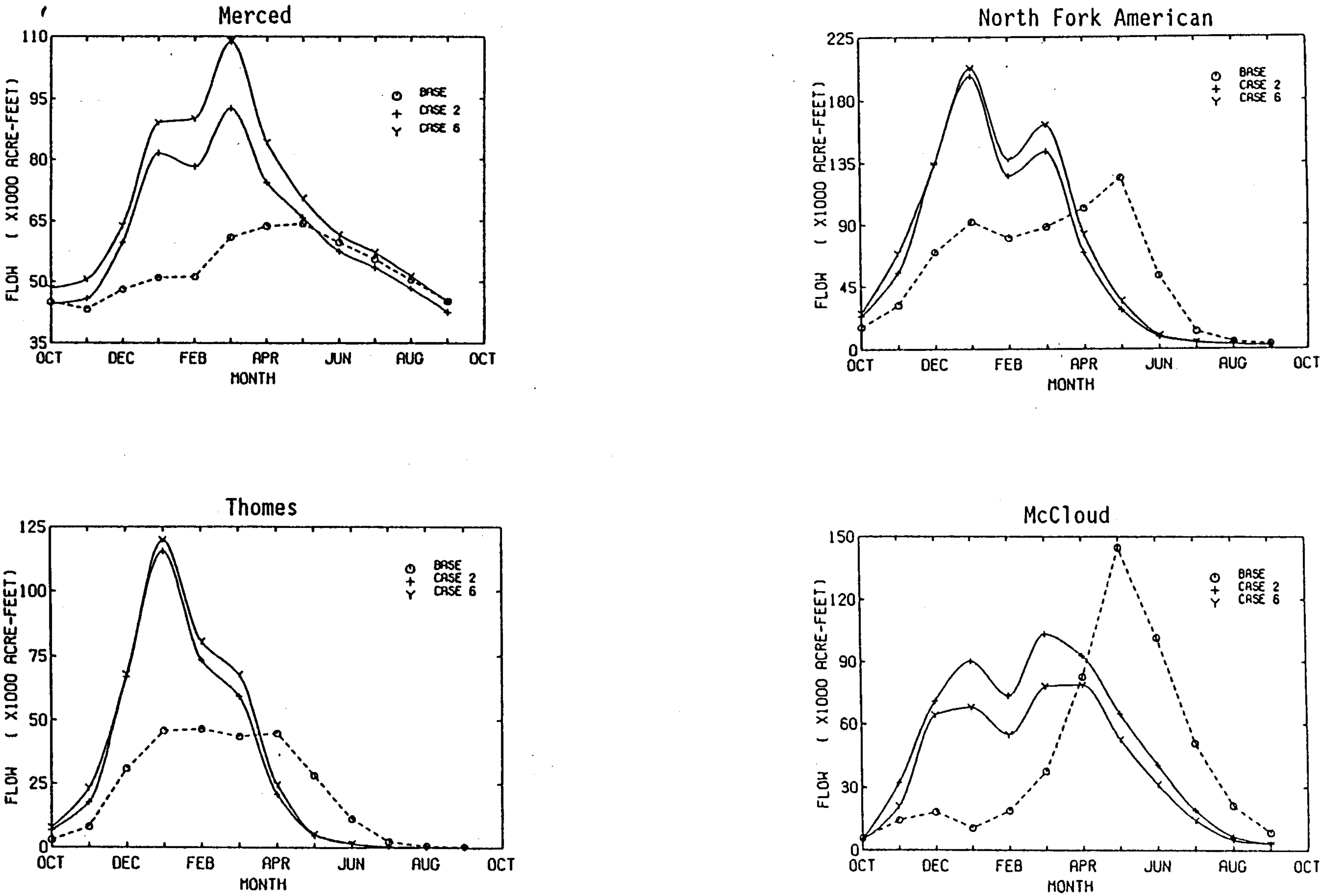


Figure B.1f Mean monthly study catchment streamflow for climate scenario Cases 0, 2, and 6

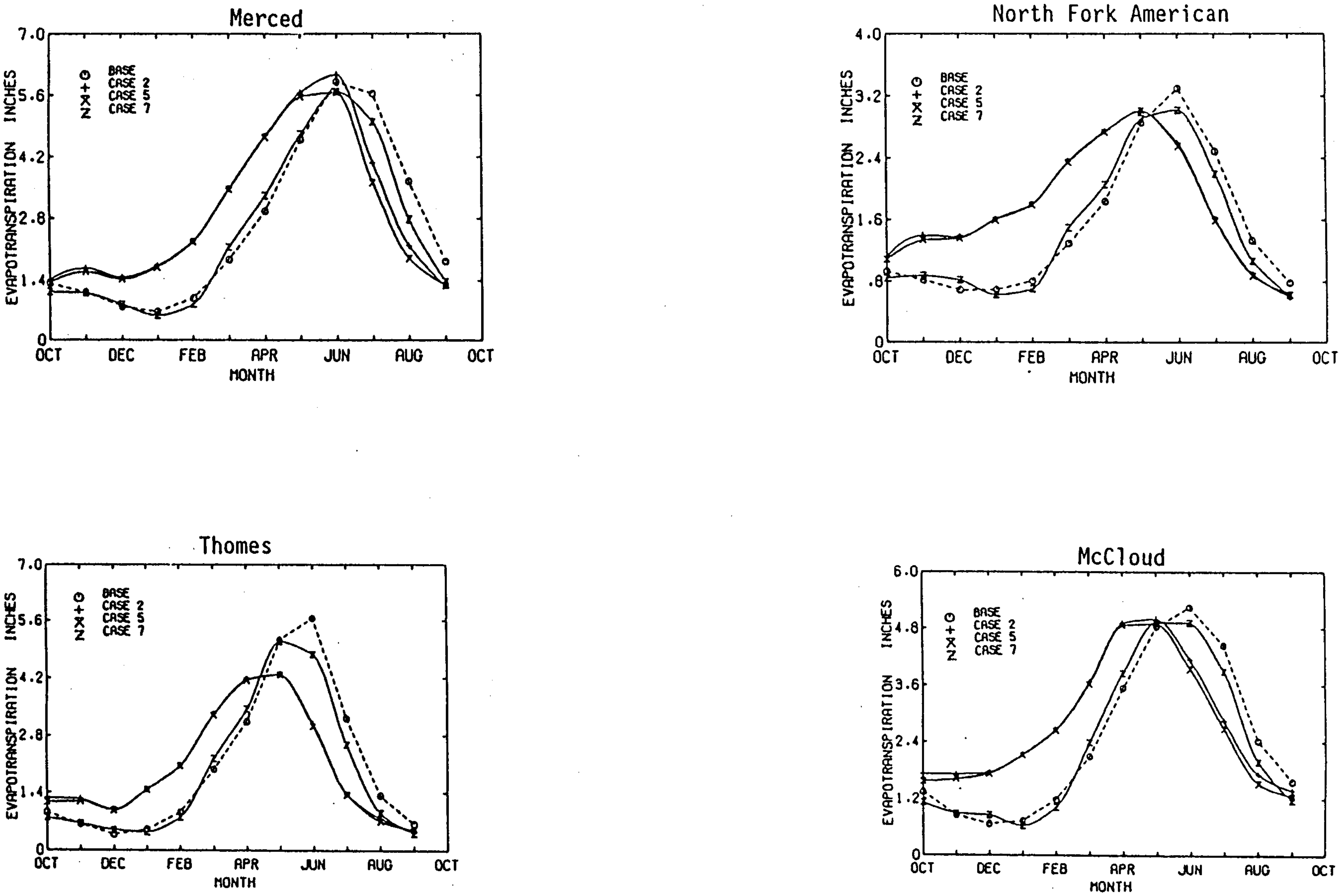


Figure B.1g Study catchment mean monthly evapotranspiration for climate scenario Cases 0, 2, 5, and 7

