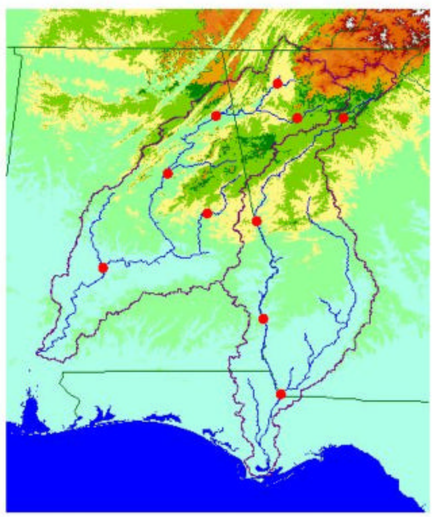
# U.S. DEPARTMENT OF THE INTERIOR

# U.S. GEOLOGICAL SURVEY


# Climate Change Impacts on Southeastern U.S. Basins


by

Aris Georgakakos[1] and Huaming Yao[1]


**Open-File Report 00-334**



This report is the basis for an article submitted for publication to *Water Resources Research.*


[1]Georgia Water Resources Institute; School of Civil and Environmental Engineering
Georgia Institute of Technology; Atlanta, GA 30332-0355 USA



August 2000

# Acknowledgments

This work was partially supported through USGS grant 98HQAG2118 as part of the National Water Sector Assessment for Climate Change and Variability. Additional support was provided by Georgia Tech. We wish to thank Briane Adams of USGS for involving us in the assessment effort and facilitating the publication of our results.

# Abstract

The work described herein aims to assess the impacts of potential climate change on the Apalachicola-Chattahoochee-Flint (ACF) and Alabama-Coosa-Talapoosa (ACT) river basins in the Southeastern US. The assessment addresses the potential impacts on watershed hydrology (soil moisture and streamflow) and on major water uses including water supply, drought management, hydropower, environmental and ecological protection, recreation, and navigation. This investigation develops new methods, establishes and uses an integrated modeling framework, and reaches several important conclusions that bear upon river basin planning and management. Although the specific impacts vary significantly with the choice of the GCM scenario, some general conclusions are that (1) soil moisture and streamflow variability is expected to increase, and (2) flexible and adaptive water sharing agreements, management strategies, and institutional processes are best suited to cope with the uncertainty associated with future climate scenarios.

# Climate Change Impacts on Southeastern U.S. Basins

## Report Outline

# Climate Change Impacts on Southeastern U.S. Basins

## 1. Introduction and Scope

The research effort described herein is part of the national assessment process to identify and analyze the potential consequences of climate variability and change. The assessment is taking place under the auspices of the US Global Change Research Program (USGCRP), which is mandated by statute with the responsibility to undertake scientific assessments of the potential consequences of global change for the United States. The purpose of the "Global Change Research Act of 1990" (P.L. 101-606) is to *"... prepare and submit to the President and the Congress an assessment which*

- *integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings;*
- *analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation9 human health and welfare, human social systems, and biological diversity; and*
- *analyzes current trends in global change, both human-inducted and natural, and projects major trends for the subsequent 25 to 100 years."*

The scope of the work reported herein is to assess the potential impacts of climate change on the Apalachicola-Chattahoochee-Flint (ACF) and Alabama-Coosa-Talapoosa (ACT) river basins in the Southeastern US. The assessment addresses the potential impacts on watershed hydrology (soil moisture and streamflow) and on major water uses including water supply, drought management, hydropower, environmental and ecological protection, recreation, and navigation. The assessment effort develops new methods, establishes and uses an integrated modeling framework, and reaches several important conclusions that bear upon river basin planning and management.

The report includes six sections. Section 2 provides a general description of the ACF and ACT river basins. Section 3 describes the climate scenarios and models used in the assessment. Section 4 introduces, evaluates, and applies a new hydrologic watershed model to assess the response of several ACF and ACT sub-basins to historical and future climate scenarios. Section 5 uses the hydrologic model results to assess the climate change impacts on the ACF water uses. Lastly, Section 6 summarizes the major research conclusions.

# 2. The ACF and ACT River Basins

The Apalachicola-Chattahoochee-Flint (ACF) and the Alabama-Coosa-Talapoosa (ACT) river basins are shared by the States of Georgia, Alabama, and Florida and cover an extensive portion of the Southeastern U.S. Figure 2.1 shows the major ACF and ACT sub-basins, and Table 2.1a includes various sub-basin characteristics such as longitude and latitude; area; and mean, minimum, and maximum elevation. Mean rainfall over the ACF and ACT ranges (north to south) from about 1.6 to 1.2 meters per year, and mean runoff coefficient (ratio of streamflow to rainfall) from about 0.45 to 0.3 respectively. Table 2.1b summarizes the land use distribution in the ACF and ACT sub basins. Forests range from 38.1 to 79.6 percent of sub-basin area; agricultural lands from 9.9 and 40.8 percent; urban & industrial areas from 0.3 to 13.0 percent; wetlands from 0 to 33.0 percent; and open water from 1.1 to 5.1 percent.

The basins support a variety of important water uses. ACF is the major water supply for Atlanta, a city that has grown from around 0.5 million inhabitants in the 1950's to more than 3 million at present. Urban growth requires additional water supplies but also increases wastewater discharges to the rivers which, in some reaches, have reached their assimilative capacity. The basins harbor a rich diversity of fish and wildlife, with the Apalachicola Bay supporting a flourishing fishing industry. The ACF and ACT lakes (e.g., Lanier, Allatoona, and West Point) are popular recreation sites, with shorelines rapidly developing into highly valued residential property. Several hydroelectric facilities provide energy to federal and private customers. The largest reservoirs have a significant portion of their storage allocated for flood control. The lower ACF and ACT reaches are used for navigational purposes. Important surface-groundwater interactions exist in the Flint River Basin where groundwater pumping for irrigation and industrial water supply impacts streamflow. During severe droughts (such as those in the 1980's and present), basin water resources are unable to sustain unlimited water supplies for all water users. Water allocation and basin-wide management compacts are needed urgently and have been in negotiation for several years.

Water management projects include several federal and private facilities and other control points. The ACF, for example, includes four major federal reservoirs (Lanier, West Point, George, and

Woodruff), five small private reservoirs (Morgan Falls, Bartletts Ferry, Goat Rock, Oliver, and North Highlands), and 14 control nodes for major tributary inflows, water withdrawals, and returns. Table 2.2 indicates the federal reservoir conservation storage zone, while Table 2.3 summarizes the characteristics of all ACF hydroelectric facilities (federal and private). The private projects are too small to exercise basin-wide regulatory control. The ACT river basin has undergone similar development, including five major storage projects (Allatoona, Carters, Weiss, Harris, and Martin), eleven smaller hydropower projects, and 36 control nodes for major tributary inflows, water withdrawals, and returns.

This assessment will primarily focus on the ACF river basin. However, hydrologic assessments will also be performed for the major ACT sub-basins.

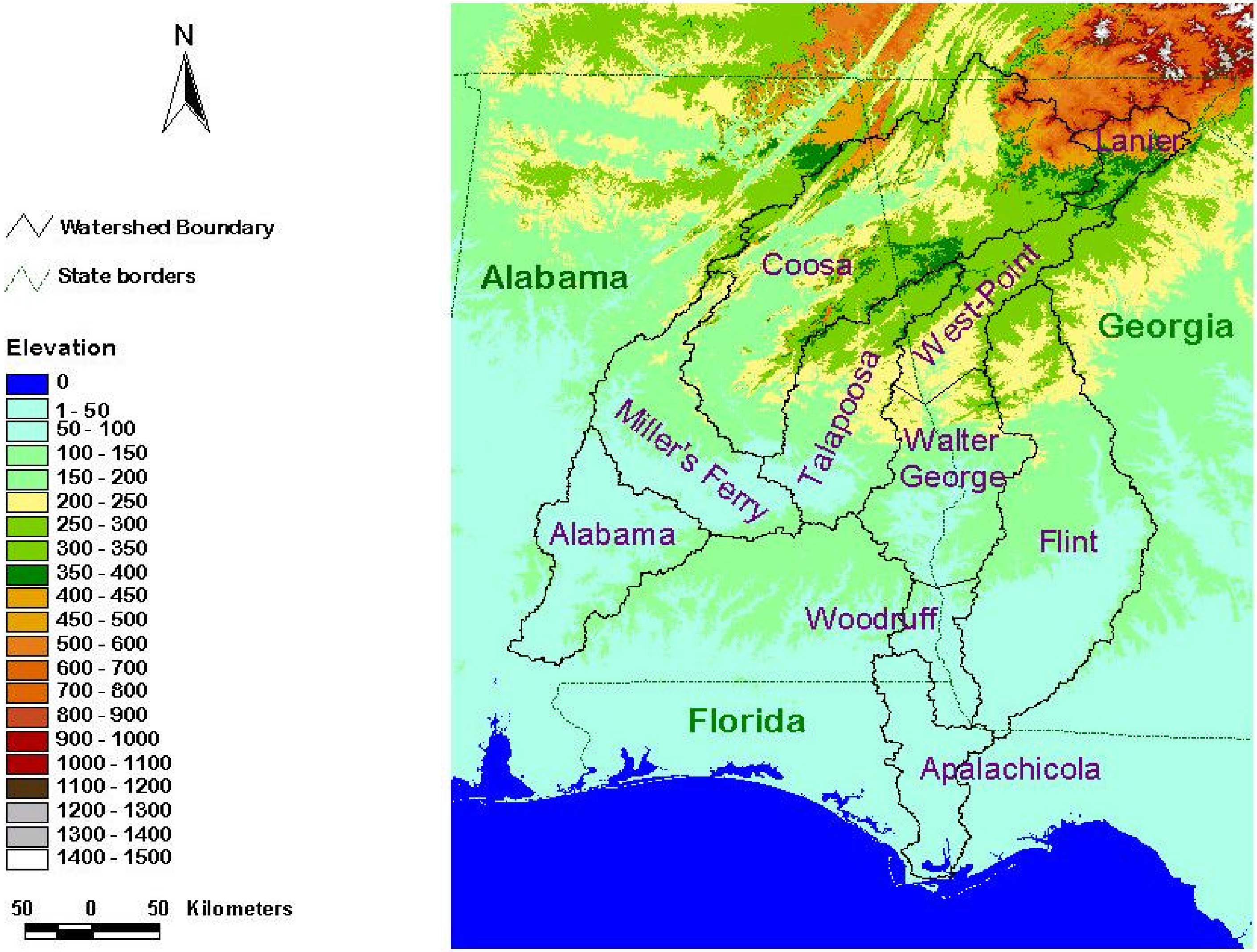



Figure 2.1: ACF and ACT Sub-basins

Table 2.1a: Characteristics of the ACF and ACT Sub-basins

| ACF and ACT Sub-basins | Latitude (Centroid) (degrees) | Longitude (Centroid) (degrees) | Area ($km^2$) | Mean Elevation (m) | Minimum Elevation (m) | Maximum Elevation (m) |
|---|---|---|---|---|---|---|
| **ACF River Basin** | | | | | | |
| Lanier | 34.51 | -83.83 | 2692 | 427 | 287 | 1311 |
| West-Point | 33.53 | -84.78 | 6058 | 269 | 168 | 488 |
| Walter F. George | 32.33 | -85.04 | 10562 | 144 | 45 | 404 |
| Woodruff | 31.24 | -85.07 | 3317 | 67 | 21 | 160 |
| Flint | 32.04 | -84.35 | 21932 | 128 | 23 | 396 |
| Apalachicola | 30.48 | -85.16 | 6206 | 31 | 0 | 103 |
| **ACT River Basin** | | | | | | |
| Alabama | 31.86 | -87.32 | 9351 | 70 | 5 | 188 |
| Coosa | 33.93 | -85.50 | 28784 | 273 | 40 | 1250 |
| Miller's Ferry | 32.63 | -86.77 | 10777 | 112 | 18 | 457 |
| Talapoosa | 32.83 | -85.87 | 9351 | 195 | 40 | 487 |

Table 2.1b: Land Use Distribution in the ACF and ACT Sub-basins

| ACF and ACT Sub-basins | Open Water (%) | Forest (%) | Urban & Industrial (%) | Agriculture (%) | Wetlands (%) | Others (%) |
|---|---|---|---|---|---|---|
| **ACF River Basin** | | | | | | |
| Lanier | 5.1 | 79.6 | 2.2 | 12.3 | 0.0 | 0.8 |
| West-Point | 2.2 | 70.8 | 13.0 | 10.0 | 2.3 | 1.7 |
| Walter F. George | 2.2 | 76.1 | 2.3 | 9.9 | 4.2 | 5.4 |
| Woodruff | 2.9 | 45.5 | 0.7 | 40.8 | 6.4 | 3.8 |
| Flint | 1.2 | 47.1 | 2.0 | 35.4 | 9.6 | 4.7 |
| Apalachicola | 2.0 | 38.1 | 0.8 | 19.7 | 33.0 | 6.3 |
| **ACT River Basin** | | | | | | |
| Alabama | 1.3 | 67.4 | 0.3 | 15.2 | 11.6 | 4.2 |
| Coosa | 1.6 | 78.7 | 2.2 | 14.9 | 0.9 | 1.7 |
| Miller's Ferry | 1.1 | 65.0 | 2.4 | 21.3 | 8.1 | 2.1 |
| Talapoosa | 2.4 | 73.8 | 1.8 | 16.5 | 4.3 | 1.2 |

Table 2.2: Conservation Storage Zones for the Major ACF Reservoirs

| Reservoir | **Minimum** | | **Maximum** | |
|---|---|---|---|---|
| | Storage (bcf) | Elevation (ft) | Storage (bcf) | Elevation (ft) |
| **Lanier** | 37.75 | 1035 | 85.2 | 1071 |
| **West Point** | 13 | 620 | 26.3 | 635 |
| **George** | 29.95 | 184 | 40.7 | 190 |
| **Woodruff** | 13 | 75 | 16.9 | 77.5 |

Table 2.3: ACF Hydroelectric Plant Characteristics

| Reservoir | Installed Capacity (MW) |
|---|---|
| **Lanier (Buford)** | 5 + 50X2 = 105 |
| **West Point** | 4 + 39.35X2 = 82.7 |
| **George** | 36.25X4 = 145 |
| **Woodruff** | 12X3 = 36 |
| **Morgan Falls** | 16.8 |
| **B. Ferry** | 173 |
| **Goat Rock** | 26.3 |
| **Oliver** | 60 |
| **N. Highlands** | 29.6 |

# 3. Climate Scenarios and Assessment Process

## 3.1 Climate Scenarios

The assessment work described herein is based on three climate scenarios. These include the historical climate from 1939 to1993, and two potential future climates generated by two different General Circulation Models (GCMs) for 1994 to 2094. Information for the historical climate is obtained from (a) the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP, Kittel et al., 1997), and (b) from various state and federal agencies in the Southeastern U.S. The VEMAP data used in this assessment include monthly rainfall and temperature provided on a 0.5º x 0.5º spatial grid. Additional information includes unimpaired streamflows (namely, streamfllows adjusted for upstream withdrawals) at the outlets of the ACF and ACT sub-basins as well as detailed reservoir and demand data. The historical climate is used to establish the baseline basin response.

The future climate scenarios are generated by the GCMs of the Canadian Center for Climate Modeling and Analysis and the U.K. Hadley Meteorological Office. The Canadian GCM (CCCMA, 1997, model CGCM1) is a coupled atmosphere-ocean model having a surface resolution of approximately 3.75º x 3.75º and ten vertical levels. It includes an increase in atmospheric $CO_2$ at a 1% annual growth rate and the effect of sulphate aerosols. The Canadian GCM outputs have been projected onto the VEMAP 0.5º x 0.5º grid to allow for greater spatial specificity in determining local climate characteristics. Temporal GCM output resolution is monthly. The Canadian GCM is used at the recommendation of the U.S. National Climate Change and Variability Assessment to ensure consistency across various assessment sectors and activities. However it should be viewed as one of several possible choices. For comparison, this assessment also uses the GCM of the British Hadley Meteorological Office (UKMO, 2000, model HadCM2). The Hadley GCM is also a coupled atmosphere-ocean model with a surface resolution of 3.75º x 2.5º. The climate scenario generated by the Hadley GCM also assumes a 1% $CO^2$ annual increase. Figure 3.1 shows the location of the GCM surface grid nodes in relation to the ACF and ACT river basins.

Figures 3.2, 3.3, 3.4, and 3.5 depict the GCM annual temperature and rainfall predictions over the ACF and ACT river basins for the 1940 to 2099 period. Both models indicate increasing temperature trends, with the Canadian GCM exhibiting a steeper temperature rise. By contrast, the rainfall trends are inconsistent. The Canadian GCM predicts a sharp rainfall decline, while the Hadley a mild increase. The question, "Which model is more trustworthy?" does not have a definitive answer among climatologists at the present time. Our own comparative tests with the two models for the historical 1939 to 1993 period indicate that the Hadley GCM has more skill in replicating rainfall fluctuations over the ACF/ACT region than the Canadian GCM. In this assessment, however, both climate scenarios are used to investigate the potential impacts of climate change. The differences indicate the uncertainties associated with such long-range climate predictions, and the need to consider them in water resources planning and management.

## 3.2 Assessment Process

The assessment objective is to quantify the impacts of climate change on the water uses of the Southeastern US. Although some water uses are directly impacted by rainfall and temperature (e.g., agriculture), most are associated with the response of watersheds and river systems. Thus, in addition to the climate models, the assessment uses two more model groups, the first relating to watershed hydrology, and the second to river basin management. The hydrologic model is introduced here for the first time, while the river management model has recently been developed by the authors (Georgakakos and Yao, 1999) to support the on-going water allocation negotiations among the States of Georgia, Alabama, and Florida. It is important to note that the assessment is based on an integrated use of these models. Thus, climate models provide input to the hydrologic models which, in turn, provide input to the river basin management models. Lastly, the results of the river basin management models indicate what modifications would be necessary to make the hydrologic and climate model outputs more useful for future assessments.