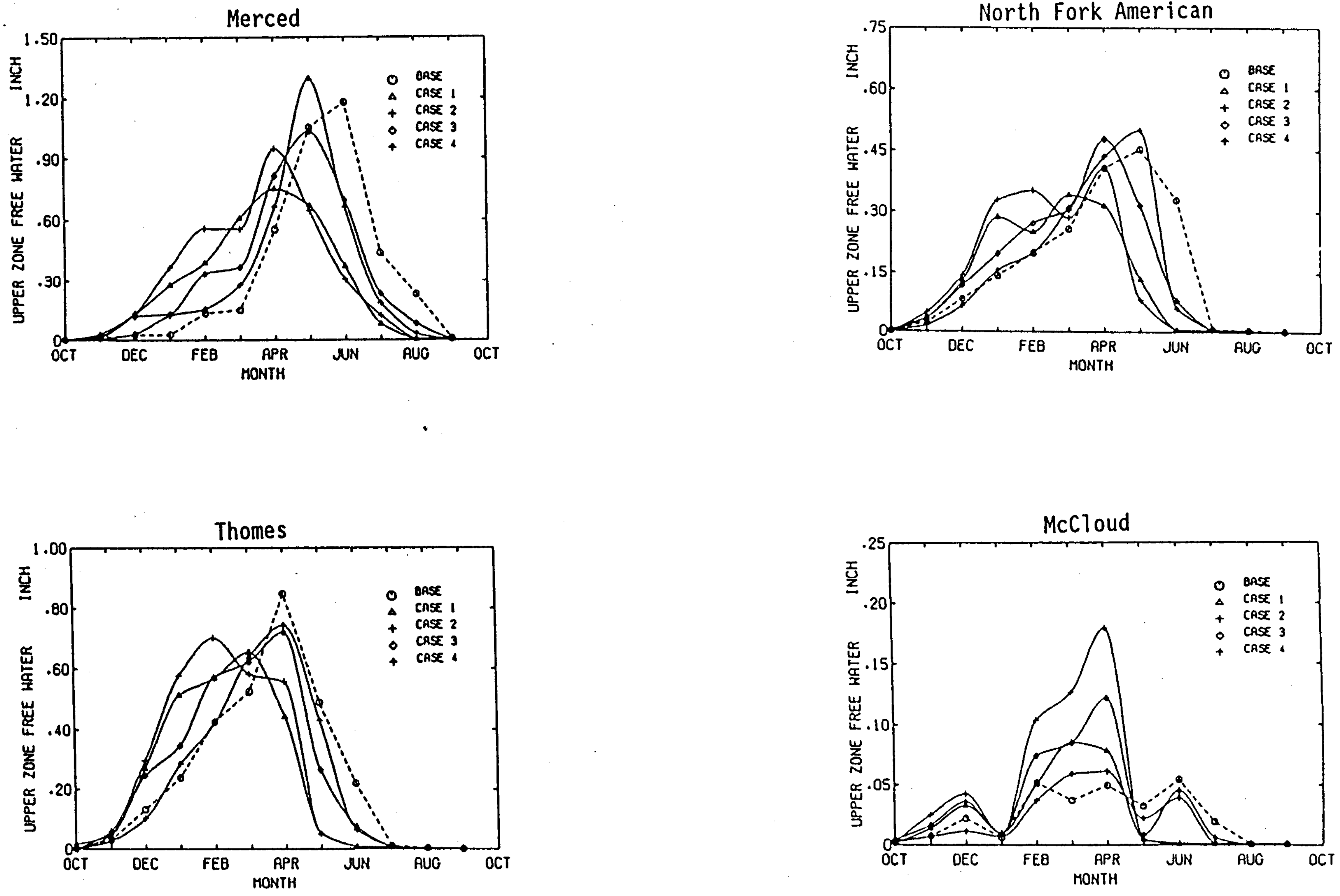


Figure B.2a Study catchment monthly mean upper zone free water for climate scenario Cases 0-4

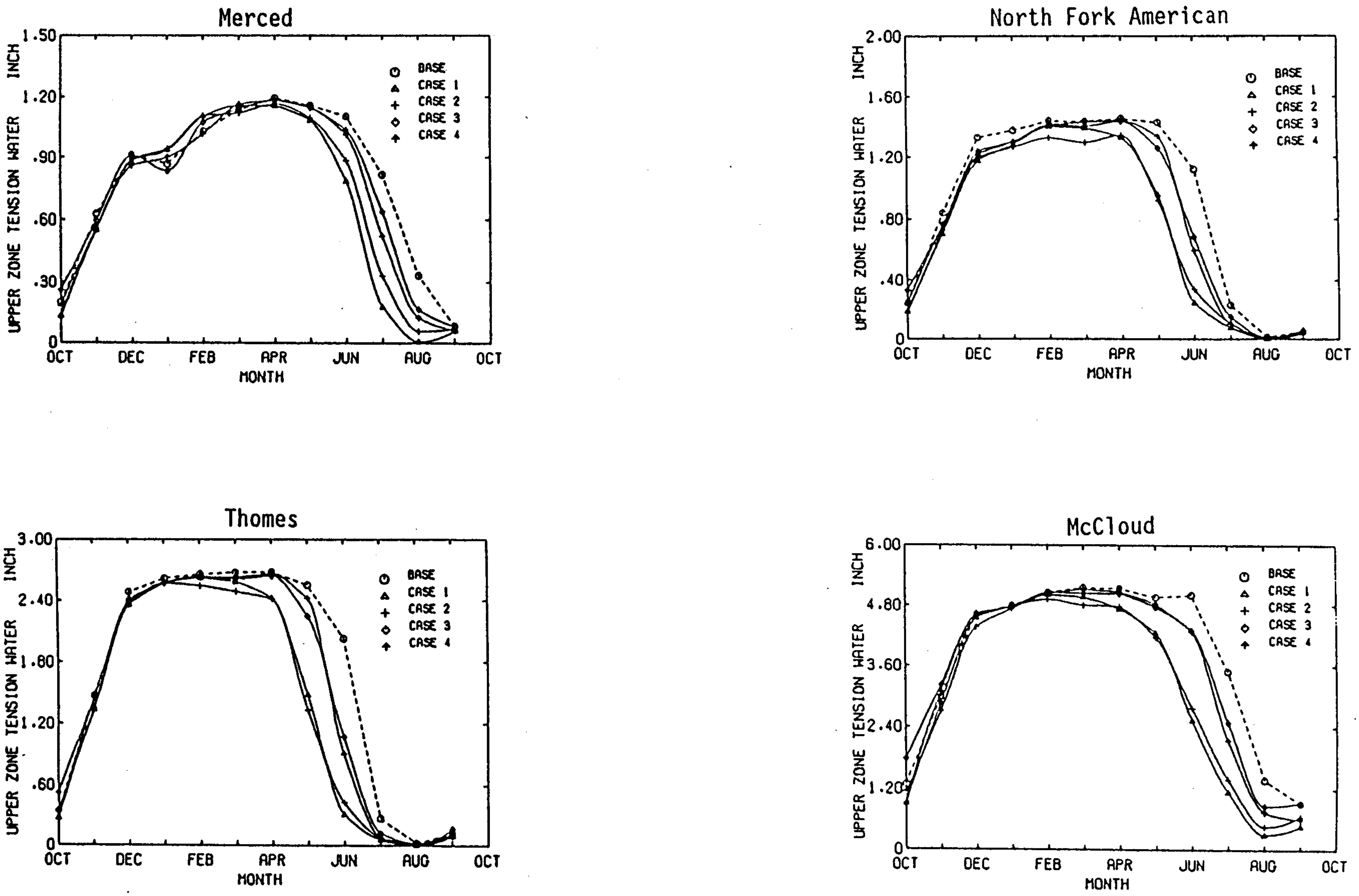


Figure B.2b Study catchment monthly mean upper zone tension water for climate scenario Cases 0-4

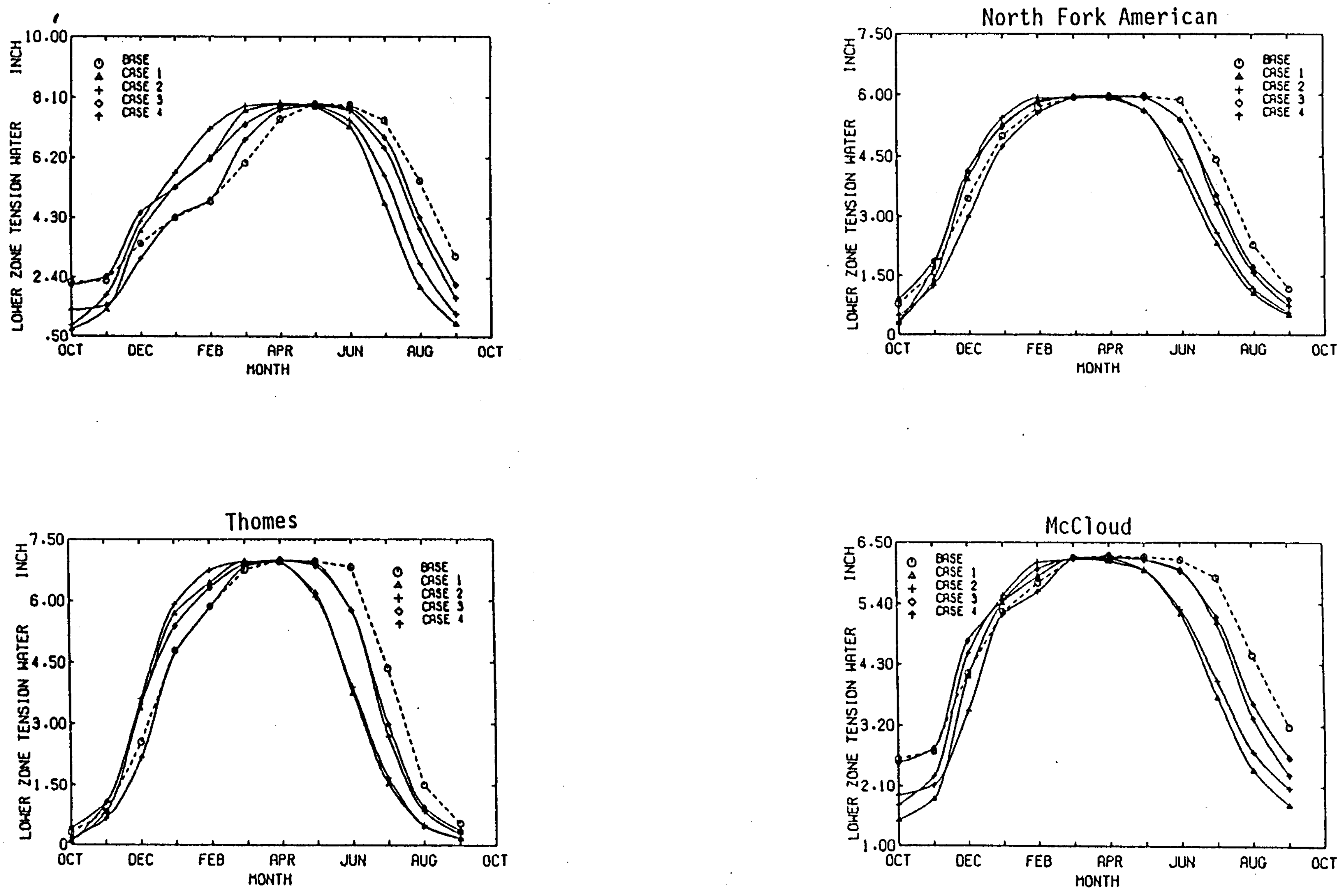


Figure B.2c Study catchment monthly mean lower zone tension water for climate scenario Cases 0-4