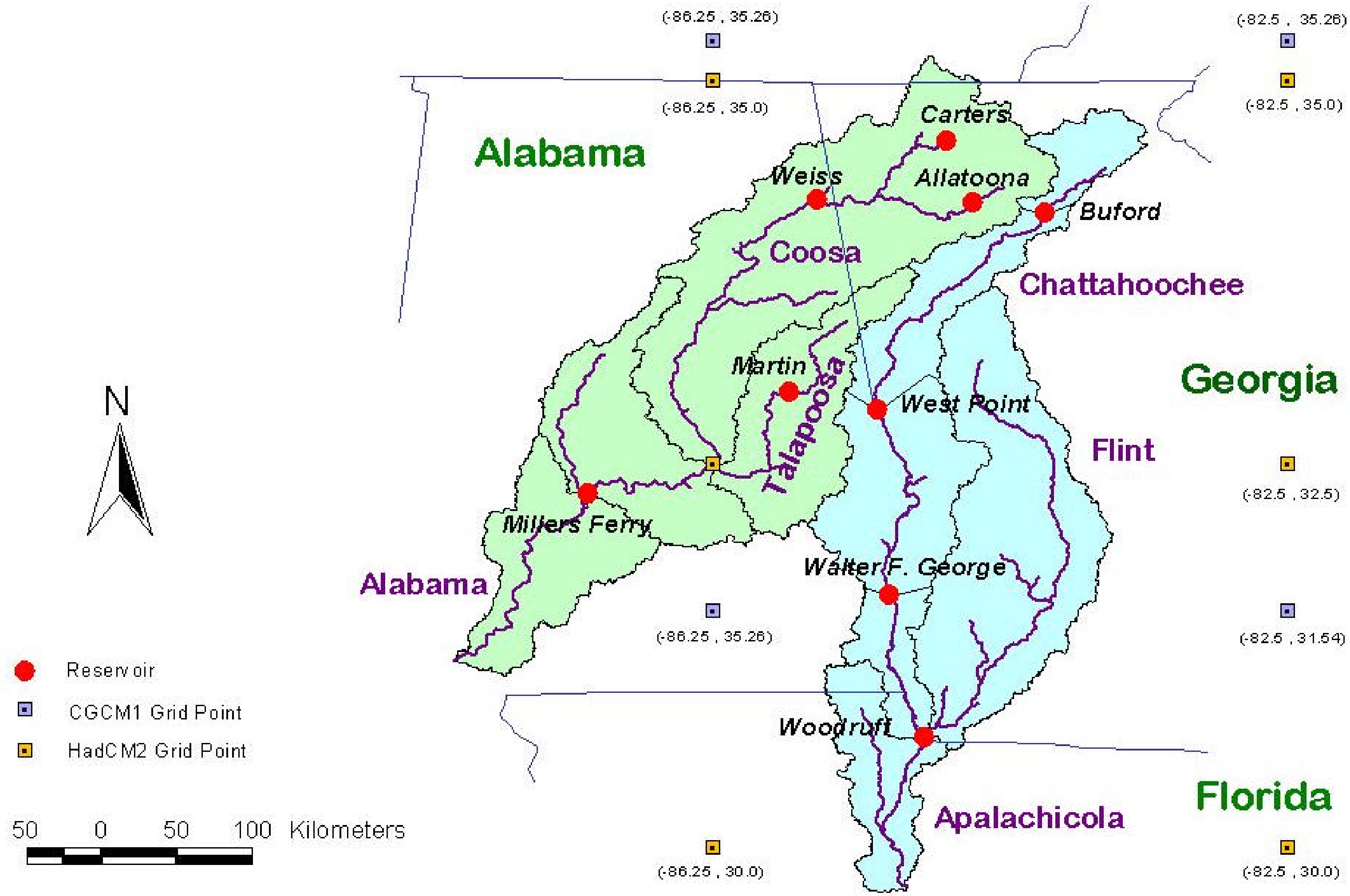



Figure 3.1: GCM Grid Points Near the ACF and ACT River Basins

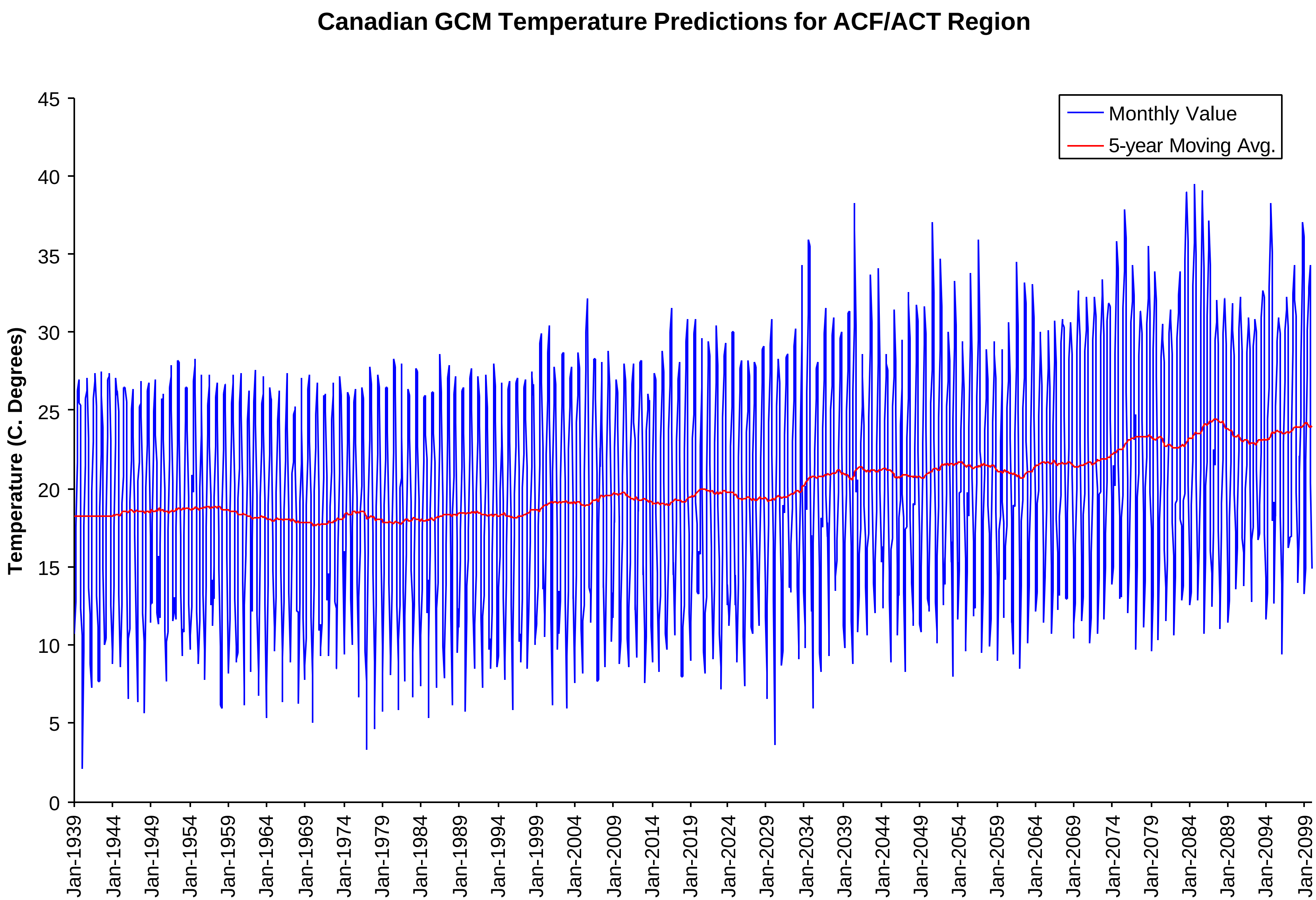



Figure 3.2: Canadian GCM Annual Temperature Predictions for the ACF/ACT Region

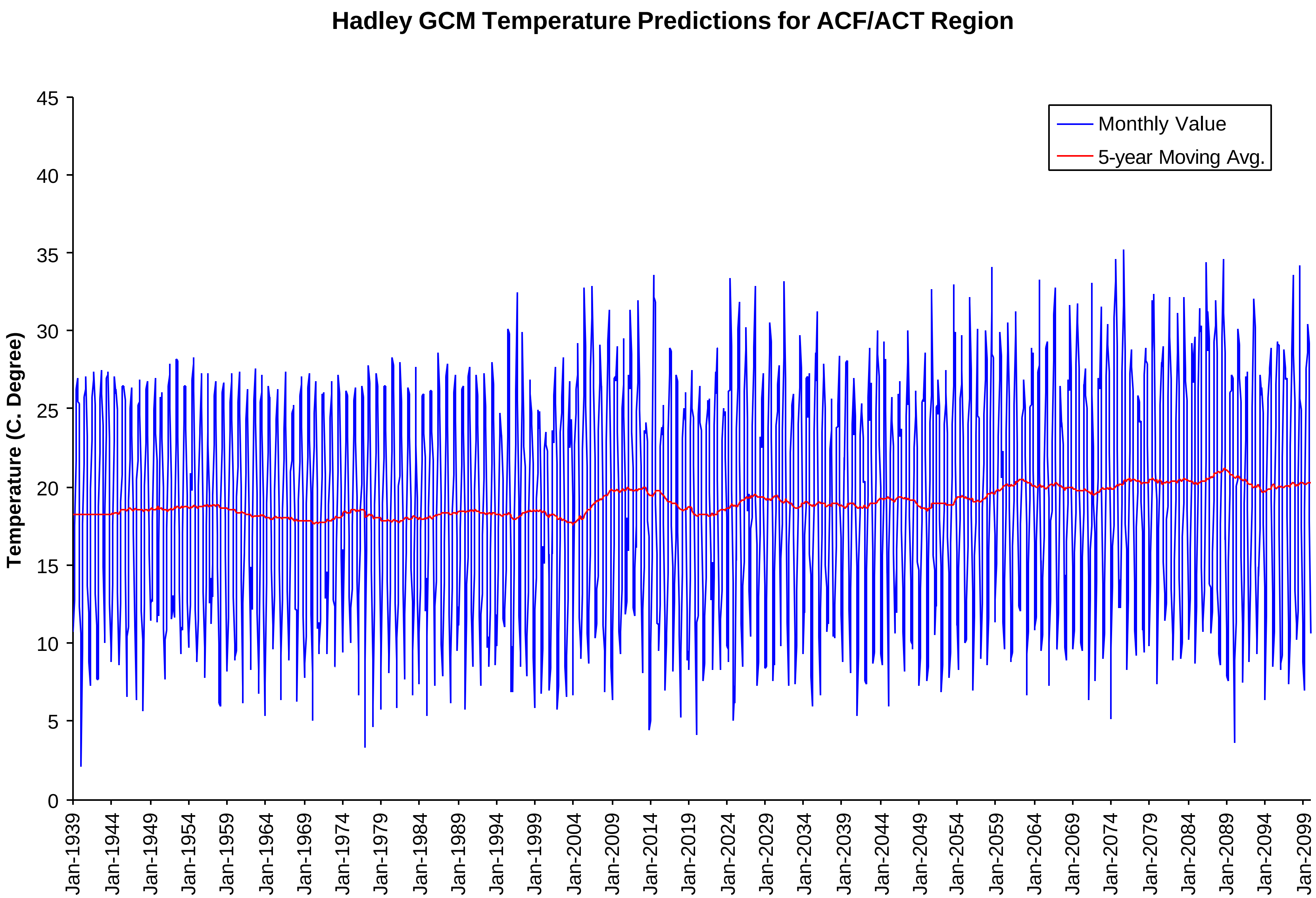



Figure 3.3: Hadley GCM Annual Temperature Predictions for the ACF/ACT Region

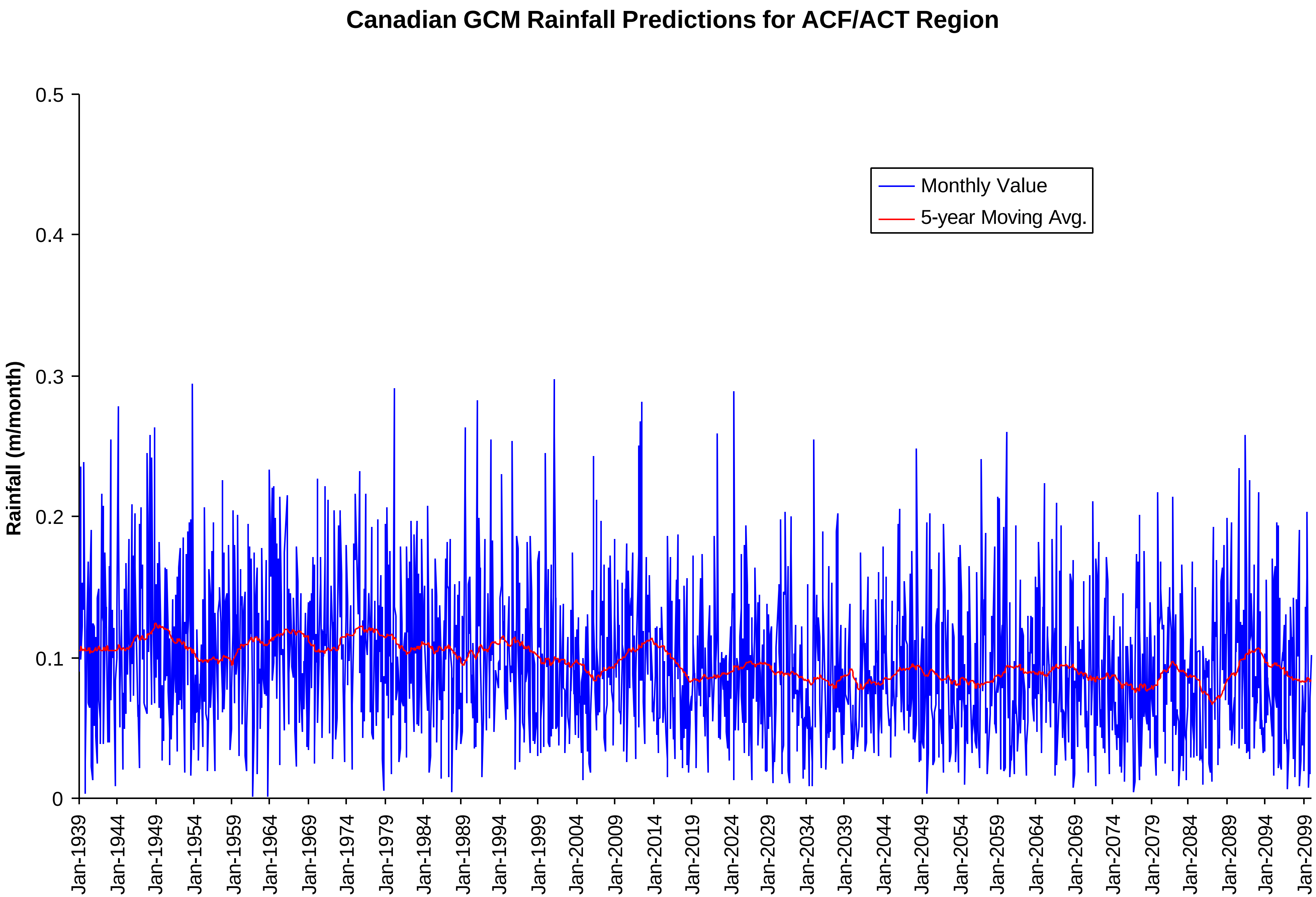



Figure 3.4: Canadian GCM Annual Rainfall Predictions for the ACF/ACT Region

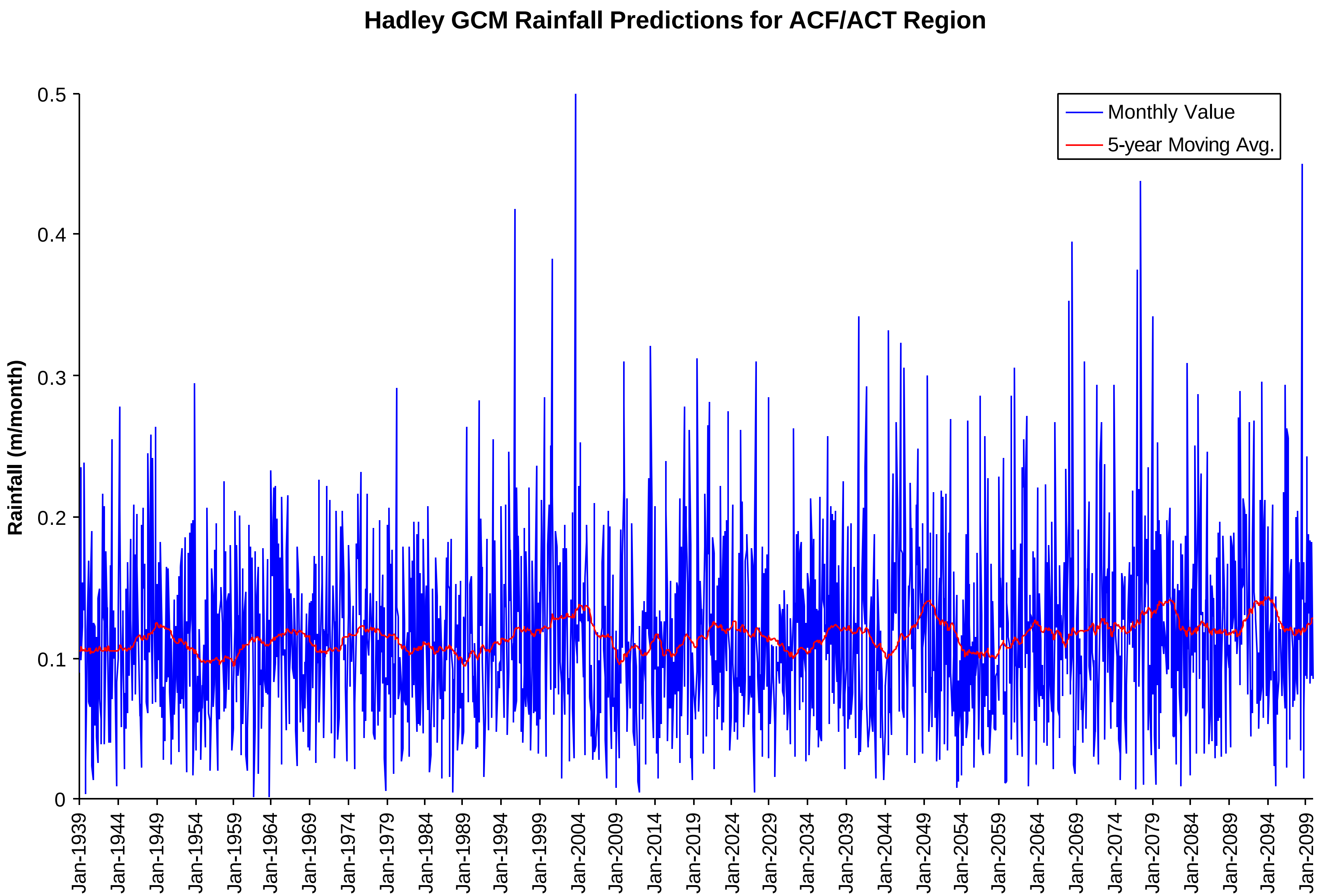



Figure 3.5: Hadley GCM Annual Rainfall Predictions for the ACF/ACT Region

# 4. Watershed Hydrology

## 4.1 Introduction

The next step in the assessment process (Section 3) is to convert the climate scenarios of rainfall and temperature to streamflow. One may consider several rainfall-runoff models, but the choice must be compatible with the study objectives and the other models used. The following general model selection guidelines were considered: (a) Compatibility with the time resolution of GCM outputs and river/reservoir model inputs; (b) sufficient skill to represent the relationship between atmospheric forcing and streamflow over a wide range of watershed response;(c) ease of implementation and parsimony.