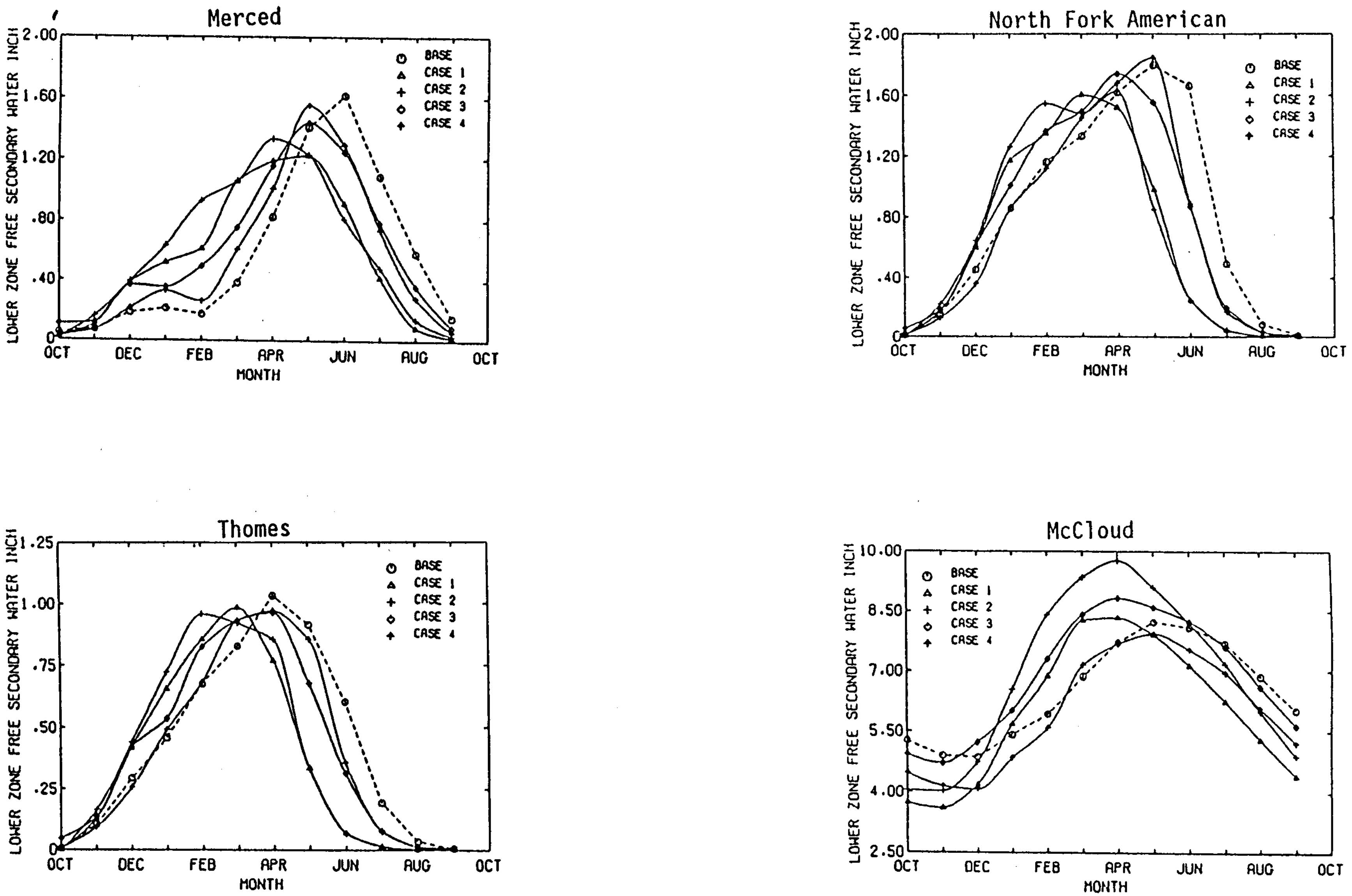


Figure B.2d Study catchment monthly mean lower zone free secondary water for climate scenario Cases 0-4

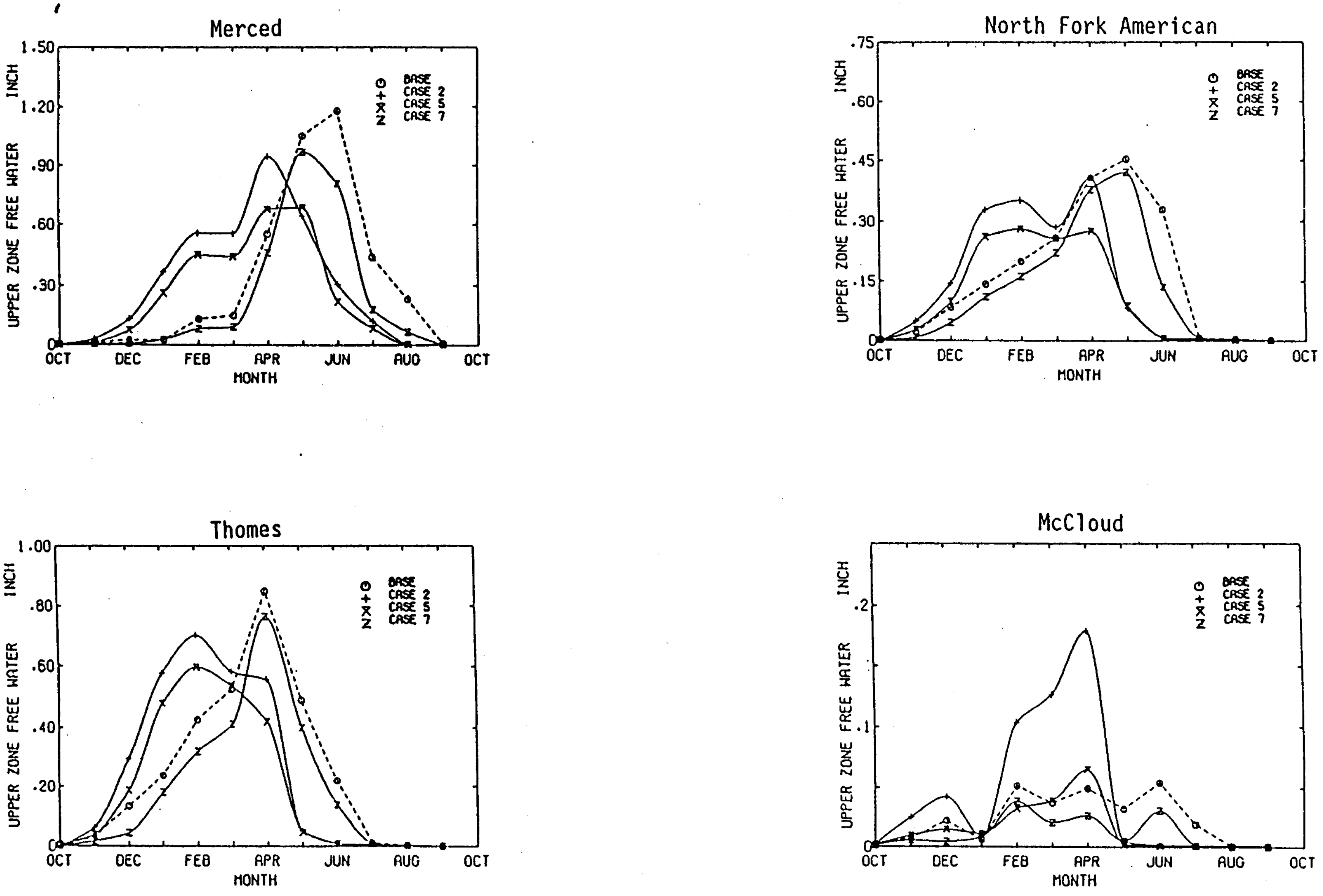
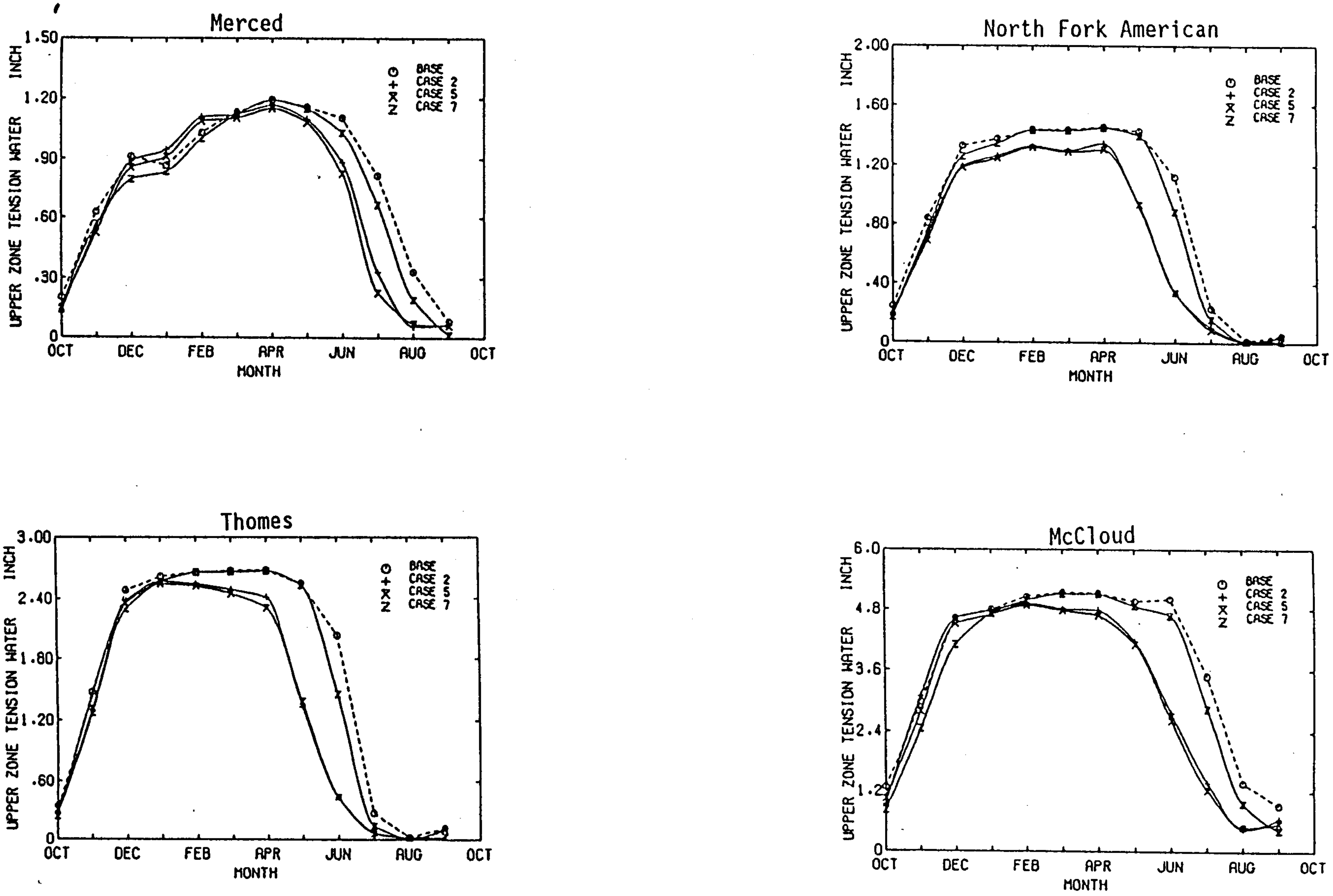


Figure B.2e Study catchment monthly mean upper zone free water for climate scenario Cases 0, 2, 5, and 7



Merced

North Fork American

Thomes

McCloud

Figure B.2f Study catchment monthly mean upper zone tension water for climate scenario Cases 0, 2, 5, and 7

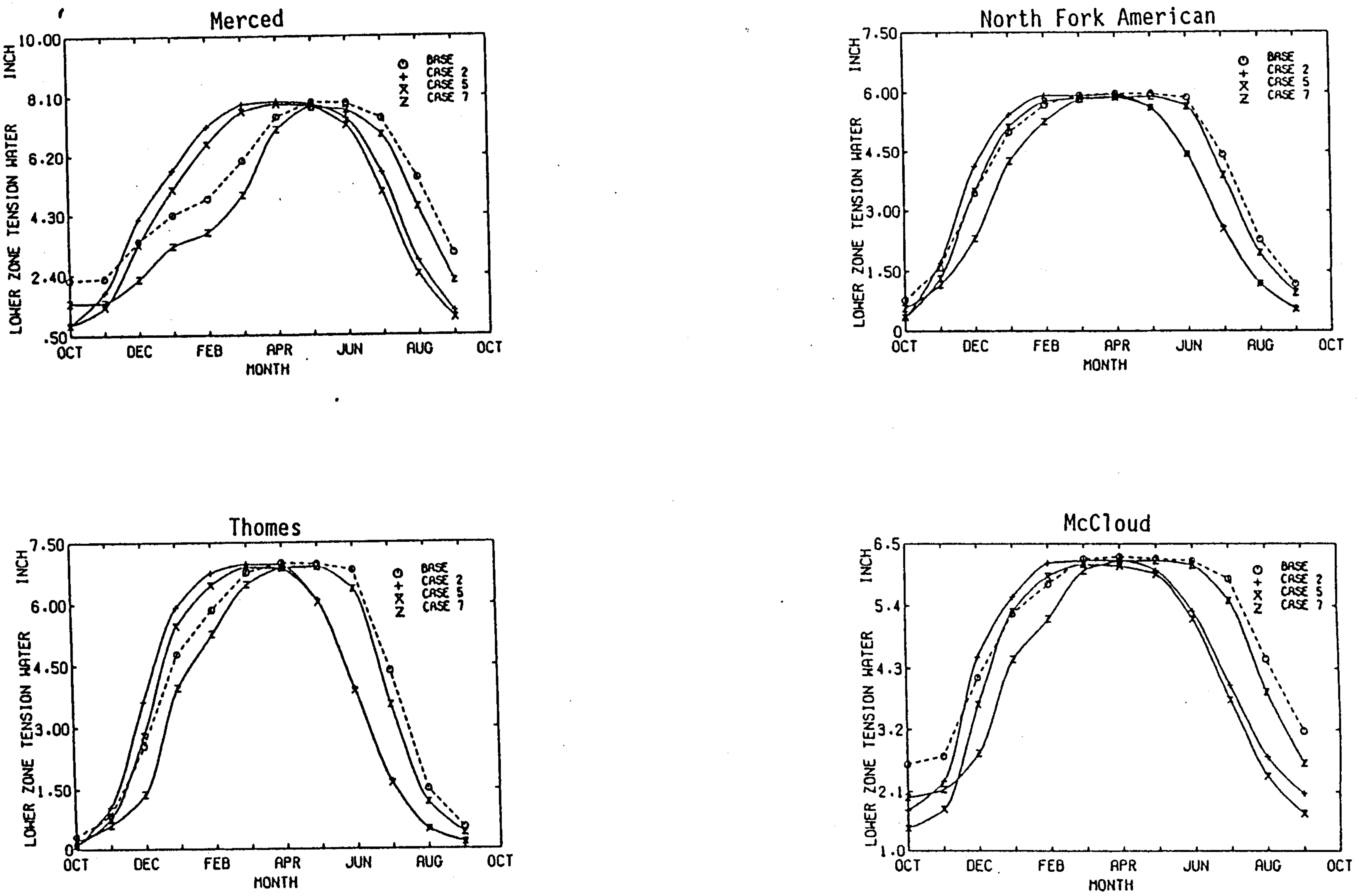


Figure B.2g Study catchment monthly mean lower zone tension water for climate scenario Cases 0, 2, 5, and 7

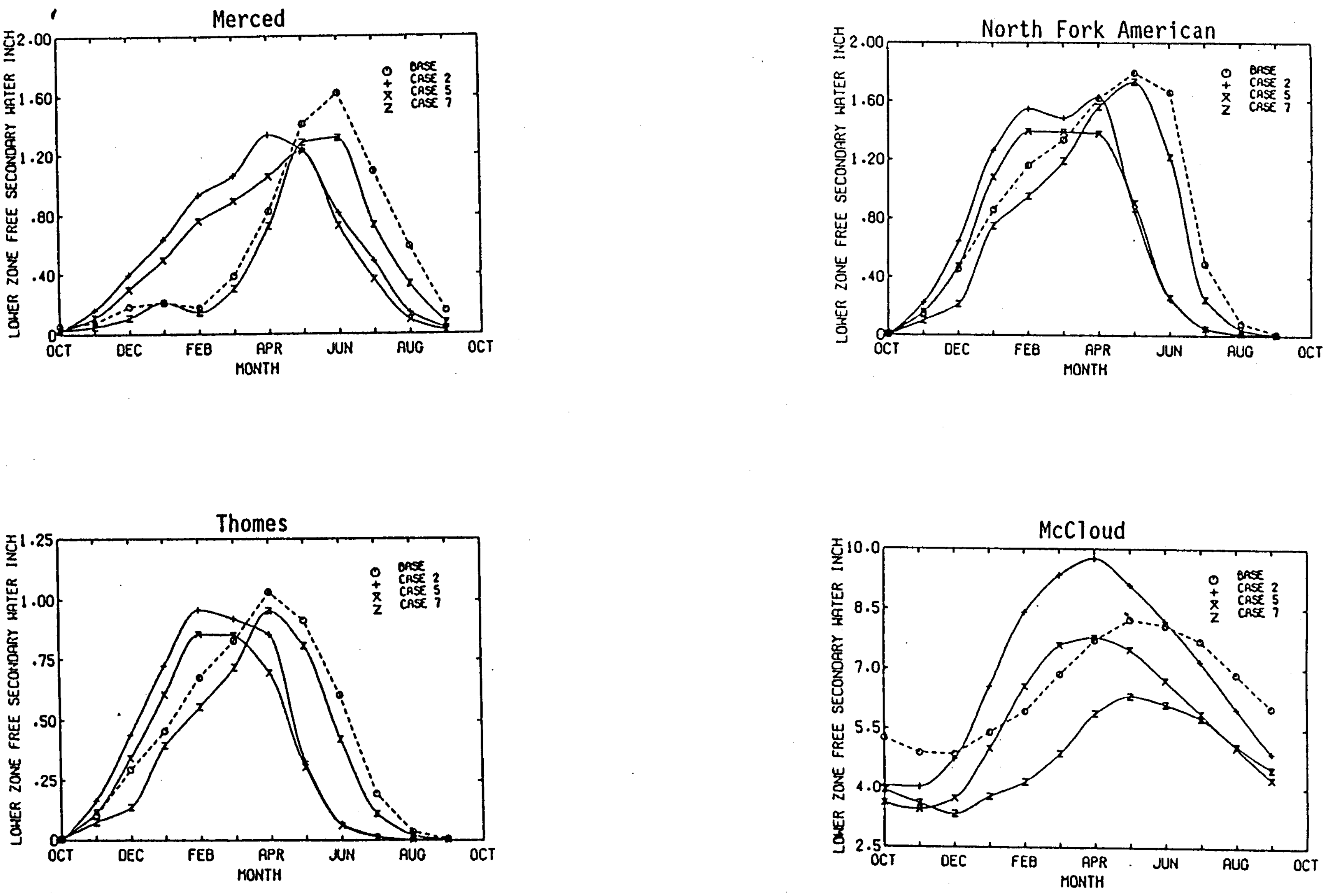


Figure B.2h Study catchment monthly mean lower zone secondary free water for climate scenario Cases 0, 2, 5, and 7