In view of the time resolution of the other models used in the assessment, we restrict our attention to *monthly* hydrologic models. Such models have been developed and used by several investigators including Thornwaite,1948, Thornwaite and Mather, 1955, Palmer, 1965, Alley, 1984, Mohseni and Stefan, 1998, and Georgakakos and Baumer, 1996. The common basis for all these models is the watershed water balance and the representation of the processes that affect it, including rainfall, evapotranspiration, infiltration, percolation, runoff, and soil moisture storage. The models differ in the form and complexity of these representations. Application experience with the simpler (two to four parameter) models (Alley, 1984) shows that they have limited predictive skill and exhibit relatively low correlations between observed and simulated streamflows. These correlations range between 0.5 to 0.65 (Mohseni and Stefan, 1998) and indicate that these models can only account for 25 to 40% of the observed streamflow variance. Alternatively, the more complex models (Mohseni and Stefan, 1998, and Georgakakos and Baumer, 1996) exhibit higher correlations (between 0.7 to 0.9) and are able to explain a significant portion (50 to 80%) of the observed streamflow variance. However, they require more detailed watershed knowledge (soil type, soil porosity, land use, vegetation type, stream length, watershed slope, etc.) and include several unknown parameters (soil layer storage capacities, maximum percolation rates, water redistribution ratios, basin response constants, etc.) that call for elaborate calibration procedures. Thus, the effort to develop such models for all sub-watersheds of a large basin (e.g., the ACF) is significant and time consuming. Sufficiently skilled and easily implementable monthly hydrologic models are not readily available. The purpose of this section is to explore whether they can be developed.

## 4.2 A Conceptual Monthly Hydrologic Model

Our general approach is to start from simple rainfall-runoff associations and consider possible enhancements that would increase their predictive skill. As a first step, twelve monthly rainfall-streamflow models were developed through regression analysis of the historical record from 1939 to 1968 (30 years). The regressions were performed for each month using the corresponding observed rainfall and streamflow data. The models were then used to predict streamflow from the historically observed rainfall for the 1969 to 1993 time period. Table 4.1 reports the monthly correlations between observed and simulated streamflows for each of the four major ACF sub-watersheds. The correlations range from 0.2 to 0.9 and are generally higher for the winter months and the upstream watersheds. This is expected because (1) a much higher percentage of rainfall becomes streamflow during winter and (2) the Flint and the Lower Chattahoochee Rivers are hydraulically connected to the Upper Floridan Aquifer (Torak et al., 1996). Thus, monthly rainfall helps explain some portion of streamflow variability, but a significant portion remains unexplained.

The next step in this preliminary analysis is to consider both rainfall and potential evapotranspiration (PET) in the regression equations. PET is estimated based on the mean monthly temperature from the following equation (Dingman, 1994):

$$PET = 0.409 \times 6.11 \times \exp\left(\frac{17.3 \times T}{T + 237.3}\right) , \qquad (4.2.1)$$

where T denotes the mean monthly temperature in $^{o}$C, and PET is obtained in cm per month. Table 4.2 reports the correlation results for this case showing that some improvements are possible compared to the rainfall-based models, especially for the summer months, albeit with the addition of several more parameters. Overall, the performance of the regression models is reasonable but is inconsistent through the year. For all watersheds, there exist months where the correlation of the observed and predicted streamflows drops to 0.5 or even to 0.3 (e.g., for Woodruff). In what follows, these results will provide a baseline performance for comparison purposes.

The conceptual weakness of the regression models is that they do not allow for a lagged watershed response. In reality, streamflow at a particular month is the result of the atmospheric forcing in that month but also in preceding months. The cumulative history of the antecedent atmospheric forcing is reflected in the watershed water storage that mainly exists in soil moisture form. Thus, soil moisture, or some representative soil moisture index, would be a potentially useful explanatory variable for streamflow.

Let k denote a particular month, s(k) the watershed storage at the beginning of month k, P(k) the precipitation during month k, Q(k) the streamflow, and PET(k) the potential evapotranspiration estimated from Equation (4.2.1). Then, the watershed water balance could be stated as follows:

$$s(k+1) = s(k) + P(k) - PET(k)\ [\alpha\ s(k) + \beta] - \gamma\ s(k) - Q(k), \qquad (4.2.2)$$

where $\alpha$, $\beta$, and $\gamma$ are model parameters. Apart from streamflow [Q(k)], Equation (4.2.2) includes two additional loss terms. The first represents evapotranspiration occurring at the potential rate applied to the current storage, and the second represents percolation to groundwater aquifers. These terms could take many different functional forms. In fact, several other forms were also tried. It turns out that Equation (4.2.2) is most effective, while additionally being simple. The most likely reason is that the loss terms represent spatially-averaged processes. Although these processes are locally best represented through nonlinear (even threshold-type) laws, their integrated effect across the watershed becomes linearized. The high spatial variability of watershed characteristics and soil moisture is an important factor contributing to this linear average response.

To be complete, Equation (4.2.2) requires a relationship between streamflow and the quantities known at time k. For example, Q(k) could be functionally related to s(k) and P(k) with a few more calibration parameters. This, however, would not be any different from the approaches mentioned in the introductory section (e.g., Thorntwaite and Mather, 1955, Palmer, 1965), and would not lead to any significant model performance improvements.

The conceptual difference of this work is that we view the water balance equation (4.2.2) as a means to generate a soil moisture *index*, not necessarily the soil moisture itself. An index can have a different variation range than the quantity it serves to indicate, but it is useful if its variation is relatively similar to the variation of the true quantity. Thus, rather than directly relating streamflow to particular model quantities, we seek to establish a correspondence based on *relative* variations.

What would be the attributes of an ideal streamflow index? Denote IQ such an unknown index. IQ would be an ideal index for Q, if and only if $IQ_1 \leq IQ_2$ implies and is implied by $Q_1 \leq Q_2$ for all [$IQ_1$, $IQ_2$] and [$Q_1$, $Q_2$] pairs in the respective ranges of IQ and Q. (Note that if IQ and Q were linearly related, this condition would hold, but the reverse is not always true. Namely, an ideal index does not *have* to be linearly related to the quantity it indicates.) However, the previous condition implies that the events $\{IQ \leq IQ_2\}$ and $\{Q \leq Q_2\}$, where $IQ_2$ and $Q_2$ are two specific values in the IQ and Q variable range, occur with the same frequency. Namely,

$$\Pr obability\{IQ \leq IQ_2\} \equiv \Pr obability\{Q \leq Q_2\}. \qquad (4.2.3)$$

This frequency equivalence applied to all values of $IQ_2$ and $Q_2$ is a necessary condition for IQ to be an ideal index for Q. (We note that this is not a sufficient condition as two variables for which it is valid are not necessarily ideal indicators of each other.)

Equation (4.2.3) provides the mathematical justification for estimating streamflow based on frequency matching with model-generated variables. There are several ways to accomplish this. Two are described below. Consider first a hydrologic period for which monthly watershed rainfall, temperature, and streamflow are available. For some specific α, β, γ, and s(0) values, Equation (4.2.2) can be iterated to yield a monthly sequence [s(k), k=0,1,...,N]. Next, for some value of δ in the range [0,1], the following quantity can be computed,

$$IQ(k) = \delta\ s(k) + (1 - \delta)\ P(k), \tag{4.2.4}$$

where δ is a parameter placing more emphasis on s(k) or P(k), depending on which variable is better associated with streamflow . The monthly frequency position (or rank) of IQ and Q (after ordering the data in a descending order) can next be computed, and the model parameters (α, β, γ, and δ) can be determined such that the monthly frequency differences of IQ(k) and Q(k) are minimized. (s(0) can be set equal to an appropriate monthly average soil moisture value.) This can be accomplished by minimizing the sum of squares of the frequency position differences, or the sum of their absolute values. The smaller these differences, the better streamflow index IQ will be. Note that index IQ could also include an evapotranspiration term, or it could have assumed another functional form. For example, an interesting possibility is to determine δ such that the quantity [$\delta\ F_{s(k)} + (1-\delta)\ F_{P(k)}$] approximates $F_{Q(k)}$ as closely as possible, where $F_{s(k)}$ , $F_{P(k)}$ , and $F_{Q(k)}$ denote the frequency positions of s(k), P(k), and Q(k) respectively. While the parameter calibration procedure does not depend on the specific index form, the verification exercises showed that both of these options perform well.

If a sample of N observations is available for a variable X, the frequency position of a new observation x can be estimated using, for example, the Cunane formula:

$$F_X = \Pr obability\{X \le x\} = 1 - \frac{m_X - 0.4}{N + 0.2}, \tag{4.2.5}$$

where $m_x$ is the rank of x among the N available observations ranked in a descending order.

When the model is used in predictive mode, the IQ value for the current month can be computed from (4.2.4), and the IQ frequency position can be estimated from the past IQ values for that month from (4.2.5). Then, based on the correspondence between IQ and Q (e.g., Equation 4.2.3), one can assume that streamflow will take on a value that has the same frequency position as the IQ, and thus determine its magnitude based on the frequency distribution of past observed streamflows.

Another, more convenient model calibration approach would be to use a second hydrologic period with observed rainfall, temperature, and streamflow and minimize the square difference of the observed and simulated streamflows. Although this procedure uses a different minimization criterion, it too identifies parameters that match the frequency positions of IQ and Q. In this case, the control data set for determining the frequency distributions of IQ and Q and for selecting Q should not include data from the second hydrologic record.

## 4.3 Model Verification

The previous hydrologic model was applied to four ACF sub-basins including Lanier, West Point, George, and Woodruff. Model calibration was performed using the 1939 to 1968 historical record, while the period from 1969 to 1993 was used for model verification. Results are presented for the streamflow index defined in Equation (4.2.4) with the parameters calibrated using the second calibration approach. The other options lead to similar model performance. The optimal model parameters are reported in Table 4.3. Figures 4.1 through 4.4 present the results for each watershed. The top panels of these figures depict the monthly means and standard deviations of the observed and simulated streamflows for the verification period (1969 to 1993) and for the observed streamflows for the calibration period (1939 to 1968); the middle panels depict the observed and simulated streamflow sequences for the verification period; and the bottom panels depict the simulated soil moisture sequences for the entire record. The results support the following conclusions:

- The model reproduces the streamflow climatology fairly well, both relative to the mean as well as the standard deviation. For Lanier and West Point, the two upstream watersheds, the correspondence is very good throughout the year. For George, some discrepancies exist for the summer and early fall where the mean simulated streamflow is somewhat higher than the mean observed streamflow. For Woodruff, discrepancies exist in the first three months of the year where the mean simulated streamflow is somewhat lower than the mean observed streamflow. These differences, however, are also present between the observed streamflows of the calibration and verification periods and are most likely due to recent changes in the pumping patterns of the Upper Floridan Aquifer.

- The middle panels show that simulated streamflows follow the observed streamflows rather well. Table 4.4 reports the monthly correlation statistics and indicates a marked improvement over the regression models of the previous section. For example, the average monthly correlation coefficient for Lanier is 0.92, for West Point 0.89, for George 0.87, and for Woodruff 0.87. This implies that the models explain 80% or more of the observed streamflow variance. Rainfall, temperature, and streamflow data uncertainties probably account for most of the unexplained portion.

- The simulated soil moisture sequence for West Point is somewhat lower than for Lanier. This is expected because West Point is at a lower latitude and elevation than Lanier, and a higher portion of its rainfall evapotranspires. This trend, however, is reversed for George the soil moisture of which is between Lanier's and West Point's, and for Woodruff which exhibits the highest soil moisture levels among all watersheds. This difference occurs because George and Woodruff are influenced by the Upper Floridan Aquifer.

- The optimal $\delta$ values indicate the importance of soil moisture (or watershed storage) for streamflow generation. The optimal streamflow index (Equation 4.2.4) is based 35 to 45% on soil moisture and 65 to 55% respectively on rainfall. This is the main reason that the model developed herein is clearly better than the regression models. For the same rainfall and temperature conditions, the latter generate the same streamflow. In reality, however, this happens only if soil moisture is also at a similar state.

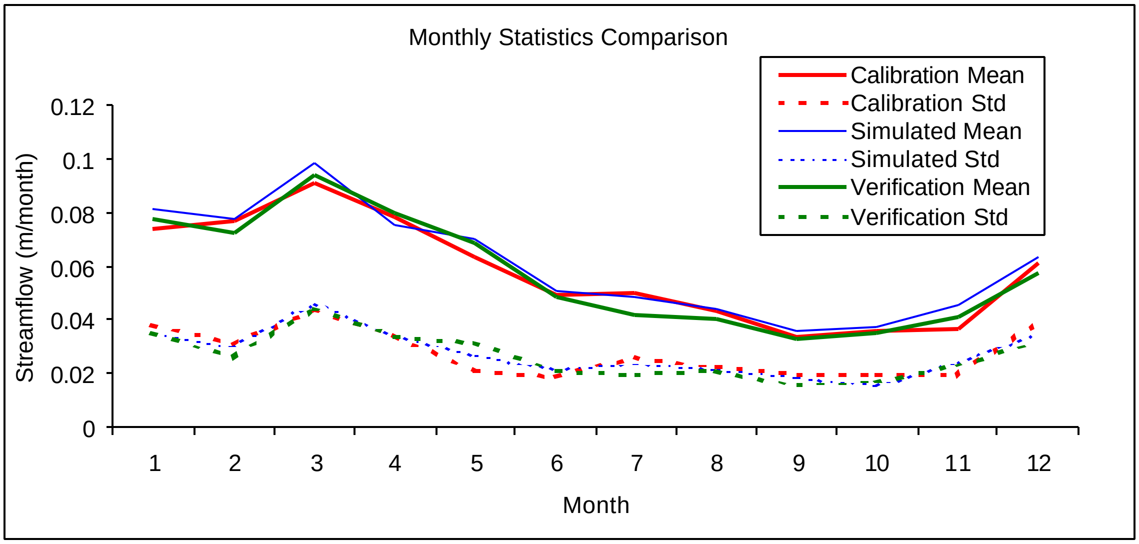
## 4.4 Climate Change Assessments

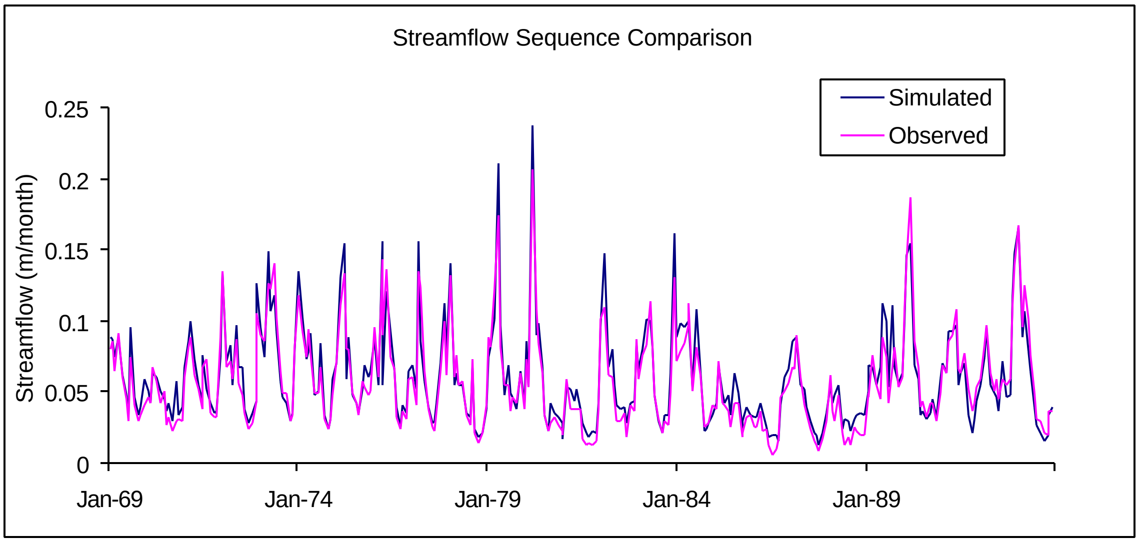
In this section, we use the climate scenarios generated by the Canadian and the Hadley GCMs to assess the potential response of the ACF sub-basins. We also repeat the assessment for four ACT sub-basins. The analysis is straightforward. The GCM rainfall and temperature scenarios are used as atmospheric forcing in the hydrologic models which generate sequences of soil moisture and streamflow. The control data set for the frequency matching includes all historical data from 1939 to 1993. The climatic variability of the 65-year historical record is significant, including both wet periods and extreme droughts. It is thus expected that most future conditions will be within this range, and the assumption of streamflow generation based on frequency matching with historical data will be applicable. We will comment on this assumption after the presentation of the results.

Figures 4.5, 4.6, 4.7, and 4.8 present the ACF response for the Canadian GCM climate scenario, and Figures 4.9, 4.10, 4.11, and 4.12 present the results for the Hadley GCM climate scenario. The figures include four panels comparing GCM statistics with those of the historical record. The statistics include monthly means and standard deviations for rainfall (first panel), potential evapotranspiration (second panel), soil moisture (third panel), and streamflow (fourth panel). Table 4.5 summarizes the results relative to annual precipitation, evapotranspiration, runoff (streamflow), and runoff coefficient (ratio of runoff to precipitation) for the four ACF and ACT basins . The following comments can be noted:

- Compared to the historical (baseline) response, under the Canadian Climate Scenario, all basins exhibit less precipitation (ranging from 15 to 22 % of the historical values), increased evapotranspiration (16 to 22 % of the historical values), less runoff (28 to 48% of the historical values), and smaller runoff coefficients (13 to 35 % of the historical values). By contrast, under the Hadley Climate Scenario, the basins experience higher precipitation (7 to 14 % of the historical values), higher evapotranspiration (8 to 11 % of the historical values), higher runoff (7 to 21 % of the historical values), and higher runoff coefficients (1 to 10 % of the historical values). The Canadian GCM scenario indicates that the rainfall peak that usually occurs in July will shift to June throughout the ACF, and PET will peak somewhat later in August. The Hadley GCM indicates no appreciable seasonal shift for any variable. Both models record consistent changes in mean and variability. Namely, higher mean runoff exhibits higher variability. As will be discussed next, soil moisture is an exception to this tendency.

- Soil moisture is expected to decline sharply (by as much as 30 to 40%) under the Canadian Climate Scenario, and somewhat increase (by 10 to 20%) under the Hadley Scenario. Figure 4.13 portrays the simulated soil moisture sequences (normalized by their historical levels) for the four ACF sub-basins, and clearly depicts these trends. The figure also indicates the soil moisture tendency to become more and more variable under both scenarios. We note that the CGCM soil moisture sequences significantly exceed the range of their historical variation. In view of this, during extreme and prolonged droughts, the hydrologic model is expected to somewhat over-estimate runoff and under-estimate soil moisture. These corrections, however, are marginal and in no way alter the striking trends shown in the figure. The Hadley scenario stays around the historical variation range and is less liable to such discrepancies. Lastly, Figure 4.14 shows the soil moisture frequency curves (with all months included) for the ACF sub-basins. The downward shift of the Canadian GCM soil moisture relative to the historical and the Hadley scenarios is clear. The figures show the tendency of the Hadley GCM to generate higher than historical wet extremes, and the tendency of the Canadian GCM to generate worse than historical droughts.