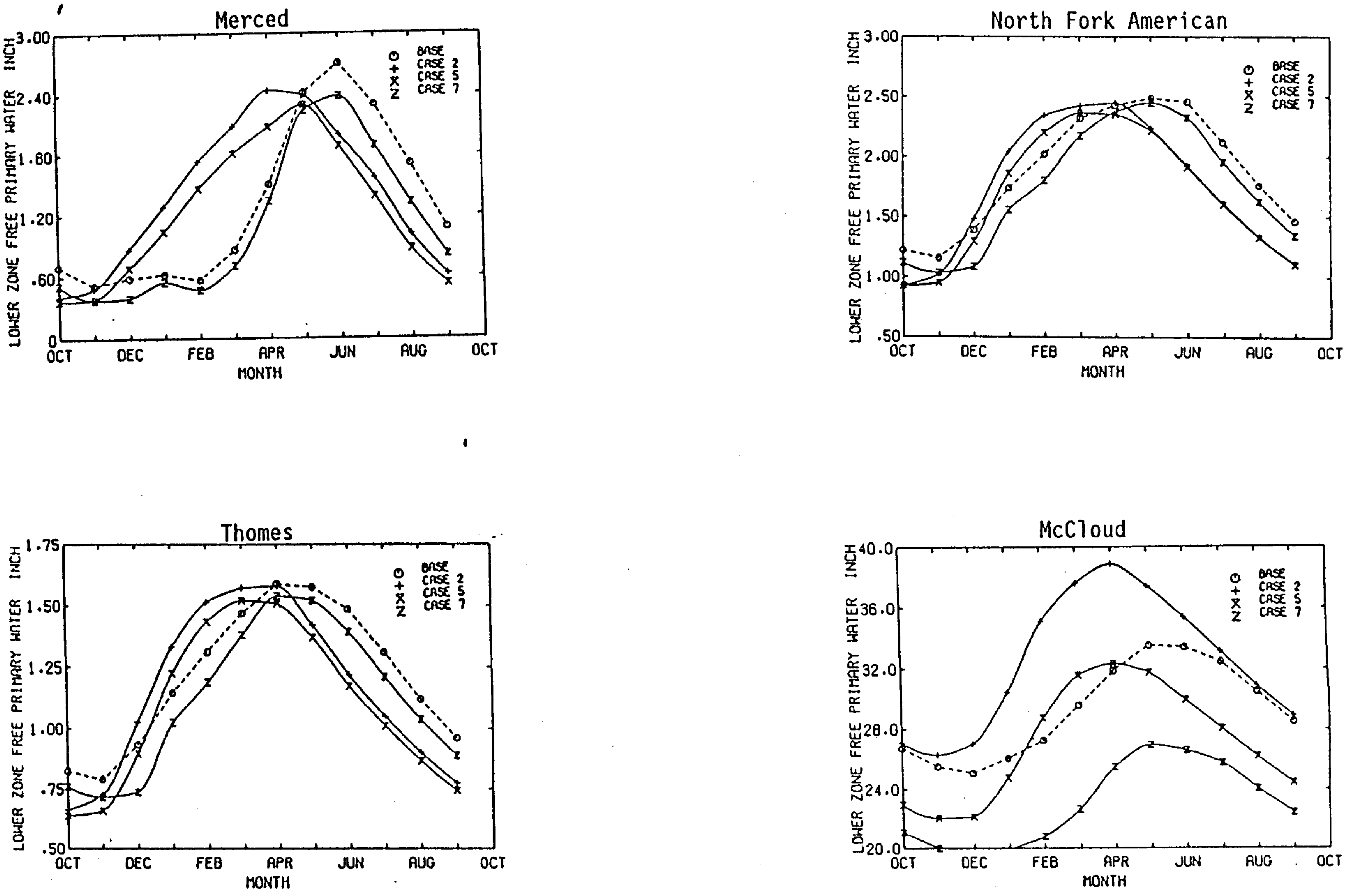


Figure B.2i Study catchment monthly mean lower zone primary free water for climate scenario Cases 0, 2, 5, and 7

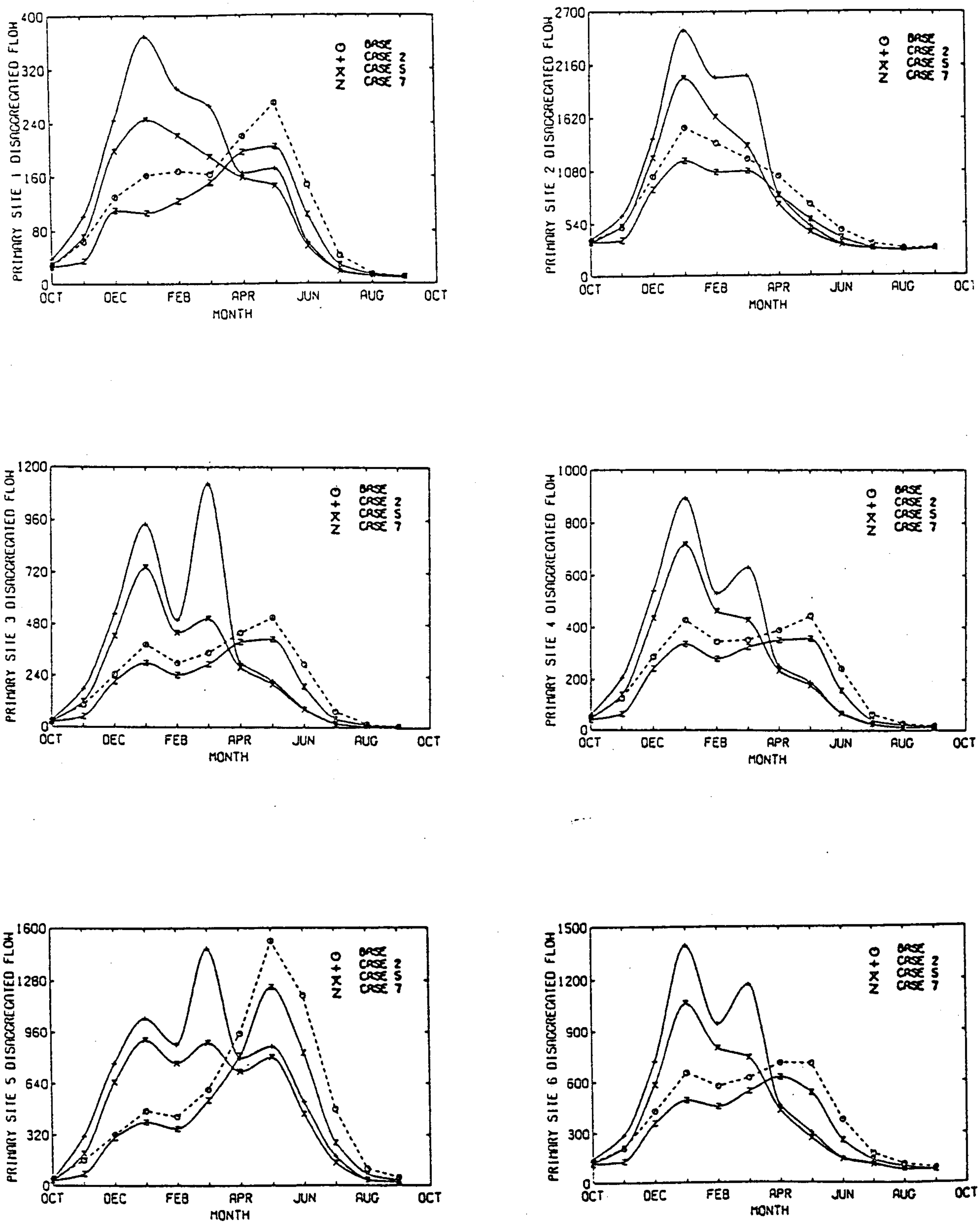


Figure B.3a Water resource system primary node mean monthly streamflow for climate scenario Cases 0, 2, 5, and 7

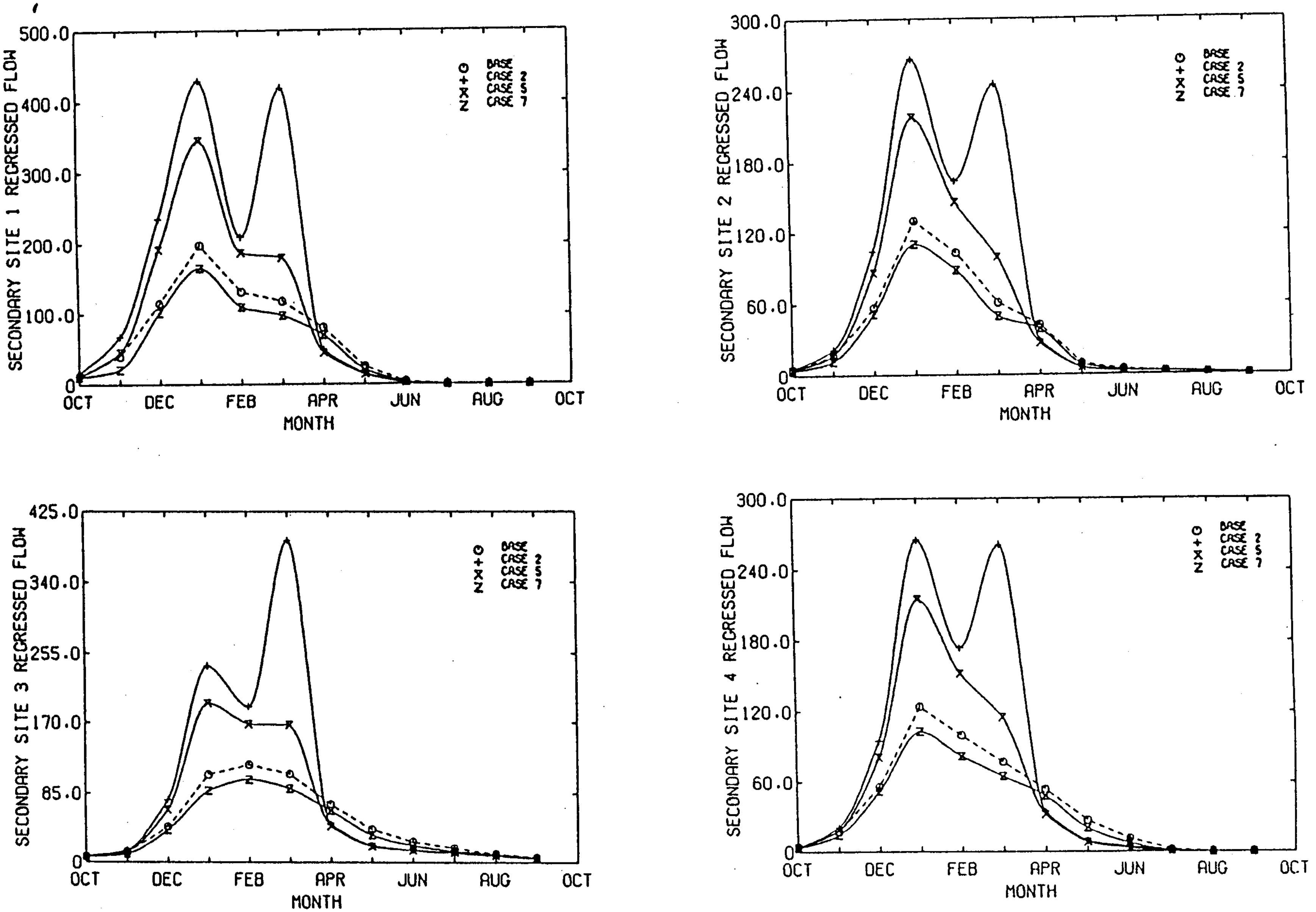


Figure B.3b Water resource system secondary node mean monthly streamflow for climate scenario Cases 0, 2, 5, and 7