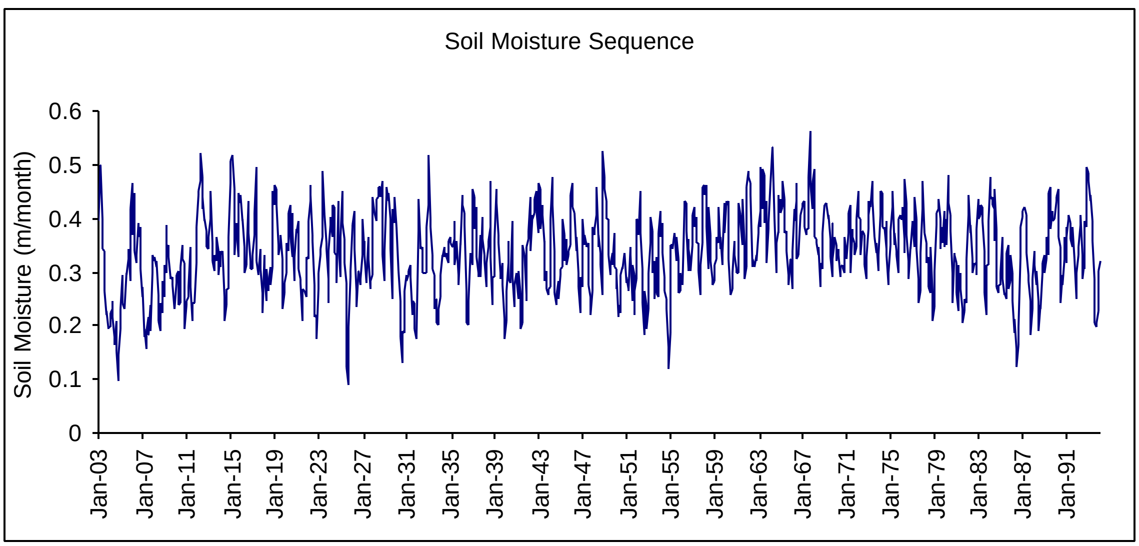
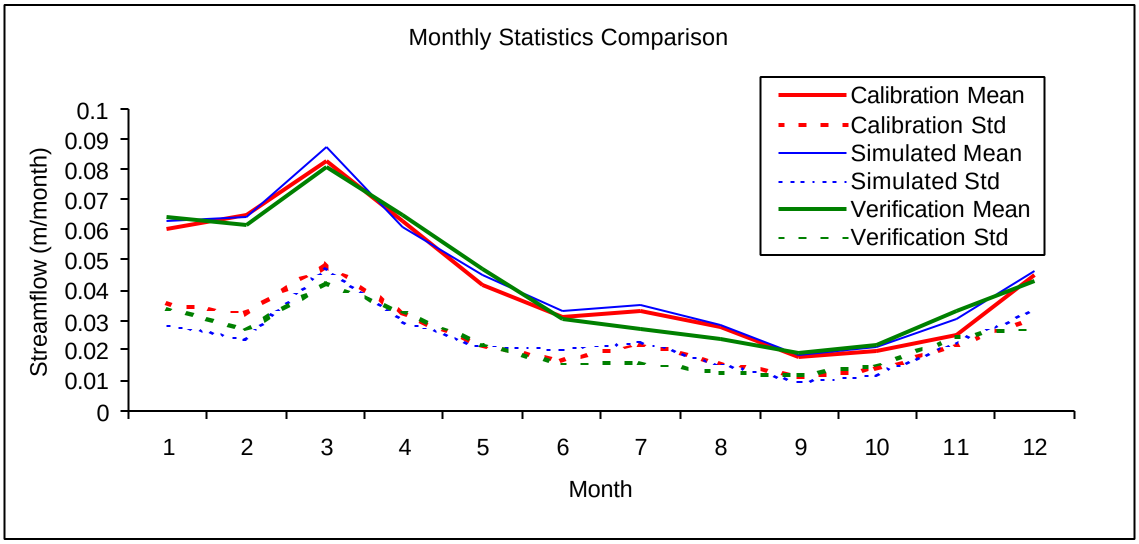
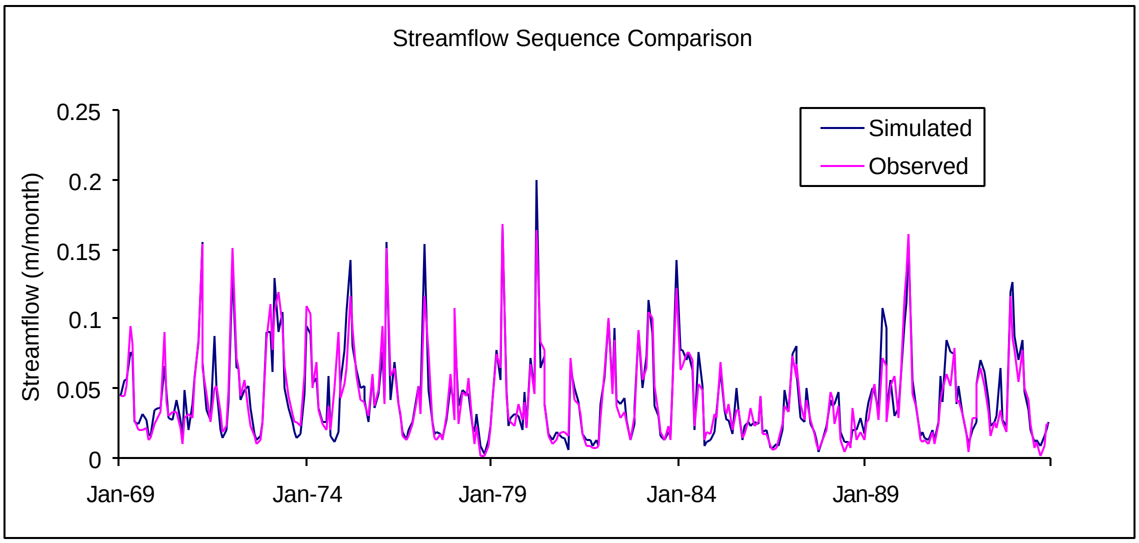




Figure 4.1: Streamflow Model Calibration Results; Lanier



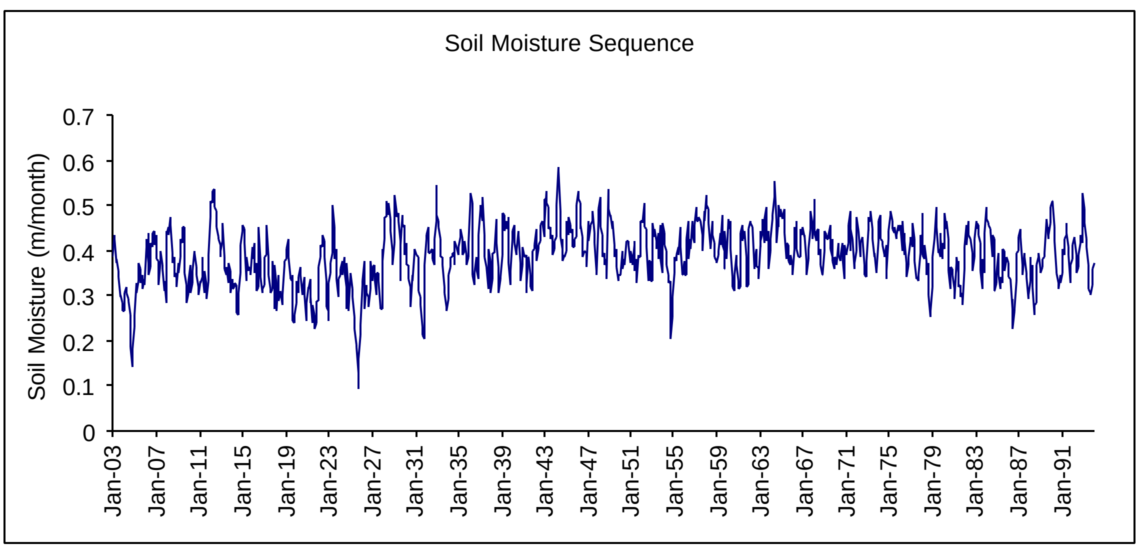
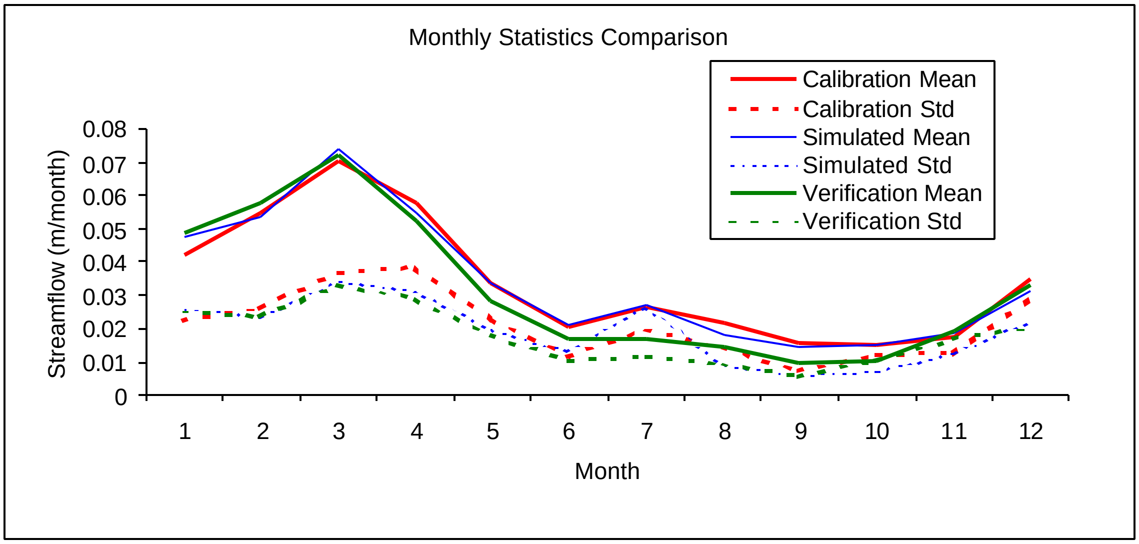
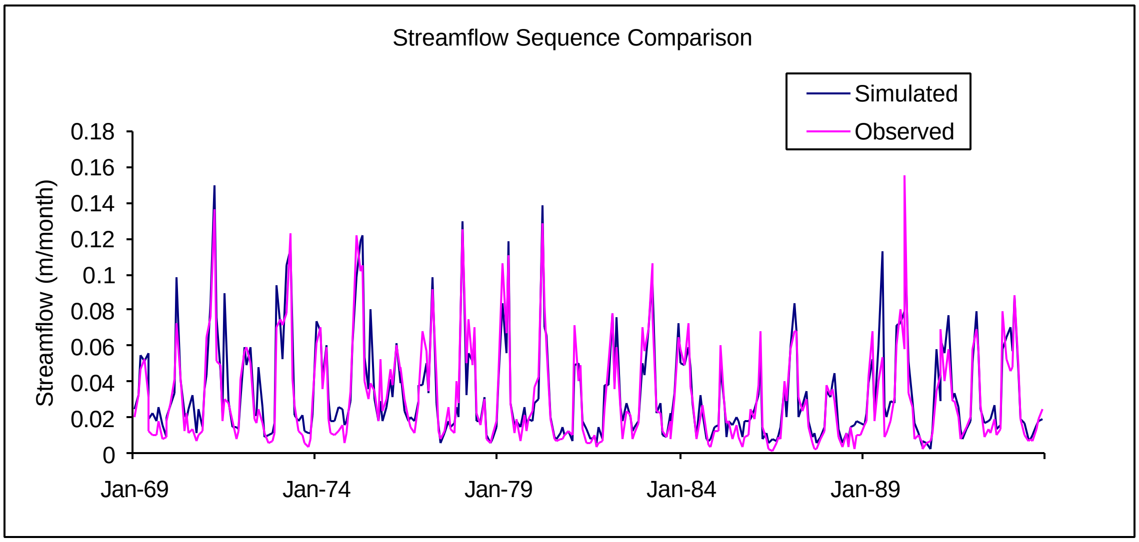