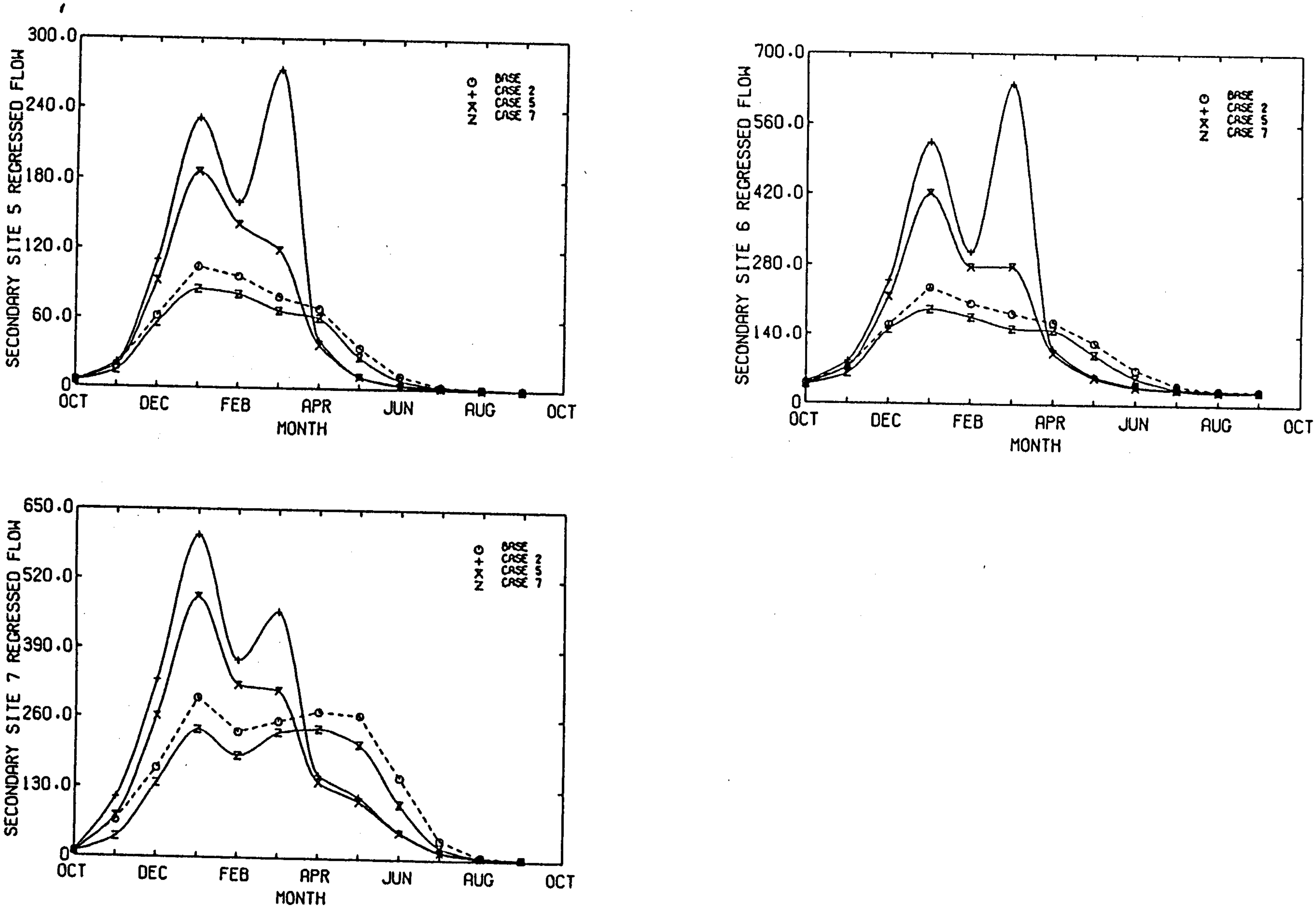


Figure B.3b Continued

APPENDIX C: REVIEWERS' COMMENTS AND RESPONSE

C.1 INTRODUCTION

The first draft of this report was submitted to four independent reviewers selected by EPA. The review comments are included here in their entirety as received, with minor reformatting for consistency. Many of the detailed comments have been incorporated in the final draft. Some of the comments regarding the study design and approach are philosophical in nature, and are addressed in Section C.2, Response to Reviewers' Comments.

C.1.1 Review 1

The authors use snowmelt and precipitation-runoff models to assess the influence of possible climate changes on streamflow quantities and timing within a large river basin in California. I can find no fault with their choice of models. The National Weather Service snowmelt and soil-moisture accounting models should give quite reasonable results for the catchments studied. The disaggregation model used has some limitations which are clearly stated by the authors. However the failure of the disaggregation model to reproduce the lag one correlations does not influence the major conclusions of this study.

The catchments chosen for analysis represent a range of aspect, elevation and runoff response characteristics and should allow interpretations to be made regarding the comparative response of these catchments to climatic change. Although all four catchments have wide ranges in elevation, only one precipitation station was used to provide model input for each catchment and the station used was always in the lowest elevation range. Analysis of precipitation data as a function of elevation shows that the precipitation increase with elevation is accompanied by increases in the number of wet days as well as an increase in the mean amount of precipitation per wet day. Therefore the author's technique of precipitation adjustment for elevation given by equation (2.5a) will underestimate the number of wet days at higher elevations and overestimate the precipitation amounts per day. This bias probably does not have serious effects under the current climatic regime because some of it is accounted for in the calibration procedure and the estimate of P_f. Also, under the current climatic regime most of the precipitation occurs as snow and contributes to an accumulating snow pack. However under the scenarios where temperatures have increased sufficiently so that most of the precipitation occurs as rain this adjustment will quite likely result in a bias toward "flashier" runoff. The authors should address this point.

The report discusses the difficulty of converting the predictions made by GCM's to estimates of inputs to hydrologic models at the appropriate time and space scales. The estimates of PET are of major importance in the water balance calculations and therefore in estimates of water yield. In the sensitivity study it was pointed out that the Penman estimate of ET is most sensitive to wind speed. Do the GCM projections provide any estimates of changes in wind speed with increases in temperature?

This study most certainly adds to our knowledge of the sensitivities of California catchments to climate change. The principal conclusion, that the general warming predicted by the Gcm's will result in decreases in snow accumulation and an increase in winter runoff followed by decreases in spring and summer runoff, can be made with a reasonably high degree of certainty. The authors have clearly stated the assumptions involved in the analysis and have provided sufficient caveats so that the conclusions should not be misinterpreted.

C.1.2 Review 2

C.1.2.1 General Comments

This extremely well written report describes how existing hydrologic modeling techniques were used to estimate the effects of hypothetical climate change scenarios on streamflow in four sub-catchments of the Sacramento-San Joaquin River Basin. The researchers have anticipated many of the questions that this type of study normally raises and they have addressed issues in a thoughtful and realistic manner. The hypothetical nature of the problem scenario, bordering on science fiction, is dealt with in a forthright and professional manner.

The limitations of the existing computer models, the difficulties of calibration, and the impossibility of verification in circumstances which have yet to materialize, are critically discussed and realistically interpreted within an appreciation for how the watershed model components interact. The study shows that, if the hypothesized global warming actually takes place at some future date, there will be a major change in the hydrological behavior of watersheds, particularly those which are subject to snowmelt. The report provides a sound scientific basis for this conclusion and presents the rationale in a format which is consistent with intuition.

The basic goal of the study was to provide a general overview of the direction and severity of the effects of the hypothetical climate change scenarios on hydrology of these basins. The study approached this goal in the most direct way - historical temperature and precipitation data were simply incremented by a constant amount equal to the projected monthly average shift in temperature and precipitation. This approach ignores any internal structural changes to the distribution of the fundamental parameters, such as effects of climate change on the inter-storm durations, event volumes and durations, and effects of climate change on other key hydrological parameters. Investigation of these additional factors would have been beyond the intended scope of the study and would have increased the level of uncertainty and complexity in interpretation of the analytical results. The modeling approach used is direct, simple to understand, and commendable.

The report does not deal with the issue of which, if any, of the alternative global circulation models is the most appropriate. It would be helpful to have a brief introduction, perhaps written by some other authority, which outlines the level of speculation, or science fiction, which resides in these GCM predictions. Some background on the GCM modeling assumptions is required to provide relevance for these hydrological studies.

The reader needs some assurance that the basic motivation for this hydrological study is more than an opportunistic response to a currently popular fiction made possible by the availability of abundant supercomputer capacity. The bottom line for a study such as this is the credibility of the underlying assumption about climate change.