Figure 4.2: Streamflow Model Calibration Results; West Point



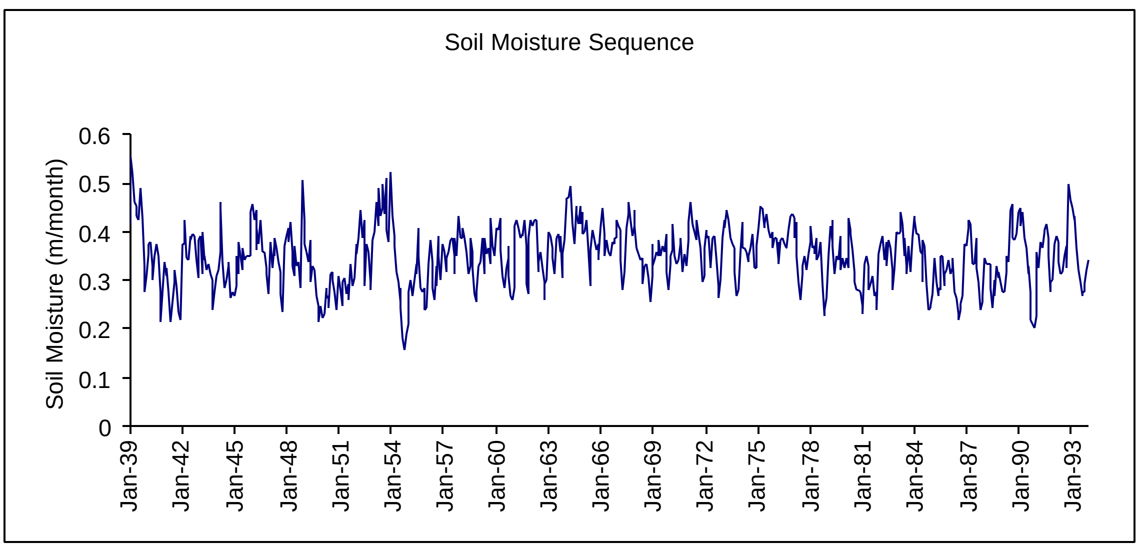




Figure 4.3: Streamflow Model Calibration Results; George

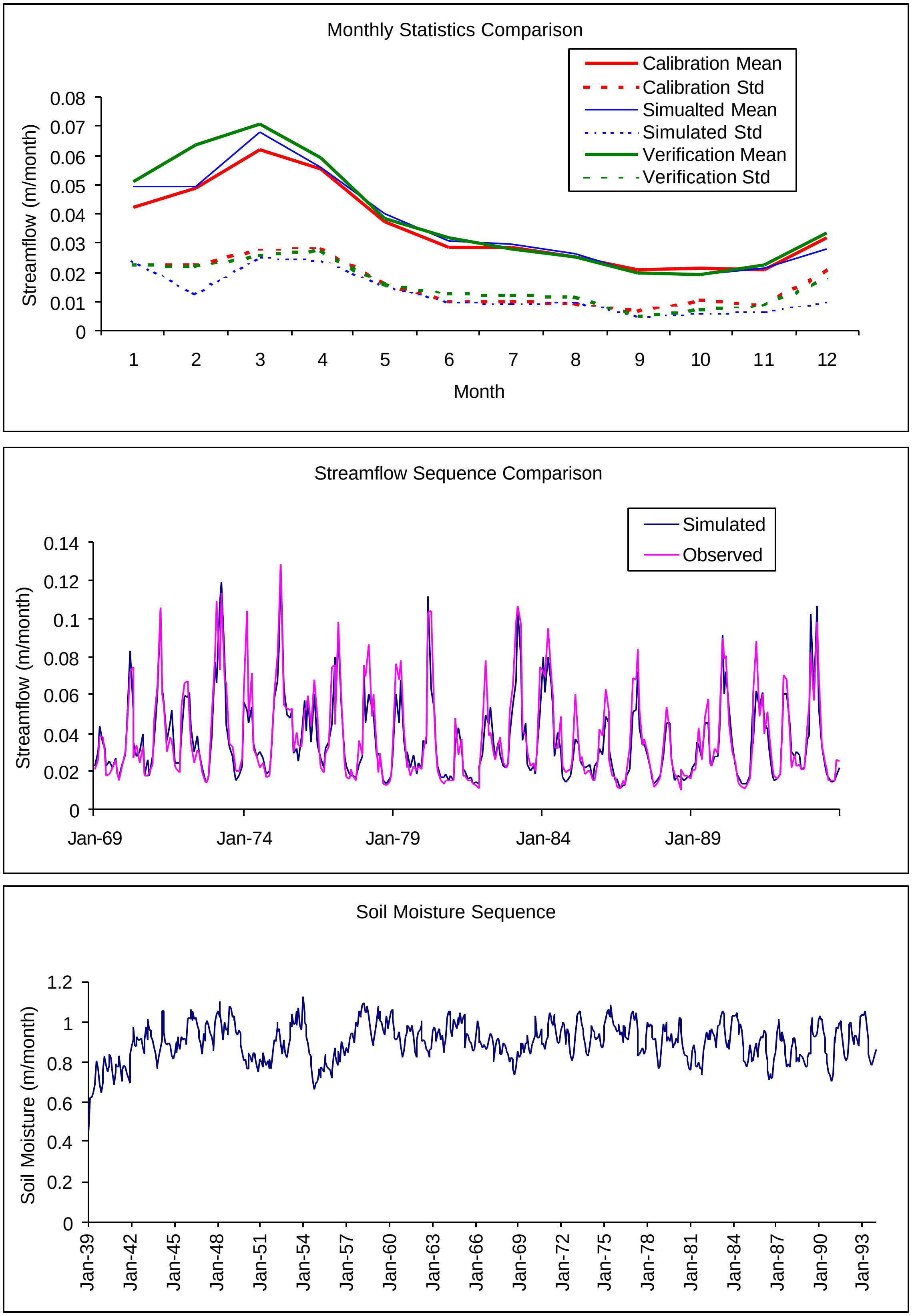



Figure 4.4: Streamflow Model Calibration Results; Woodruff

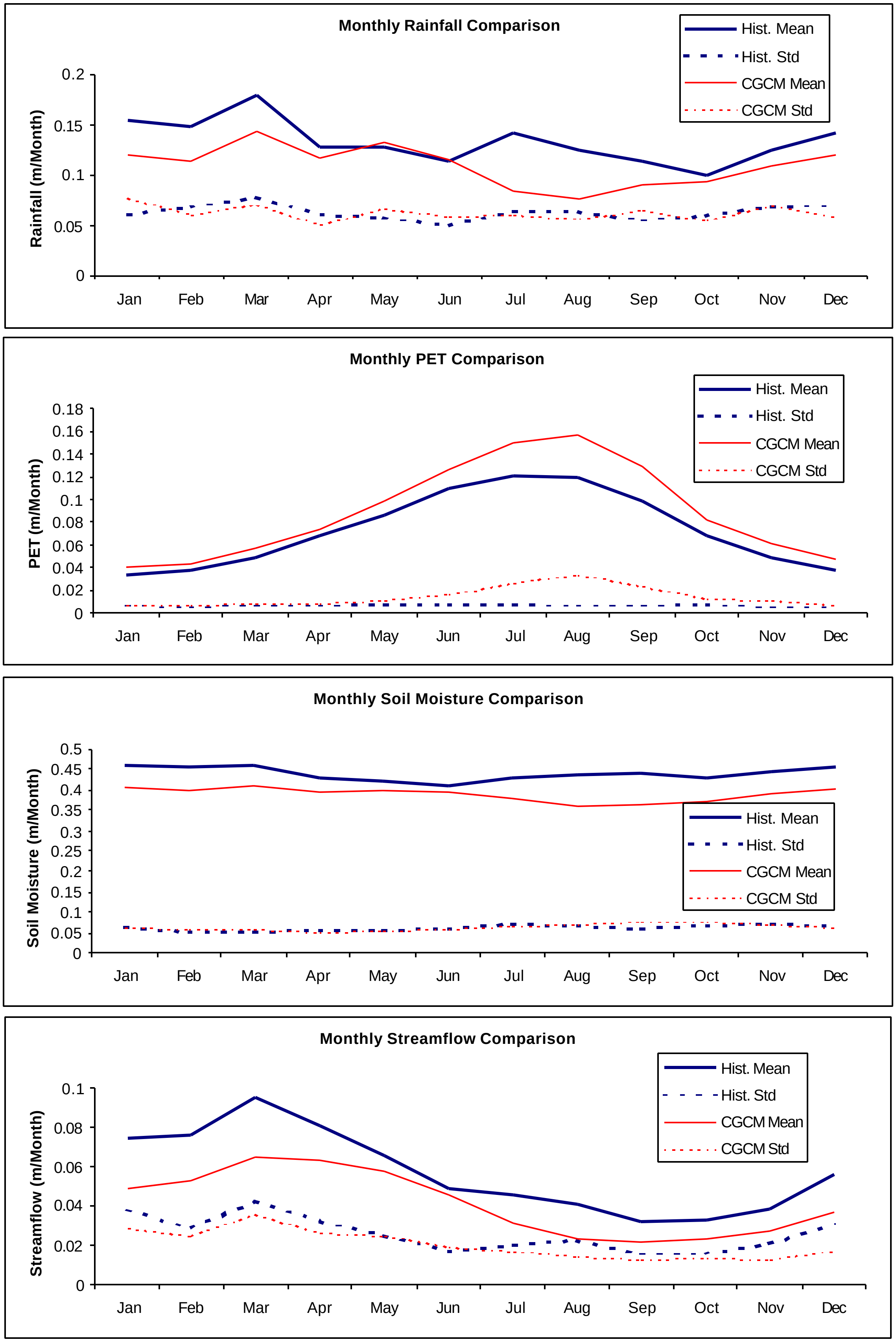



Figure 4.5: Canadian GMC Climate Assessment; Lanier

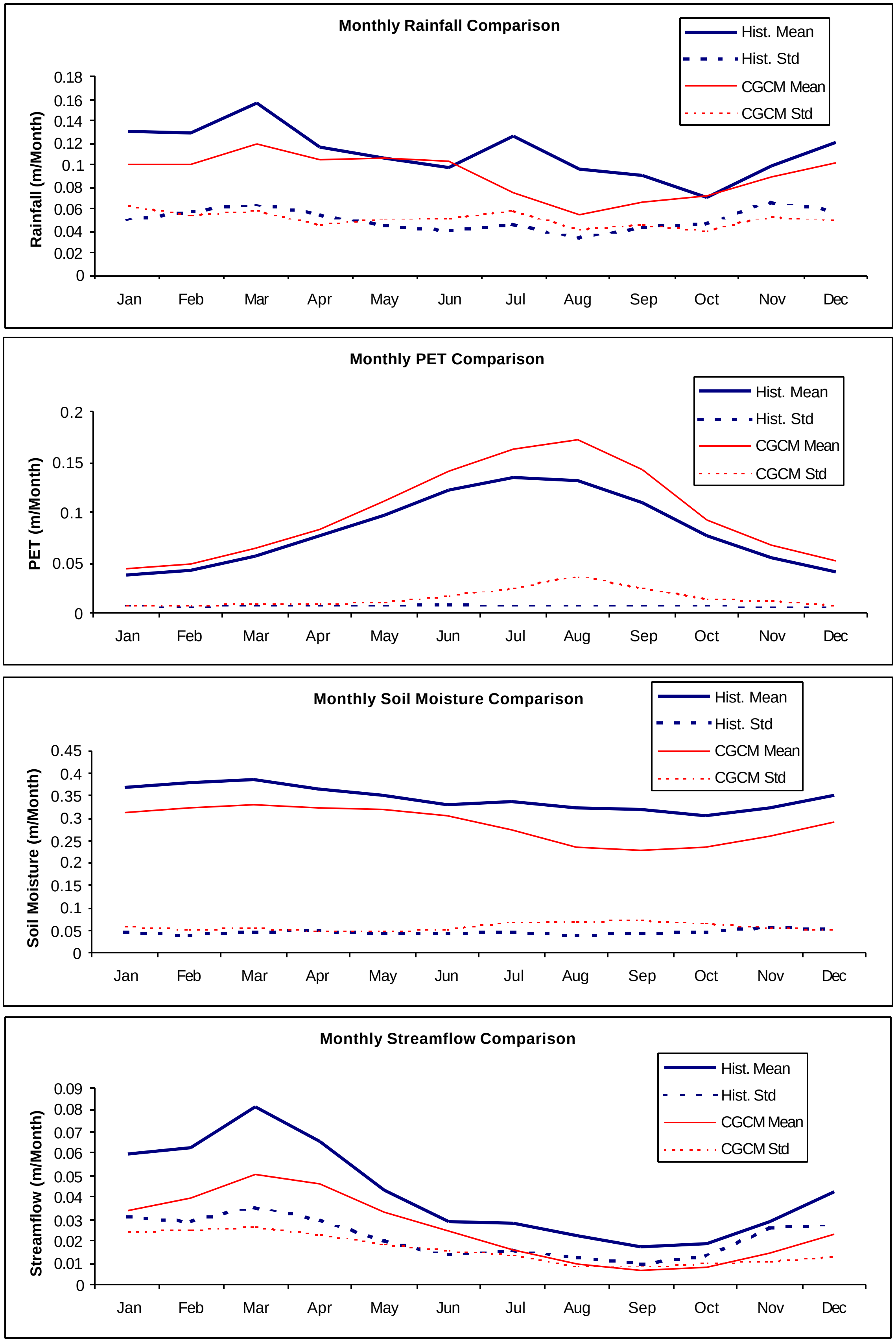



Figure 4.6: Canadian GMC Climate Assessment; West Point

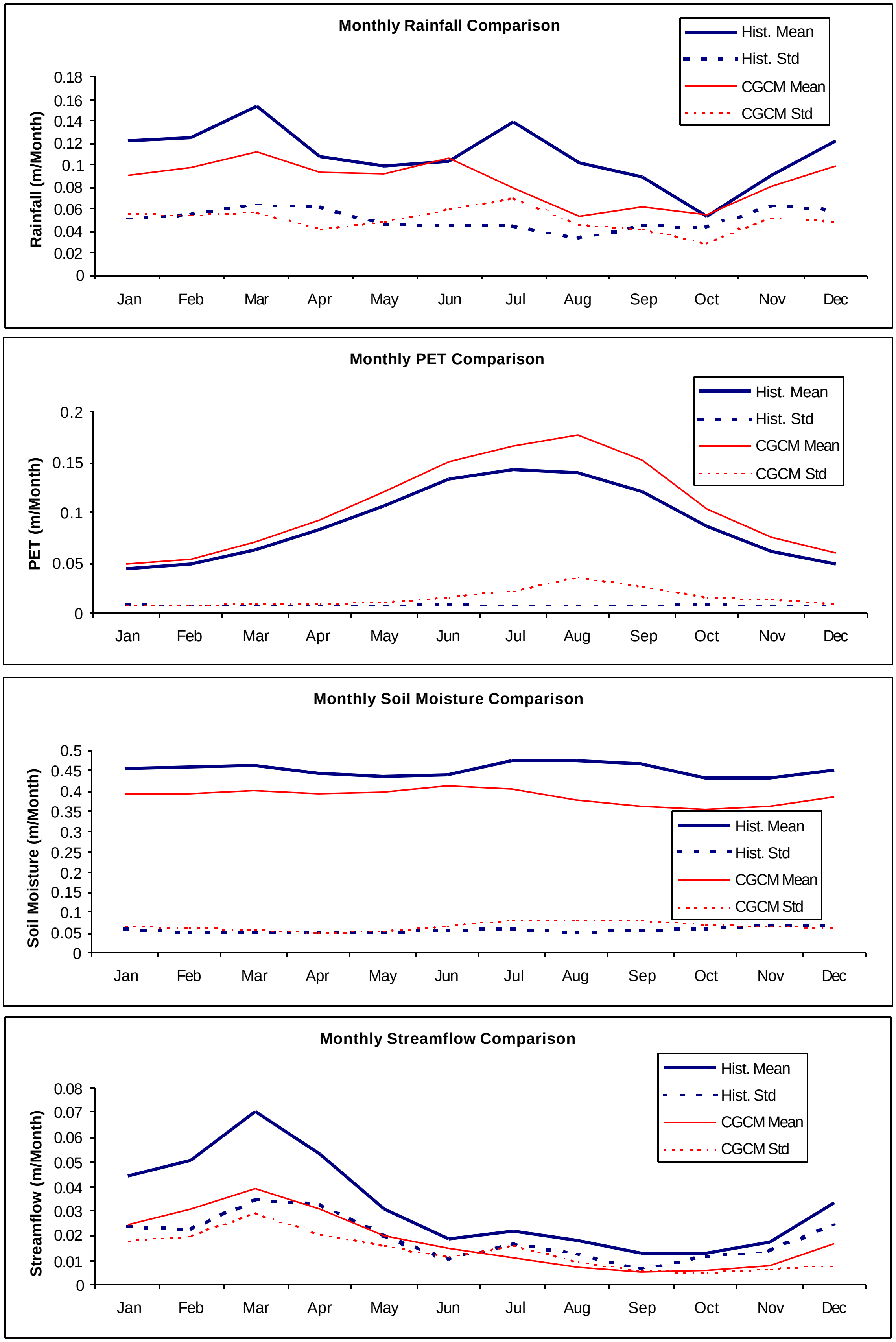



Figure 4.7: Canadian GMC Climate Assessment; George

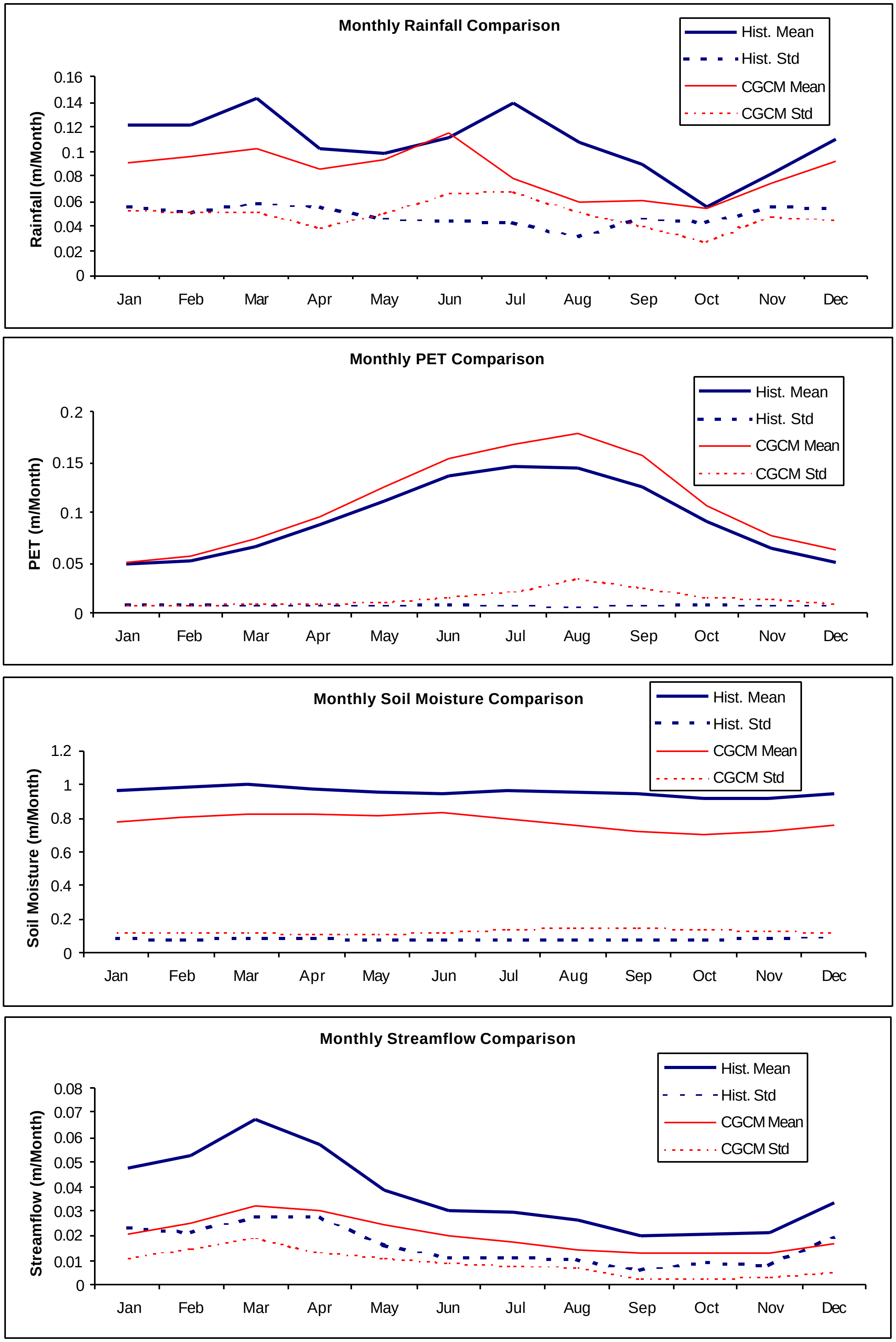



Figure 4.8: Canadian GMC Climate Assessment; Woodruff

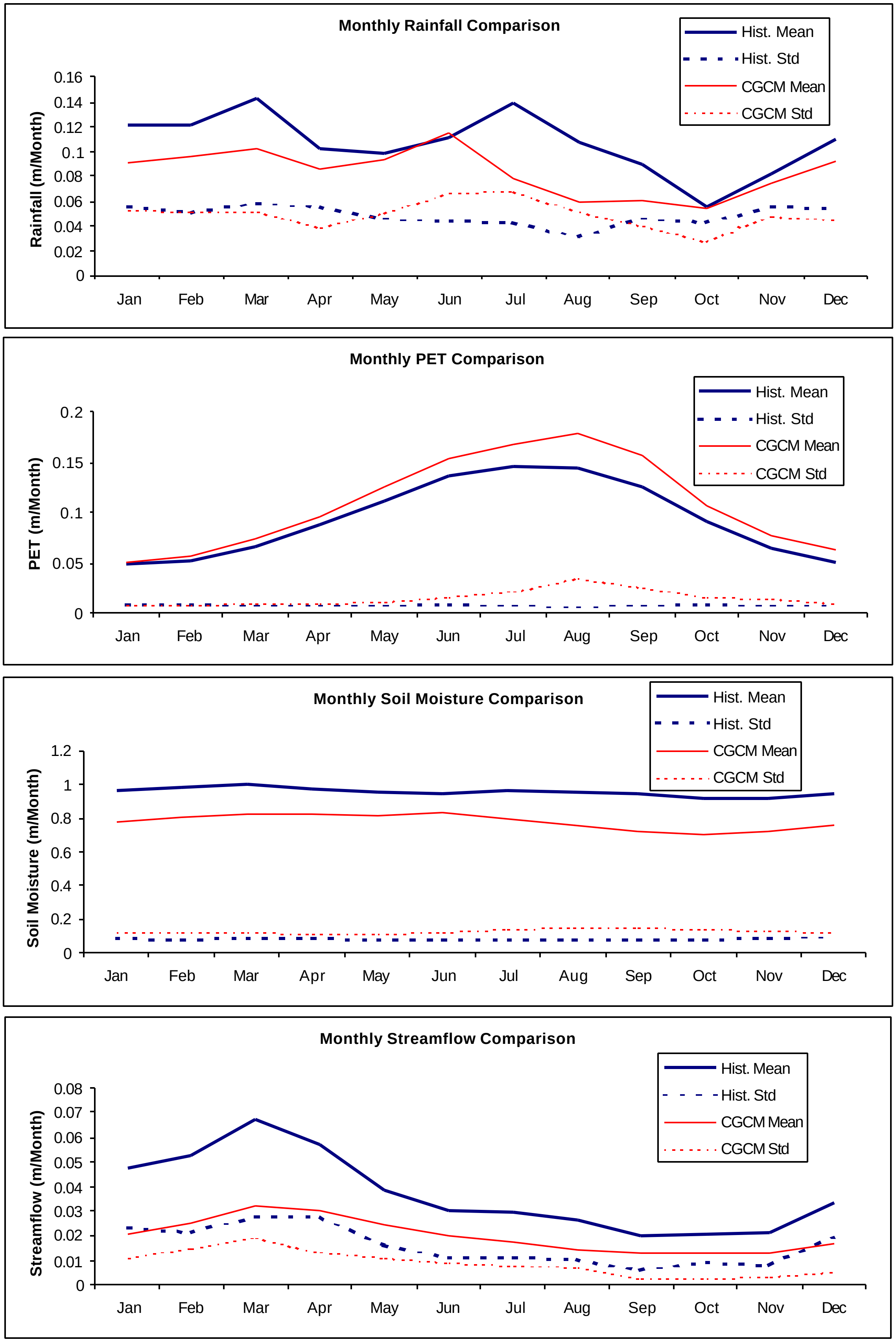



Figure 4.9: Hadley GMC Climate Assessment; Lanier

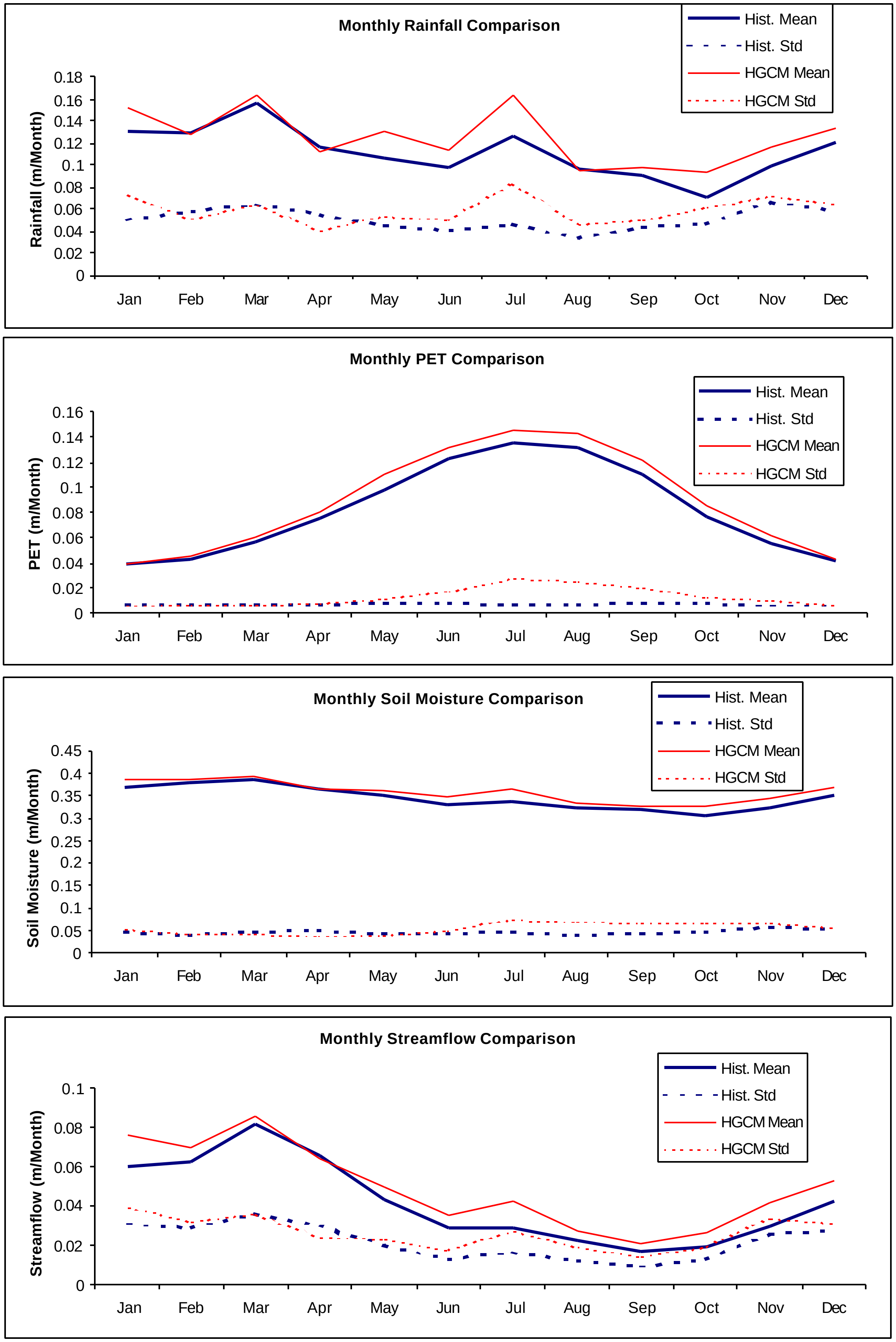



Figure 4.10: Hadley GMC Climate Assessment; West Point

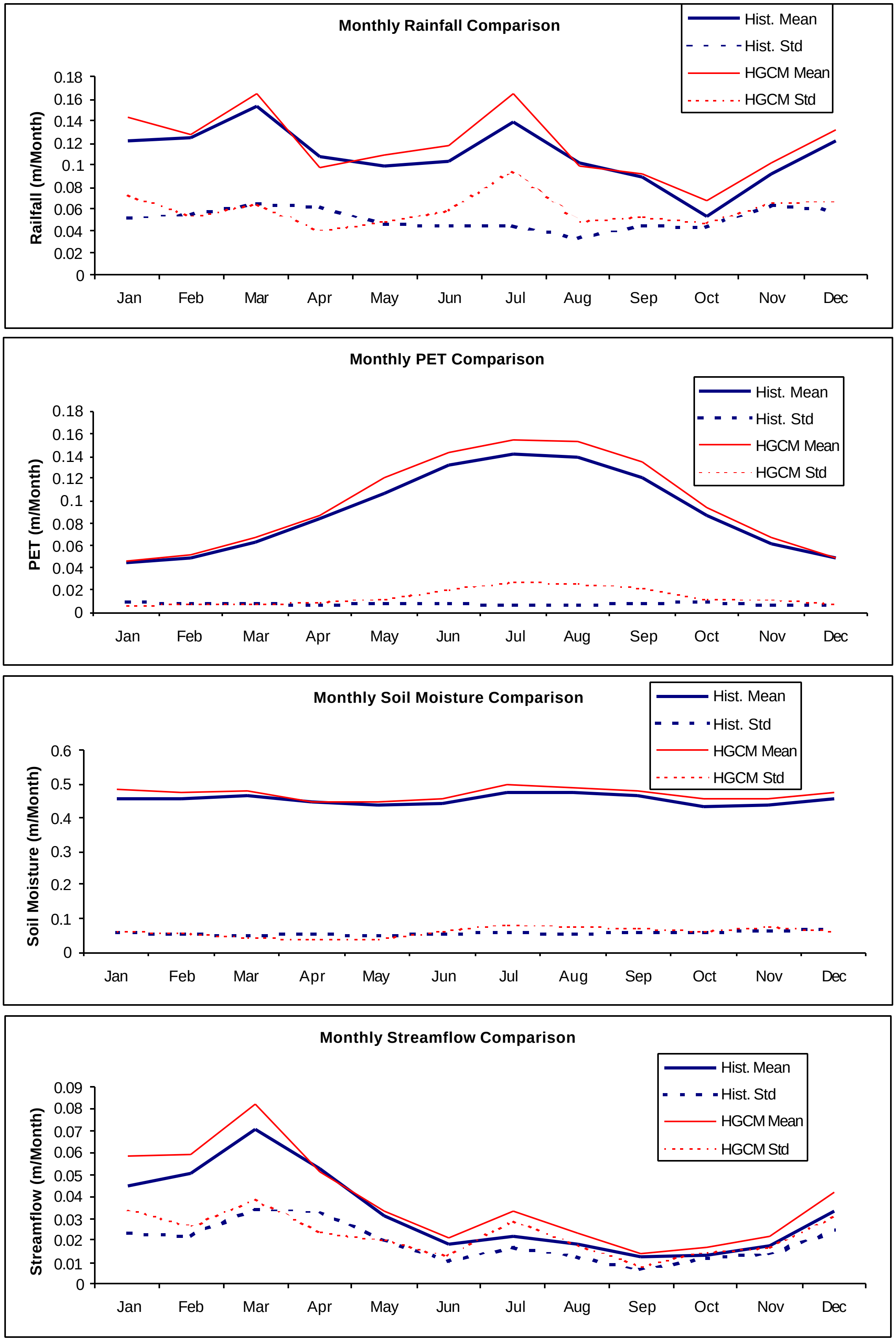
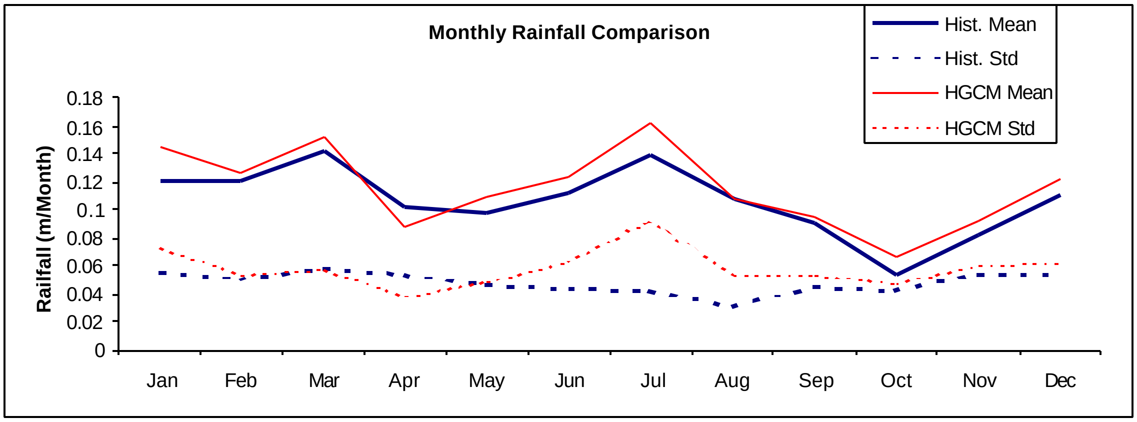
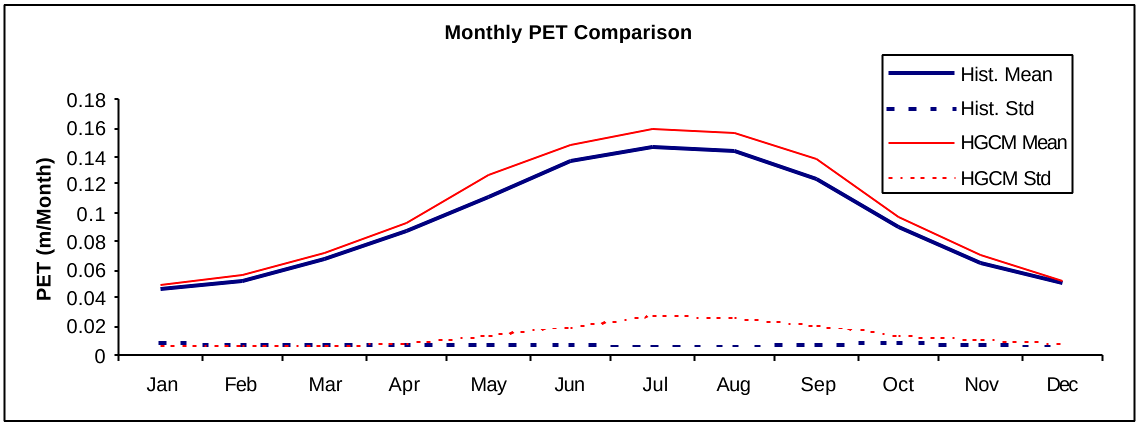
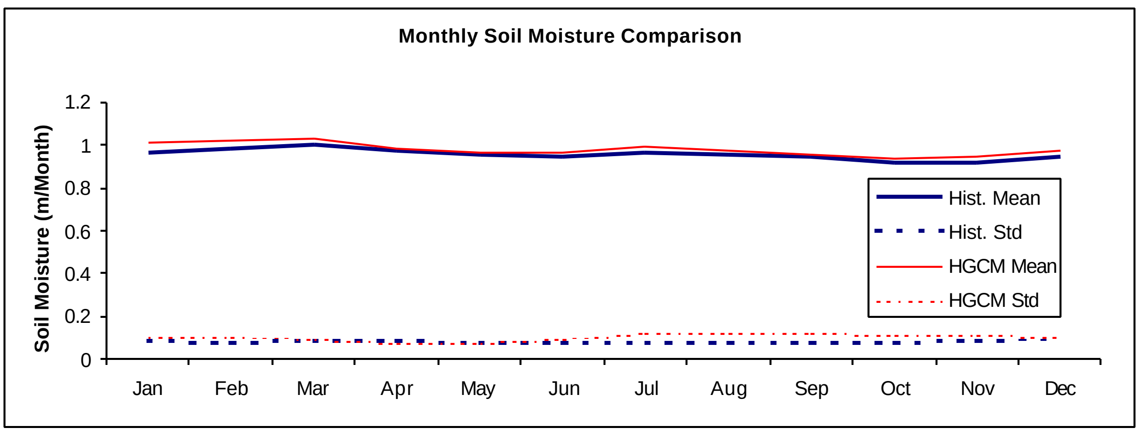



Figure 4.11: Hadley GMC Climate Assessment; George



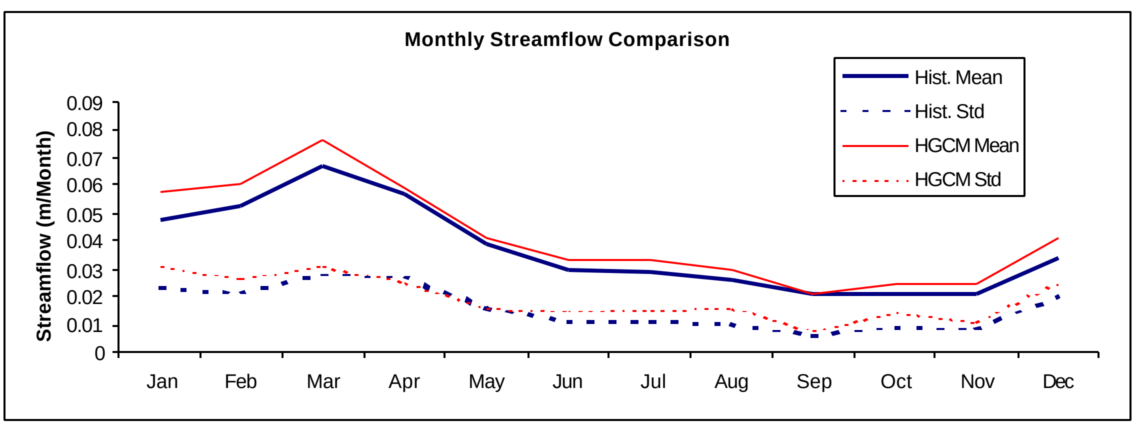




Figure 4.12: Hadley GMC Climate Assessment; Woodruff

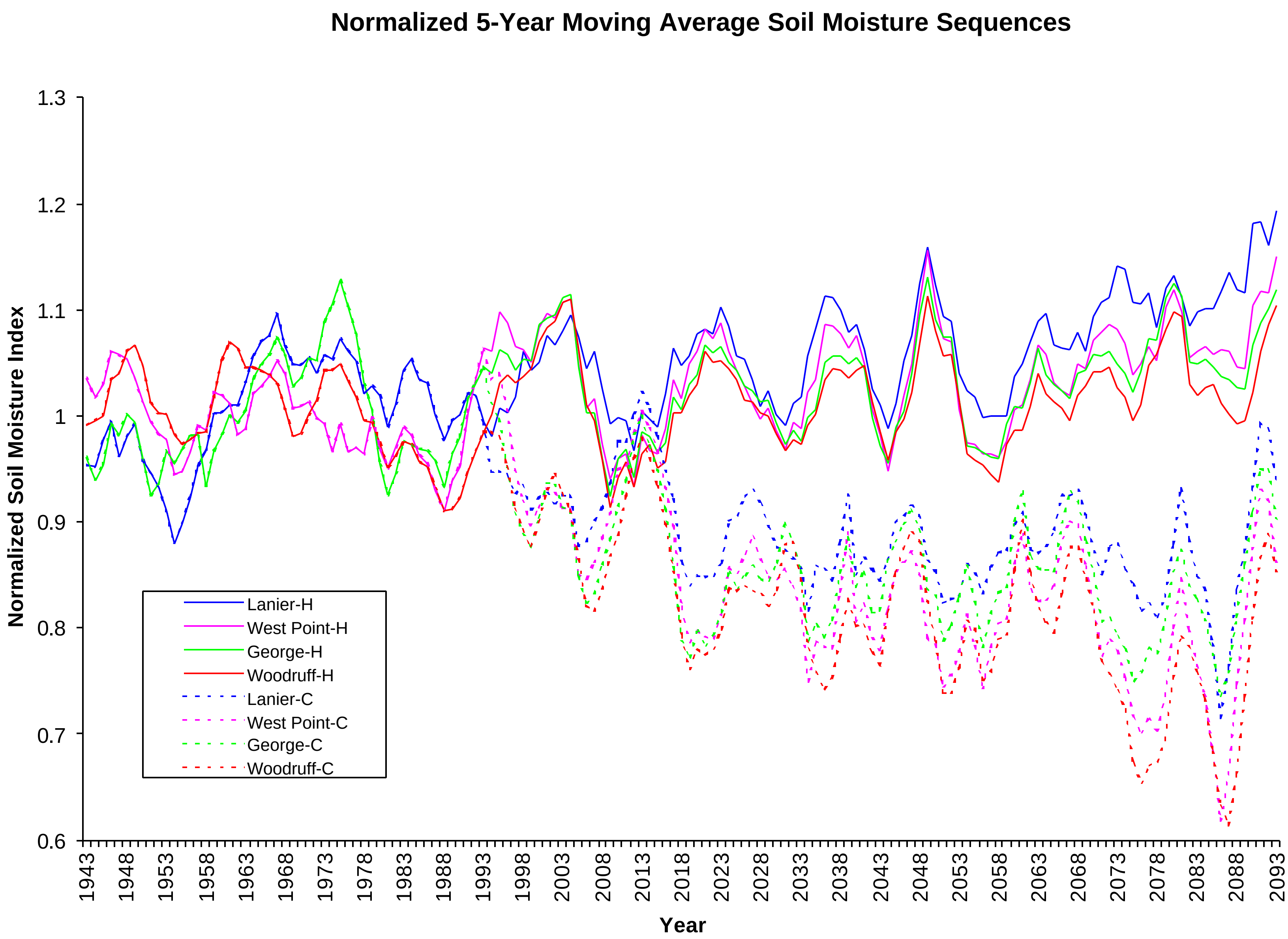



Figure 4.13: Historical and Future Soil Moisture Sequences

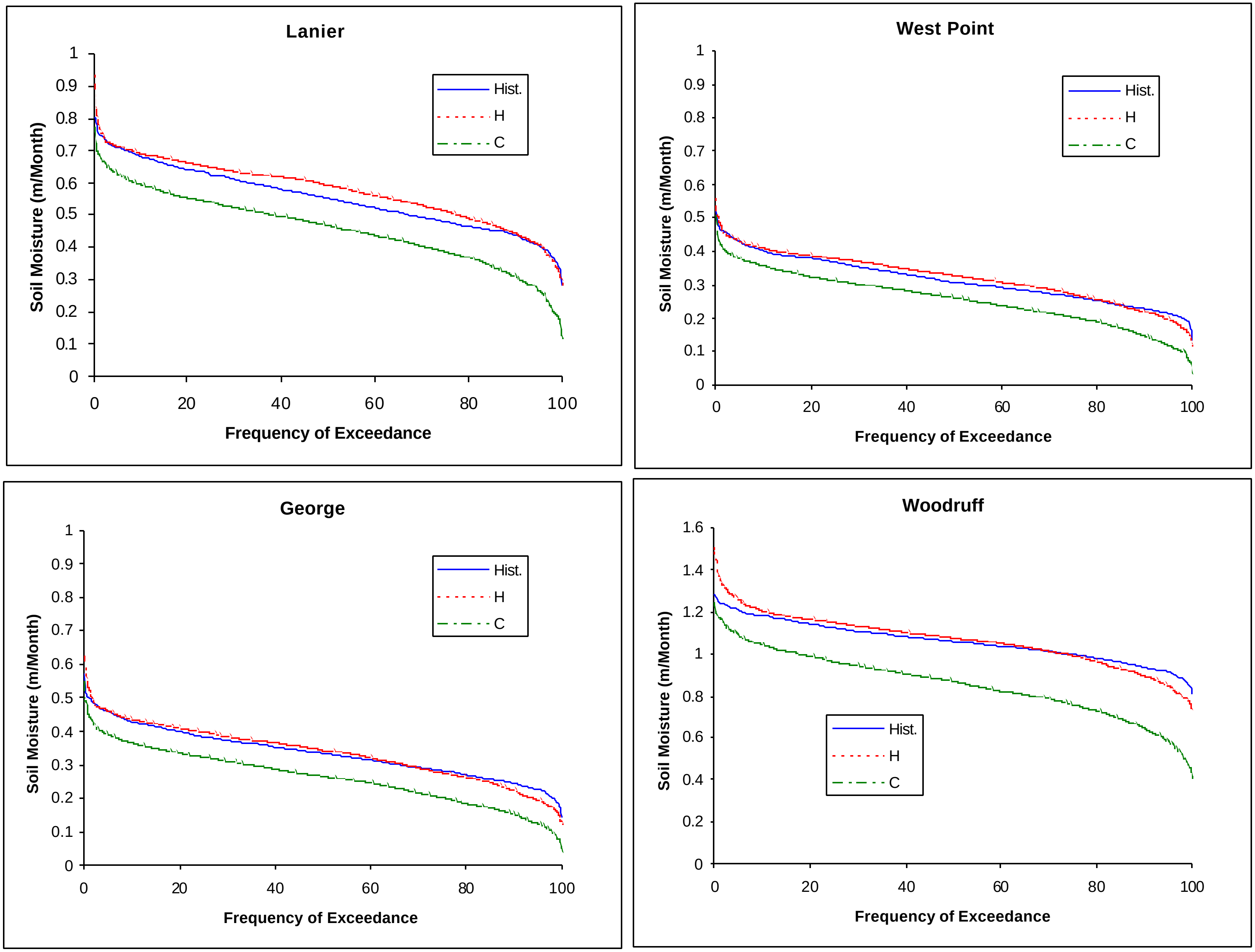



Figure 4.14: Soil Moisture Frequency Curves for Historical and Potential Climate Scenarios