C.1.2.2 Specific Comments

The historic conditions of Case 0 (1951-1980), should be discussed in the context of a longer period record dating back to the 1890's. Other researchers are working on stochastic processes of geophysical time series and techniques for detecting changes in hydrologic time series. It is not obvious that the 1951-1980 period is either representative or stationary. The point here is that it may not matter, since the projected effects of climate change are so dramatic, as shown by this study.

Figure 2.1 is a very helpful sketch. Is the "130-year" period under Model Estimation a typographical error?

The drainage areas of the sub-catchments could be broken out of the text and shown in tabular format alongside Table 2.8. Runoff from the sub-catchments and the node locations could be summarized in dimensional form so that the relative scale of the watersheds can be appreciated more clearly.

A tabular presentation of correlation co-efficients would be boring, but some presentation, tabular or graphical, is needed to support the discussion in the text. Were the correlations carried out on local runoff (e.g., the difference between measured flows at two points on the same stream) or simply on total runoff recorded at two different locations? How much of the apparent correlations are spurious, if any?

The paragraphs dealing with specific sub-catchments could mention the drainage areas, annual runoff, etc. While this information may be embodied somewhere else in the text, it deserves to be mentioned in the specific paragraphs which describe these subcatchments.

Anderson developed two snowmelt models (1973, 1976). The one discussed in this report is the temperature index mode. This type of snowmelt model is adequate for melt conditions dominated by convective-condensation conditions and can be adapted to predominantly radiation melt climates by an appropriate choice of the base temperature (i.e., by developing a relationship which allows melting at air temperatures less than 32°F). The temperature index melt model is well suited to the climatic conditions considered in the sub-catchments. It is not necessary that the snowpack be isothermal for melt during non-rain periods.

It would be useful to list the snowmelt parameter values in a table.

The discussion of soil moisture water storage and actual evapotranspiration contains the essence of current controversy regarding the relevance of watershed modeling to assessments of the impacts of climate change. Some people believe that it is impossible to properly calibrate a watershed model to represent the hydrologic conditions which will prevail after global climate change.

The report points out that soil moisture storage, which controls base flow, is dominant in one of the four test sub-catchments. It might be appropriate to expand the discussion of the relative importance of calibration to prediction.

The spatial disaggregation model is a sub-set of a more general approach developed about 20 years ago by Schaake et al. at MIT. One or two additional sentences could clarify why spatial disaggregation was believed to be necessary. It might be useful to change the terms "real space and log space" to "time and log-time" and to overcome the reader's initial confusion about the use of these terms to represent logical reality, as opposed to physical reality.

The matrix B in equation 2.3 is a problem in this type of work, but it might be better to estimate it crudely rather than to eliminate it completely. The reader is left with some concern for how accurately the seasonal behavior of the streams has been represented by this modeling. Perhaps the one-dimensional autocorrelation of each record could be presented to show that the simulated and actual data do indeed have similar seasonal behavior.

The choice of a single meteorological station for each subcatchment is common practice, but it might be appropriate to consider changes in lapse rates on a monthly or seasonal basis for the stations. This can be accomplished with reference to radiosonde data for the region. A proper evaluation of temperature lapse rates may be more important for snowmelt and accumulation than development of a non-linear precipitation-elevation adjustment factor. The latter can be accommodated by direct calibration, whereas the temperature effects are inherently dependent upon sequences and are therefore much more difficult to evaluate empirically through calibration.

Comments on the inappropriate use of snow course data are correct. It is more appropriate to calibrate with snow line observations.

Seasonal melt factors which are incorporated in the text could be extracted and presented in tabular format in consistent metric or English units.

The wide range of possible values for soil moisture accounting parameters points out the need for a reasonable method for parameter selection.

The areas of the GCM grid cells could be presented so that the watershed areas can be placed in context. It would be useful to see some additional discussion of the pros and cons of the GCM assumptions and methodology, including factors in the ecosystem such as the potentially moderating influence of the response of ocean plankton to increased CO_2 levels.

In the discussion of potential evapo-transpiration there might be some confusion in the reader's mind about Basic Conditions from the GCM studies and actual historic conditions (see the first sentence of Chapter 3).

The report outlines the approximations in the statistical models which were used to generate synthetic records for water resource management modeling. It would be useful to present a final table comparing the statistical properties of the real time series with the statistical properties of the final results.

In the introduction to the report, or in the basin descriptions, it would be appropriate to comment that the Merced River is controlled more by snowfall and snowmelt than the other basins. This is an important distinction because of the significant temperature change predicted by the GCM's compared to the insignificant change in precipitation. Along the same lines, Table 3.3. could be further subdivided to show changes in seasonal distribution.

The conclusions about the importance of the shift in the annual runoff distribution to water resources management depends strongly on the volumes of reservoirs which are available for water management. It happens that in California this volume is not large compared to the runoff. In other areas this may not be true. A table showing reservoir volumes and annual runoff would be useful.

Chapter 3 introduces a brief discussion of the long-term (1890-1980) regime at the same stations. This is confusing since it was not brought into the report earlier.

The 1930's drought resulted primarily from reduced precipitation, whereas the global effects predicted by the GCM's is primarily a temperature phenomenon. This is an important observation that might aid popular understanding of the phenomena being discussed.

A deficiency in the modeling approach is the absence of between-storm dynamic effects from the GCM results. If the GCM data results contain some information on this aspect it should be somehow incorporated into the discussion to indicate the general direction of inter-storm dynamics. Will precipitation tend to be more concentrated during shorter time intervals, will high temperature sequences tend to longer runs as well as higher averages?

It is potentially significant, and therefore disturbing, that the serial correlations between nodes was not preserved. The report might comment on why the reader need not be disturbed - what, if any, is the operational significance?

Is the spatial variability of the output hydrographs changed by the effects on snowmelt and base flow (Chapter 4, 1b)?

C.1.3 Review 3

In general, the model used to evaluate data in the paper was as good as what is available. Reviewer did not have any problems with the assumptions in the paper, however, he does not know much about the global models and the original assumptions used in the models. He is a skeptic of the greenhouse effect and does not think this summer's (1988) heat is a part of such an effect. Historical data will show that there have been other equally hot summers and there are still many questions to be answered about whether the greenhouse effect actually does exist or are these phenomenon simply part of a normal climate variability. The reviewer did not have any problems with the approach used to adjusting the GCM grid cell predictions to the catchment scale the author worked with. He felt the authors pointed out areas of weakness in their data and papers, particularly their need to interpolate from the GCM grid scale down to the data they used in their paper. He felt that they did a good job in light of the time in which they had to prepare the paper.

The paper by Lettenmaier included a discussion of how a change in climate conditions would also result in a change in vegetation , however, the author pointed out that a discussion of vegetation changes was beyond the scope of the report. The author did say that he assumed vegetation would remain constant for the purposes of the report.

The reviewer did not have any specific comments or questions on the report, except to say that some figures and a page were missing from the manuscript he received.

C.1.4 Review 4

I reviewed the study "Interpretation of Hydrologic Effects of Climate Change in the Sacramento - San Joaquin Basin, California" by D.P. Lettenmaier and D.R. Dawdy, June, 1988, prepared for the U.S. Environmental Protection Agency's Office of Policy, Planning, and Evaluation. The purpose of this study was:

1. Develop a method to interpret the possible hydrologic impacts of global climate change;
2. Assess hydrologic effects of changes predicted by available General Circulation Models (GCM's) of the atmosphere/climate system;
3. Assess differences in the hydrologic implications of the different GCM's - at monthly intervals;
4. Provide hydrologic data to assess water resource system impacts of global climate change

Before addressing the questions posed in the review guidelines, I want to say this is an excellent study because it is done using "state of the art" technology. That is not to say there aren't potential problems with how the technology was used and, therefore, with the results. I suggest some of these below in my response to the questions.

C.1.4.1 Models, Data, and Assumptions

The guidelines ask for evaluation of what the investigator did. In this case, the investigator was directed to use certain climate change scenarios that also affect the technical merits of the report. The GCM's can provide only a general sense of the temperature and precipitation changes that might occur. Local results at any GCM grid point (which represents an area at least as large as the state of Colorado, even for the most detailed GCM's) do not represent the climate at that grid point very well. Therefore, there is a major flaw in EPA's design of this study, and that flaw has caused a major erroneous conclusion to be produced by the investigators.

The investigators recognized they could not use the historical climate from the GCM as the primary basis for their simulations, so they wisely used local climatological data to form the base case for their analysis. The problem with this study begins when GCM data for a single grid point are used as the basis for the climate change study. In my opinion it was unwise to simulate the hydrologic response to the specific changes from individual GCM's because this suggests a false sense of confidence in the numbers, and it leads to an underestimate of the possible range of climate change. Even in this study, putting complex patterns of change into hydrologic models (i.e. the GCM scenarios) made it harder for the investigators to see sensitivity to change than if they had been asked to decide for themselves how to do this. Also, the limits of what we really know about the sensitivity of climate to hydrology would have been possible to assess. As it is, the possible limitations of the analysis were not investigated, nor was this a clear objective of the study.

Some of the things that were not considered and could be important are the following. First, the main source of water supply in the West is orographic winter season precipitation. The amount of this in any year depends on the directions of the storm tracks and the amount of water vapor in the storms. Storm track direction is important for individual drainage basins because storms travelling along a ridge produce much less precipitation than storms orthogonal to the ridge. Also, water vapor available at a given location varies with storm direction. If the atmosphere changes, changes in storm directions and moisture flow will have subtle but important local effects. Only the storm track piece of this puzzle can be seen from a global scale model. Local implications of the changes require a mesoscale model of orographic precipitation, such models exist and can be applied to this problem. Furthermore, these mesoscale models may be useful to adjust parameters in the more detailed GCM's to improve their accuracy.

Second, the relationship between GCM results and local climate change seems to have been largely ignored (not by the investigators, but by EPA). When one compares GCM simulations of the current climate with observations, there are significant local spatial shifts in location of dominant circulation patterns. I don't know if the following has been studied, but I expect (on the basis of my general experience with these models) that the strongest correlation between local climate and GCM results may be spatially shifted in the GCM model from the local location of interest. Similarly, the local effects of a changed atmosphere could be shifted as well. The significance of this is that the real range of uncertainty in the climate changes that should have been investigated in this study are far greater than were actually considered in the scenarios.

Finally, changes in potential evapotranspiration may occur. The investigators used the Penman equation to estimate potential evapotranspiration, and this allows the effects of changed temperatures from the GCM's to be considered. Such an approach is about all that can be done in a study like this one. However the actual coupling between the atmosphere and land processes is far more complex. Although the saturation concentration of water vapor in the atmosphere is known to increase exponentially with temperature, potential evapotranspiration also depends on the current amount of water vapor in the atmosphere from evaporation upwind. In a warmer and more humid climate, the changes in potential evapotranspiration require assessment with a more highly coupled mesoscale modeling of the physical processes involved.

A limitation of the NWS moisture accounting model, and to some extent also the snow model, is that some of the parameters of these models are functions of climate. In other words, the parameters should be changed depending on the climate change. The exact relationships are unknown so they could not have been considered by the authors. My personal opinion is that the effect of climate change on model parameters is only a fraction of the direct effects of the changed climate input to the models., especially for the range of climate changes considered. In any case, the basic structure of the models will surely have a far more dominant bearing on the results than the values of the model parameters.

The authors have done a fine job of analyzing many of the possible limitations of the assumptions and models used by them and these are fairly accounted for in their conclusions.

C.1.4.2 Interpretation of Results

The authors' conclusions appear on pages ii and iii. I agree with them that the temperature changes will have the kind of effects they describe. I do not agree that potential changes in precipitation may have lesser effect on runoff than the temperature changes. Part of the problem here stems from the complexity of the GCM scenarios and the likelihood these scenarios do not represent the real potential uncertainty in precipitation changes. I have personally conducted some similar sensitivity studies with the same models and base my opinion on this experience.

The authors recommend areas of further study. I concur with these and suggest adding to their list a need to analyze the causes of historical orographic precipitation variability with the aid of a mesoscale orographic precipitation model. There is need to couple this analysis to analysis of large scale circulation patterns that actually occurred and to what the GCM's had to say about these patterns.

The main caveat, from a policy view, is that an extremely narrow view has been taken of how GCM results might be used to do policy analysis. In this case, important information from the GCM's has been screened out by the way the scenarios were selected. The problem is not that the scenarios were studied, but that other, simpler sensitivity studies (also using GCM results) were not done as well. The point of all of this is that computing for policy formulation should be done to gain insight, not only to get supporting evidence for specific situations.

C.2 RESPONSE TO REVIEWERS' COMMENTS

Reviewer 1 makes a valid point regarding validity of the assumption that the number of days with precipitation is adequately represented by low elevation precipitation stations. Hydrologists who have implemented precipitation-runoff models for mountainous watersheds are painfully aware of the dearth of high elevation meteorological stations, and of the problems of precipitation catch deficiency for those high elevation stations that do exist. The absence of high elevation stations with reasonably complete historic records was the reason for selection of the stations used. A future, more detailed study, might take a different approach that could selectively utilize existing high elevation data. For instance, it might be possible to construct a stochastic model of the daily precipitation arrival process (see, for example, Foufoula-Georgiou, 1985) to observed high elevation precipitation data, and to infer the distribution of precipitation amounts from the cumulative (e.g., monthly) low elevation data. Such an approach would assume that the high elevation information on occurrence/non-occurrence of precipitation is more accurate than that for precipitation amounts, which is probably the case.

The alternative approach would deviate from the study design that was followed here, which was based on direct or indirect use of observed data for the period 1951-80, however, this choice was made only for consistency with other studies commissioned by EPA, and would not be a concern in a subsequent study. The suggested alternative approach would, however, introduce a host of additional problems in the stochastic simulation of precipitation-temperature sequences at multiple stations. As the reviewer notes, errors in the base case precipitation arrival process are compensated to some extent by calibration of the models, and further, by the cumulative effect of the snowpack when precipitation occurs as snow. The latter compensation would still occur under the alternative climates at high elevations, where much of the precipitation equivalent would still be as snowfall. For this reason, while we believe the comment is valid, we also believe that a more detailed study would show that possible misrepresentation of the precipitation arrival process would not substantially affect the simulated hydrologic changes which result from reduction in snow accumulation.

Reviewer 2 emphasizes the extent to which the conclusions depend on the output of the GCM's, and therefore their accuracy. While it is certainly beyond the scope of this study to address the structure, and appropriateness, of the GCM's, future research on hydrologic effects should more closely address the linkage between the hydrologic cycle (mass and energy transport) and the internal fluxes as modeled by the GCM's. Although we have not attempted in this report to describe the structure of the three GCM's for which output was provided, a recent report by Grotch (1988) describes the GFDL, GISS, and OSU models (in addition to NCAR's Community Climate Model), and compares their performance for base case simulations. It should again be emphasized that the mechanism responsible for the most significant hydrologic change, which is a shift in the seasonality of runoff, is increased temperature, and not precipitation changes. The GCM's agree on the direction of temperature change (although not the amount). For this reason, the simulated hydrologies under the alternative climates should be more believable than they would be if precipitation changes, which vary in both direction and amount between the models, were responsible for the simulated changes.

Reviewer 2 also suggests that the 30 year base period used (1951-80) is too short to define the historic conditions properly. We agree that a longer period would have been desirable. The 1951-80 period was selected for consistency with other EPA studies, and because computer readable precipitation and temperature data are readily available only from 1948 on. Initially, we had hoped to use a data record that included the 1930's drought, but this was not feasible within the project time constraint. We believe, though, that the simulated hydrologic changes associated with the alternative climates are large enough that a slightly different definition of the historic conditions would have had little effect on the results.

Reviewer 2 makes an interesting point regarding the calibration of hydrologic models. He notes that there is disagreement among hydrologists as to whether conceptual models, calibrated for a given climate, can properly predict the hydrologic response of a catchment under long-term climate shifts. The reason for the possible calibration problem is that conceptual models are calibrated (as was done here) for a given climate, and associated "normal" excursions over a range of time scales. When climate shifts occur, the processes governing hydrologic fluxes might change, rather than just the magnitude of the fluxes. We believe this concern is largely unfounded relative to the other sources of uncertainty in the simulations. The conceptual models used do account for changes in fluxes (infiltration, direct runoff, evapotranspiration) associated with short term climatic variations. With the exception of the failure to model the effects of vegetation changes on runoff and evapotranspiration, (which, as indicated in Chapter 5, we feel should be the focus of future research) changes in the flux mechanisms, as opposed to rates, can probably be considered second order.

Finally, Reviewer 2's comments regarding the performance of the snowmelt model during non-rain periods require clarification. Based on a telephone conversation with Eric Anderson of the National Weather Service Hydrologic Research Laboratory, we verified that during non-rain periods, the model performs as follows. If the air temperature exceeds a base temperature (which we took as 32°F), the model assumes that melt takes place at the air-snow interface. However, if the snowpack is not isothermal at 32°F, the resultant heat is transferred to the snowpack (essentially through refreezing of the liquid water). Only if the snowpack is isothermal at 32°F and the liquid water content of the snowpack exceeds its holding capacity does liquid water leave the snowpack (as psuedo-precipitation).

Reviewer 4 takes exception to the design of this study, and related studies commissioned by EPA, with respect to the transformation of GCM grid cell results to the catchment scale. The approach used, which was to perturb the historic precipitation and temperature observations by the GCM-predicted grid cell means, is certainly a "zero-order" approach that should be refined in future research. The problem is complex, and is unlikely to be resolved by simply awaiting the computational power to reduce the GCM grid size. Even if it were possible for the GCM's to produce simulations for grid cells with size similar to the catchments modeled, assumptions made in the GCM's make it unlikely that the results would be usable directly. In fact, Grotch (1988) argues that use of GCM results for single grid cells in inappropriate, and that the finest scale that should be considered is on the order of ten cells. Given the constraints of the present study, the only practical way to approach this issue was through use of three different GCM's, and through the sensitivity tests that were performed. Although it is beyond the scope of this research, we believe that one area that is potentially fruitful is to relate GCM grid scale results for such internal variables as atmospheric stability to the spatial structure of precipitation, for instance, through the spatial covariance function. If significant relationships could be shown for the base cases, it might then be possible to simulate changes in the precipitation process at multiple stations. Such an approach, like that suggested in response to comments of the first reviewer, would involve construction of a stochastic model for precipitation, and probably, for temperature as well.

Another potentially fruitful approach is to evaluate the relationship of storm tracks (in a statistical sense) to GCM grid cell predictions, as suggested by the reviewer. Leytham (1982) has shown, for example, that West Coast droughts can be explained by infrequent, large scale precipitation shifts, which can be modeled as a mixture process. If shifts in the "mixture" of events could be related to variables predicted by the GCM's, it might be possible to infer in a more direct manner the likely changes in precipitation at the short time scale, and at the sub-grid spatial scale, that could be expected.

For the reasons indicated earlier in this Appendix, and in Chapter 3, we again emphasize that the major hydrologic change (shift in the seasonality of runoff) is the result of the GCM-predicted changes in temperature, rather than precipitation. The changes that would actually take place would be evidenced through a number of mechanisms, some of which could not be modeled explicitly. These include changes in orography, such as are suggested by the reviewer. We believe that the analyses reported, including the sensitivity tests, show fairly conclusively that the GCM-predicted temperature changes represent a first order cause of hydrologic change, and that other climatic changes that would accompany the temperature shift (most notably, precipitation changes) are second order for the catchment simulations.

We agree with the reviewer that the study design may have filtered out some of the information produced by the GCM's. We fully agree with his contention that the computing should be done to gain insight, and not to get "supporting evidence ...". Our statement in Section 1.1 "... current hydrologic interpretations are limited to providing descriptive results which must be interpreted in an alternative scenarios, or sensitivity analysis context." was intended to make just this point.