Table 4.1: Observed and Simulated ACF Streamflow Correlations: Rainfall-based Regression Models

| | Lanier | West Point | George | Woodruff |
|---|---|---|---|---|
| Jan | 0.88 | 0.89 | 0.68 | 0.50 |
| Feb | 0.66 | 0.81 | 0.84 | 0.51 |
| Mar | 0.85 | 0.88 | 0.86 | 0.71 |
| Apr | 0.72 | 0.86 | 0.88 | 0.69 |
| May | 0.37 | 0.43 | 0.83 | 0.78 |
| Jun | 0.37 | 0.61 | 0.81 | 0.50 |
| Jul | 0.78 | 0.65 | 0.77 | 0.57 |
| Aug | 0.66 | 0.75 | 0.54 | 0.16 |
| Sep | 0.43 | 0.60 | 0.79 | 0.43 |
| Oct | 0.83 | 0.79 | 0.58 | 0.38 |
| Nov | 0.87 | 0.94 | 0.90 | 0.74 |
| Dec | 0.81 | 0.76 | 0.75 | 0.61 |

Table 4.2: Observed and Simulated ACF Streamflow Correlations: Rainfall- and PET -based Regression Models

| | Lanier | West Point | George | Woodruff |
|---|---|---|---|---|
| Jan | 0.85 | 0.86 | 0.64 | 0.51 |
| Feb | 0.76 | 0.78 | 0.83 | 0.44 |
| Mar | 0.91 | 0.93 | 0.86 | 0.71 |
| Apr | 0.71 | 0.82 | 0.88 | 0.67 |
| May | 0.84 | 0.88 | 0.80 | 0.77 |
| Jun | 0.76 | 0.80 | 0.81 | 0.54 |
| Jul | 0.71 | 0.81 | 0.77 | 0.59 |
| Aug | 0.77 | 0.54 | 0.44 | 0.32 |
| Sep | 0.58 | 0.78 | 0.76 | 0.60 |
| Oct | 0.52 | 0.37 | 0.56 | 0.32 |
| Nov | 0.87 | 0.75 | 0.86 | 0.61 |
| Dec | 0.85 | 0.85 | 0.70 | 0.54 |

Table 4.3: Optimal Hydrological Model Parameters

| | a | ß | ? | d |
|---|---|---|---|---|
| Buford | 0.42 | 0.32 | 0.12 | 0.4 |
| West Point | 0.09 | 0.32 | 0.1 | 0.34 |
| George | 0.2 | 0.26 | 0.13 | 0.35 |
| Woodruff | 0.4 | 0.11 | 0.03 | 0.43 |

Table 4.4: Observed and Simulated ACF Streamflow Correlations: New Hydrological Models

| | Lanier | West Point | George | Woodruff |
|---|---|---|---|---|
| Jan | 0.97 | 0.95 | 0.92 | 0.93 |
| Feb | 0.92 | 0.86 | 0.87 | 0.77 |
| Mar | 0.95 | 0.96 | 0.92 | 0.85 |
| Apr | 0.88 | 0.92 | 0.93 | 0.90 |
| May | 0.94 | 0.95 | 0.91 | 0.94 |
| Jun | 0.90 | 0.89 | 0.85 | 0.86 |
| Jul | 0.91 | 0.94 | 0.91 | 0.88 |
| Aug | 0.91 | 0.87 | 0.74 | 0.82 |
| Sep | 0.82 | 0.87 | 0.82 | 0.82 |
| Oct | 0.84 | 0.67 | 0.74 | 0.84 |
| Nov | 0.97 | 0.80 | 0.94 | 0.87 |
| Dec | 0.96 | 0.95 | 0.88 | 0.94 |

Table 4.5. : Climate Assessment Annual Results: ACF and ACT Sub-basins

| Sub-Basin | | Precipitation Avg. Value (m/mon) | Precipitation % Change to Hist. | Evapotranspiration Avg. Value (m/mon) | Evapotranspiration % Change to Hist. | Runoff Avg. Value (m/mon) | Runoff % Change to Hist. | Runoff Coef. Avg. Value (%) | Runoff Coef. % Change to Hist. |
|---|---|---|---|---|---|---|---|---|---|
| Lanier | Historical | 0.133 | | 0.073 | | 0.057 | | 43.05 | |
| | Canadian | 0.110 | -17.4 | 0.089 | 21.5 | 0.041 | -27.7 | 37.67 | -12.5 |
| | Hadley | 0.151 | 13.5 | 0.079 | 7.9 | 0.069 | 21.2 | 45.97 | 6.8 |
| West Point | Historical | 0.112 | | 0.082 | | 0.042 | | 37.35 | |
| | Canadian | 0.091 | -18.4 | 0.098 | 20.1 | 0.025 | -39.0 | 27.90 | -25.3 |
| | Hadley | 0.125 | 11.8 | 0.089 | 8.5 | 0.049 | 18.2 | 39.50 | 5.8 |
| George | Historical | 0.109 | | 0.090 | | 0.032 | | 29.40 | |
| | Canadian | 0.085 | -21.4 | 0.106 | 17.7 | 0.018 | -43.9 | 20.98 | -28.6 |
| | Hadley | 0.118 | 8.5 | 0.098 | 8.8 | 0.038 | 19.0 | 32.23 | 9.6 |
| Woodruff | Historical | 0.107 | | 0.093 | | 0.037 | | 34.75 | |
| | Canadian | 0.083 | -21.8 | 0.109 | 16.2 | 0.020 | -46.0 | 24.01 | -30.9 |
| | Hadley | 0.116 | 8.7 | 0.101 | 8.6 | 0.042 | 13.0 | 36.11 | 3.9 |
| Rome | Historical | 0.119 | | 0.076 | | 0.048 | | 40.51 | |
| | Canadian | 0.100 | -16.1 | 0.093 | 22.0 | 0.031 | -35.1 | 31.34 | -22.6 |
| | Hadley | 0.128 | 7.3 | 0.085 | 10.9 | 0.051 | 6.5 | 40.20 | -0.8 |
| Coosa | Historical | 0.117 | | 0.082 | | 0.047 | | 39.92 | |
| | Canadian | 0.099 | -15.2 | 0.097 | 18.9 | 0.033 | -29.5 | 33.18 | -16.9 |
| | Hadley | 0.130 | 10.7 | 0.089 | 9.0 | 0.056 | 19.3 | 43.02 | 7.8 |
| Montegomery | Historical | 0.116 | | 0.084 | | 0.044 | | 37.60 | |
| | Canadian | 0.095 | -18.0 | 0.100 | 19.4 | 0.026 | -39.6 | 27.69 | -26.4 |
| | Hadley | 0.129 | 10.7 | 0.092 | 9.0 | 0.052 | 20.0 | 40.77 | 8.4 |
| M. Ferry | Historical | 0.115 | | 0.089 | | 0.035 | | 30.21 | |
| | Canadian | 0.092 | -19.7 | 0.104 | 16.7 | 0.018 | -47.6 | 19.71 | -34.7 |
| | Hadley | 0.124 | 7.6 | 0.098 | 9.4 | 0.037 | 7.8 | 30.28 | 0.3 |

# 5. River Basin Management

## 5.1 ACF Decision Support System Overview

What are the potential climate change implications for the water uses in the Apalachicola-Chattahoochee-Flint river basin? In this section we address this question using a comprehensive modeling system developed to support water resources planning and management in the ACF river basin (Georgakakos and Yao, 1999).

The ACF decision support system (ACF-DSS) models all major ACF storage facilities and water uses (Figure 5.1) and simulates the system response to various demand and hydrologic scenarios and management policies. ACF water uses include water supply to municipal, industrial, and agricultural areas; flood and drought protection; energy generation; environmental and ecosystem management; recreation; and navigation. Figure 5.2 shows a schematic of the ACF-DSS modeling system including three main modules: a streamflow forecasting module, a river simulation and control module, and a scenario assessment module. ACF-DSS is discussed in detail by Georgakakos and Yao, 1999. Herein, we only provide a brief description of the ACF-DSS models and capabilities.

The purpose of the streamflow forecasting component is to predict the upcoming reservoir inflows and provide an appreciation of the forecast uncertainty through multiple forecast traces. The inflow forecasting model generates forecast traces (at 23 river network nodes) based on the Analog ESP approach outlined in Yao and Georgakakos, 2000.

The second component of the ACF decision support system is the reservoir control model. Due to the multiple purposes of this model, and the different times scales over which water uses are relevant, it includes three modules: a turbine commitment and load dispatching module operating on an hourly time step, a short/mid range (hourly) control module, and a long range (weekly) control module.

The purpose of the turbine commitment and load dispatching module is to optimize hydro plant efficiency by determining the power load of each turbine such that the total plant outflow is equal to a given discharge level and total power is maximized.

The short/mid range reservoir control module is concerned with determining the best hourly power sequences for each hydropower station in the system over a period of one week. The objective it to maximize energy generation (given that all other stated objectives are met) with or without dependable capacity constraints.

The long range control module is designed to identify optimal, system-wide release schedules for each reservoir over a period of several weeks. In identifying the reservoir release sequences, the model's first priority is to meet the specified constraints related to water withdrawals, instream minimum flows, power generation commitments (i.e., hours of dependable power capacity), turbine and power plant load limits, navigation constraints, ecologically favorable flow conditions, and reservoir active ranges. Among the feasible release sequences that meet these constraints, the DSS selects those that additionally maintain reservoir levels as high as possible and maximize long-term energy generation. Thus, "optimal" release sequences are those which meet the stated constraints, safeguard the system against droughts, and maximize long-term energy generation.

The three modules of the reservoir control model constitute a multilevel control hierarchy with an operational flow that follows two directions: The lower level modules are activated first and generate information that is used by the upper levels regarding performance functions and bounds. In the course of this upward flow, the decision system simulates the system response for various water allocation and long-term operational policies, and selects those that optimize system performance subject to the stated water use requirements. Once the optimal policies are identified, the control levels are activated in the reverse order to generate the best turbine hourly sequences and loads implementing these decisions consistently across all relevant time scales.

The last ACF-DSS element, the scenario assessment module, makes it most useful for this work. Its purpose is to replicate the actual weekly operation of the ACF system for particular inflow, demand, and management scenarios. The assessment process is as follows: At the beginning of each week of the simulation horizon, the system invokes the inflow forecasting and reservoir control components, determines the most appropriate reservoir releases, simulates the response of the system for the upcoming week, and repeats this process at the beginning of the following decision time. At the completion of the forecast-control-simulation process, the program generates sequences of all system performance measures. These sequences are used herein to compare the benefits and consequences of alternative inflow scenarios. System performance criteria include statistics of energy generation (primary as well as secondary), reservoir drawdown frequency and severity, statistics of minimum flow target violations, and statistics of water withdrawal target violations.

## 5.2 Climate Change Assessments

The ACF-DSS was run for the historical and two future climate scenarios. The historical scenario consists of the 1939 to 1993 streamflow record, while the future scenarios are based on the Canadian and Hadley GCM runs for the 1994 to 2094 time frame. Both GCM models assume a 1% annual increase in atmospheric greenhouse gases. The GCM rainfall and temperature scenarios were converted to monthly streamflow as discussed in the previous section. Due to the ACF-DSS weekly time resolution, the monthly streamflow scenarios were further refined to weekly sequences. For each month of the climate scenario, this refinement was performed by searching through the historical record to find a year for which the observed streamflow volume (in the same calendar month) was approximately equal to the volume of the climate scenario. Then, the historical weekly streamflows were linearly adjusted to match the climate scenario monthly volume and used in the assessment.

The assessment runs assumed the following water use scenario. The ACF water supply targets are based on Georgia's projections for 2020 to 2050. These targets are shown on Figure 5.3 (aggregated by sub-basin) and are presently being negotiated with Alabama and Florida. All federal hydropower facilities (Lanier, West Point, George, and Woodruff) are required to generate at power capacity at least one hour each work day of the week. The minimum instream flow requirements at the Atlanta gage (Georgia) follow the seasonal pattern shown on Figure 5.4, top panel. The minimum instream flow requirements at the Chattahoochee gage (Florida) follow either the one- or the five-year monthly minimum curve shown on the bottom panel of Figure 5.4. The minimum instream flow requirements at Columbus, Georgia (near the Alabama border) are 1800 cfs. A two-week navigation window (nine feet of channel depth) is required for the Apalachicola River in July. Although, these requirements represent only one of many possible water use scenarios, they are relevant because at some stage in the on-going tri-state water compact negotiations they were proposed as a basis for a water allocation agreement.

Figures 5.5, 5.6, 5.7, 5.8, and Table 5.1 summarize the results of the historical, baseline run. Figures 5.5 and 5.6 respectively depict the level fluctuations (and storage conservation zones) of the federal ACF reservoirs (Lanier, West Point, George, and Woodruff) relative to the one- and the five-year minimum flow targets. Reservoir level fluctuations impact lake recreation but also indicate drought severity. The figures show that the impacts of the 1980 drought would be most severe throughout the entire basin especially under the five-year minimum flow target scenario. Figure 5.7 records the water supply deficits (total deficit amount and number of deficit weeks) relative to the target levels (Figure 5.3) at each of 23 basin nodes. In the graphs, upstream locations precede downstream locations. No deficits are recorded for the one-year minimum flow targets, while some deficits occur in the Upper Chattahoochee region for the five-year minimum flows. Figure 5.8 depicts the flow frequency curves at Atlanta, Columbus, and Chattahoochee for the one- and the five-year minimum flow scenarios. The figure shows that the specified minimum flow targets are met 100% of the time at all locations, with the exception of only 10 (out of 3380) weeks at the Atlanta gage under the five-year minimum flow scenario. Lastly, Table 5.1 summarizes the energy generation statistics for the federal as well as the private hydropower facilities. On the average, total annual energy generation would amount to 1047 GWH at the federal and 1203 GWH at the private reservoirs.

We note that these results assume that all reservoirs are operated according to the ACF-DSS release policies that perform dyanamic, basin-wide management. Other release rules would most likely lead to more severe reservoir drawdowns and more frequent water supply and flow target violations.

Figures 5.9, 5.10, 5.11, 5.12, and Table 5.2 summarize the results of the Canadian GCM climate scenario in the same format as the historical run. The results support the following comments.

- Frequent and very severe reservoir drawdowns would occur under the Canadian GCM climate scenario throughout the ACF basin (Figures 5.9 and 5.10). In fact, the basin would experience constant stress and would be unable to meet the specified demand targets. At some locations (e.g., Atlanta), water supply target violations would experience a 100-fold increase relative to the historical climate run (Figure 5.11, five-year minimum flow targets). The instream flows at all locations would shift toward substantively drier regimes and could be devastating to the ecology and the environment (Figure 5.12). Energy generation would decrease by about 30% relative to the historical generation levels (Table 5.2).

Figures 5.13, 5.14, 5.15, 5.16, and Table 5.3 summarizes the results of the Hadley GCM climate scenario in the same format as the previous two runs. The results support the following comments.

- Reservoir level fluctuations under the Hadley climate scenario are comparable to those of the historical run (Figures 5.13 and 5.14). No appreciable water supply deficits are expected to occur (Figure 5.15), while the flow regimes at all locations would shift toward wetter (than the historical) regimes (Figure 5.16). Energy generation would increase by about 20% relative to the historical levels.

To place the historical and future climate scenario differences in perspective, Figure 5.17 depicts the historical and potential future water level fluctuations for Lake Lanier, the largest of the ACF reservoirs. The figure clearly illustrates the uncertainty associated with climate scenarios. However, regardless of which scenario is more likely to occur, the need for *flexible and adaptive* water allocation agreements, management strategies, and institutional processes cannot be over-emphasized.

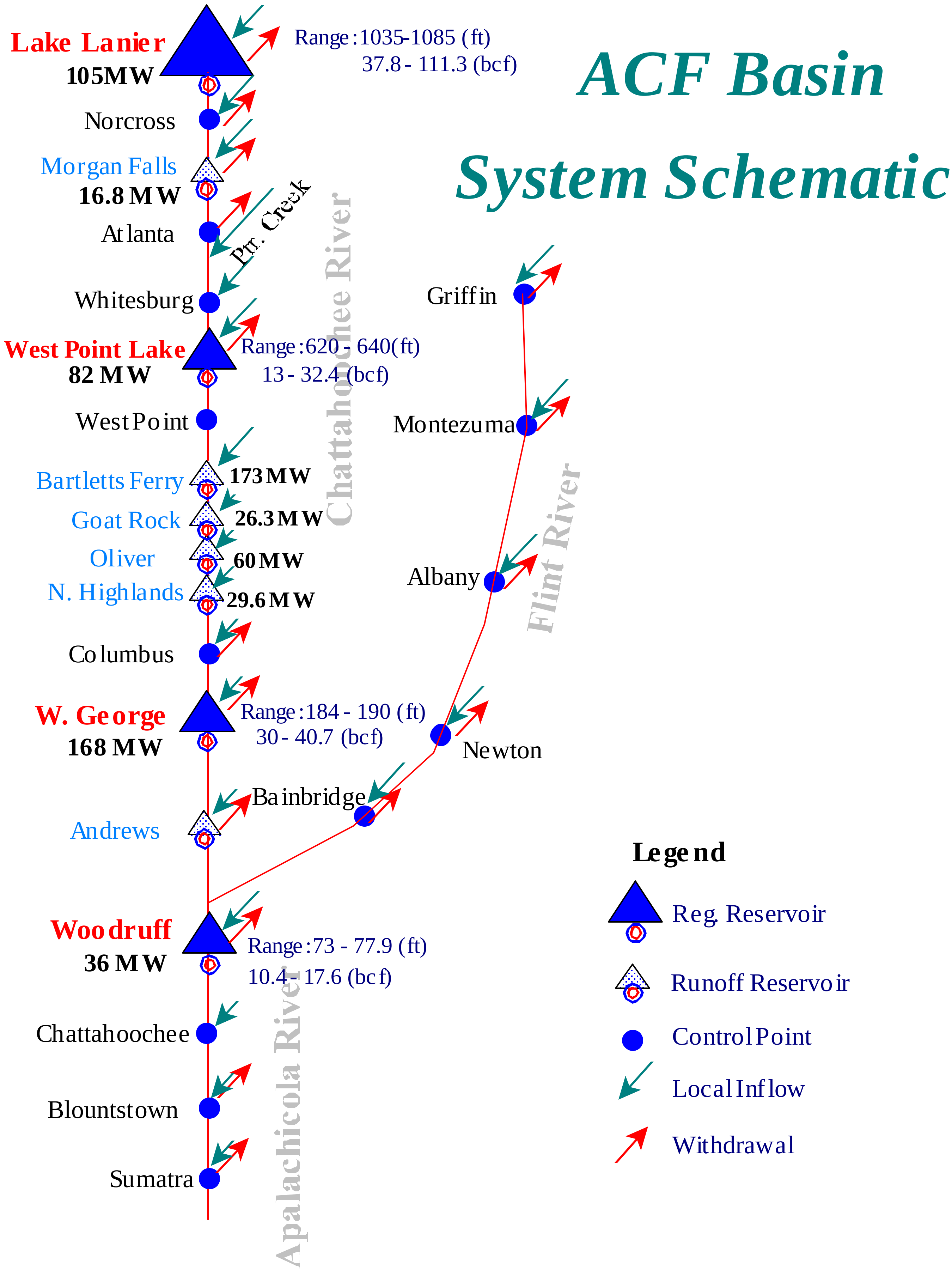



Figure 5.1: ACF Basin System Schematic

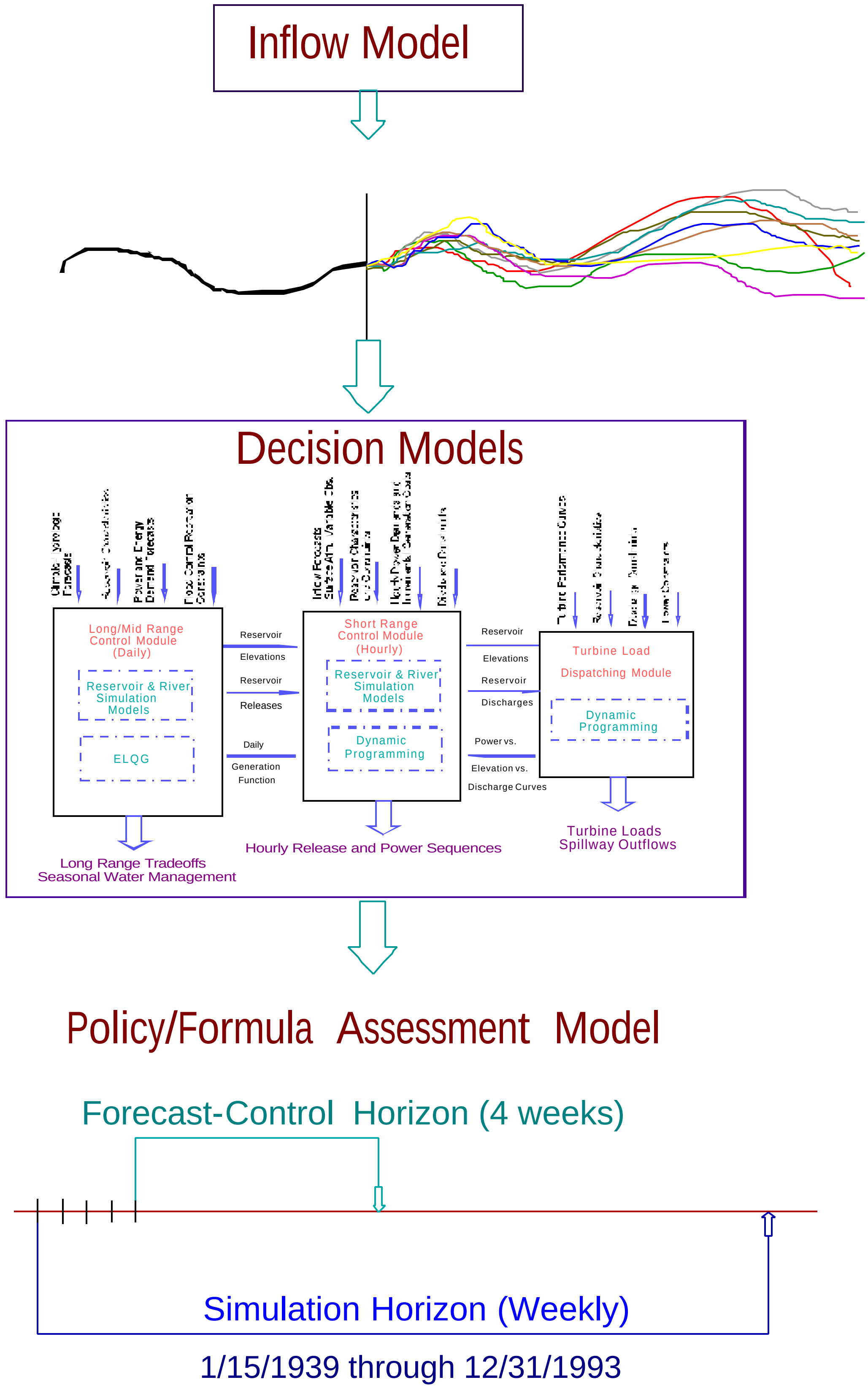
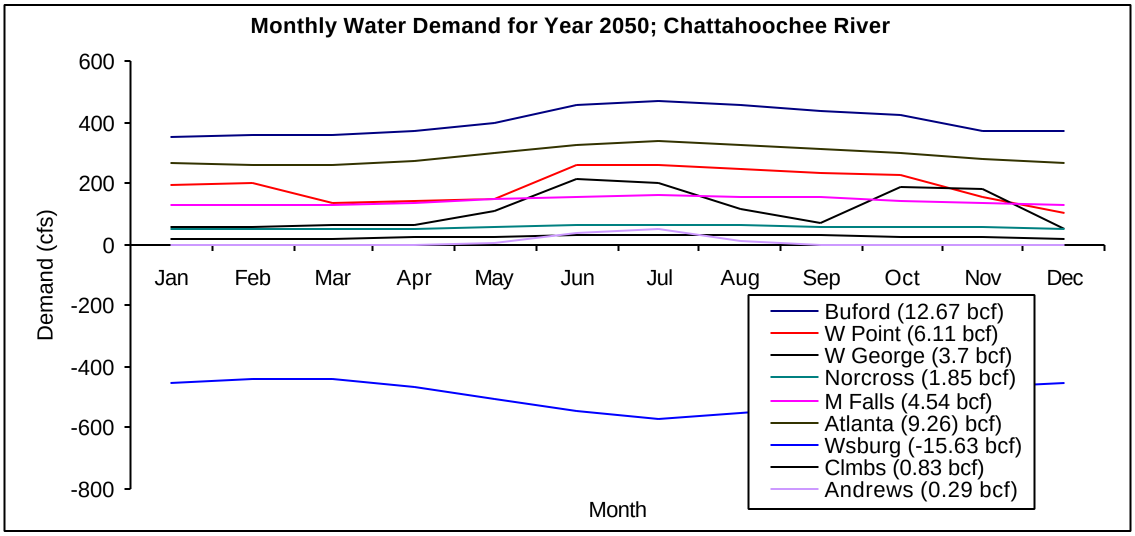
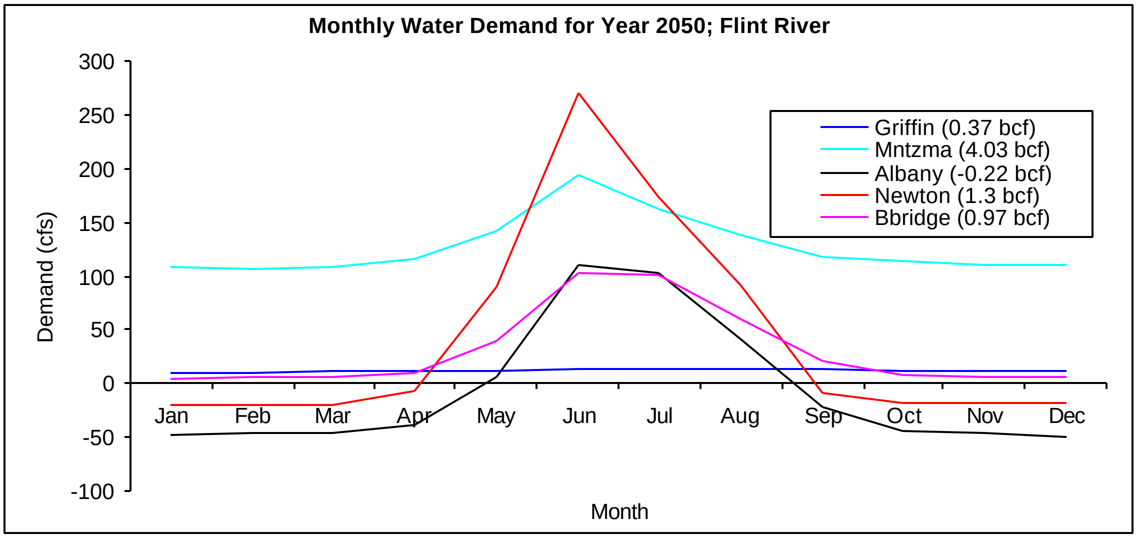



Figure 5.2: ACF-DSS Modeling Components



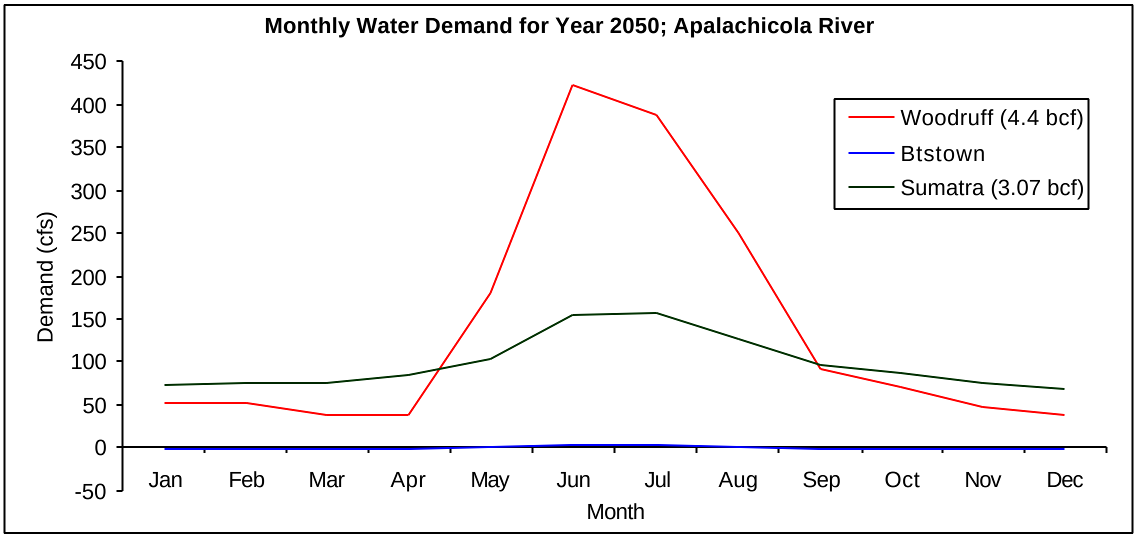
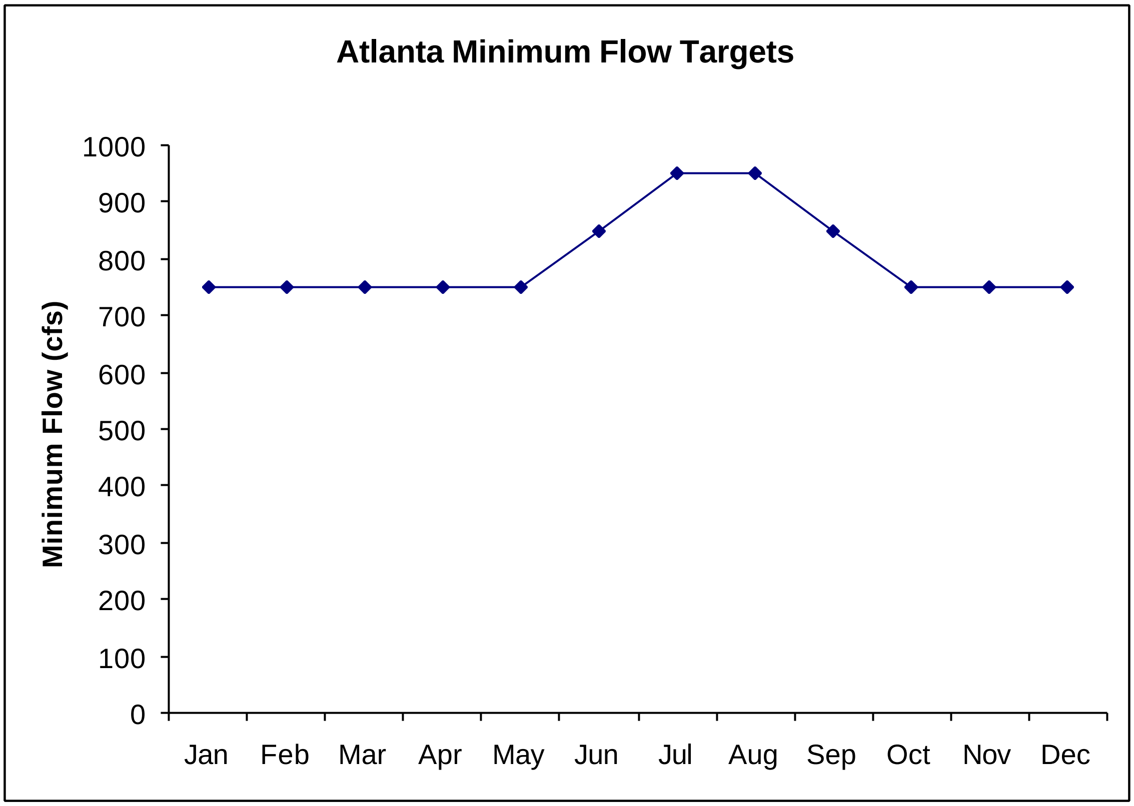




Figure 5.3: Water Supply Target Levels



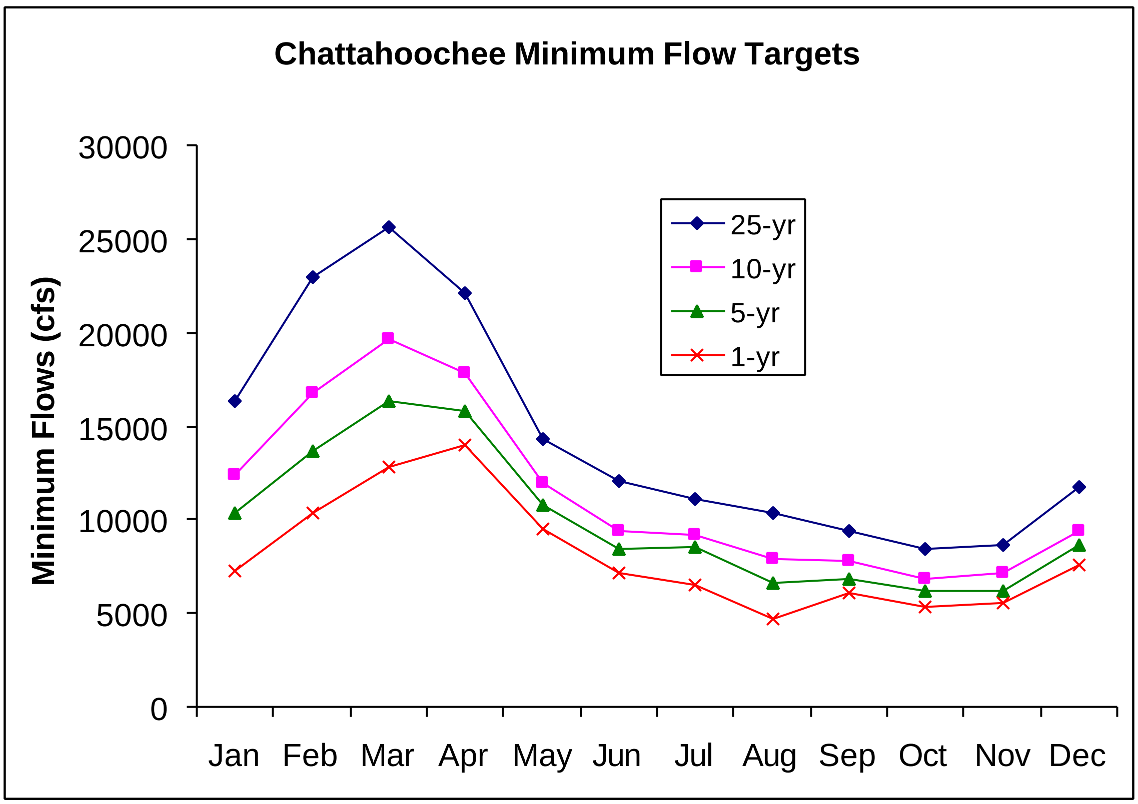




Figure 5.4: Minimum Flow Target Levels at Atlanta and Chattahoochee

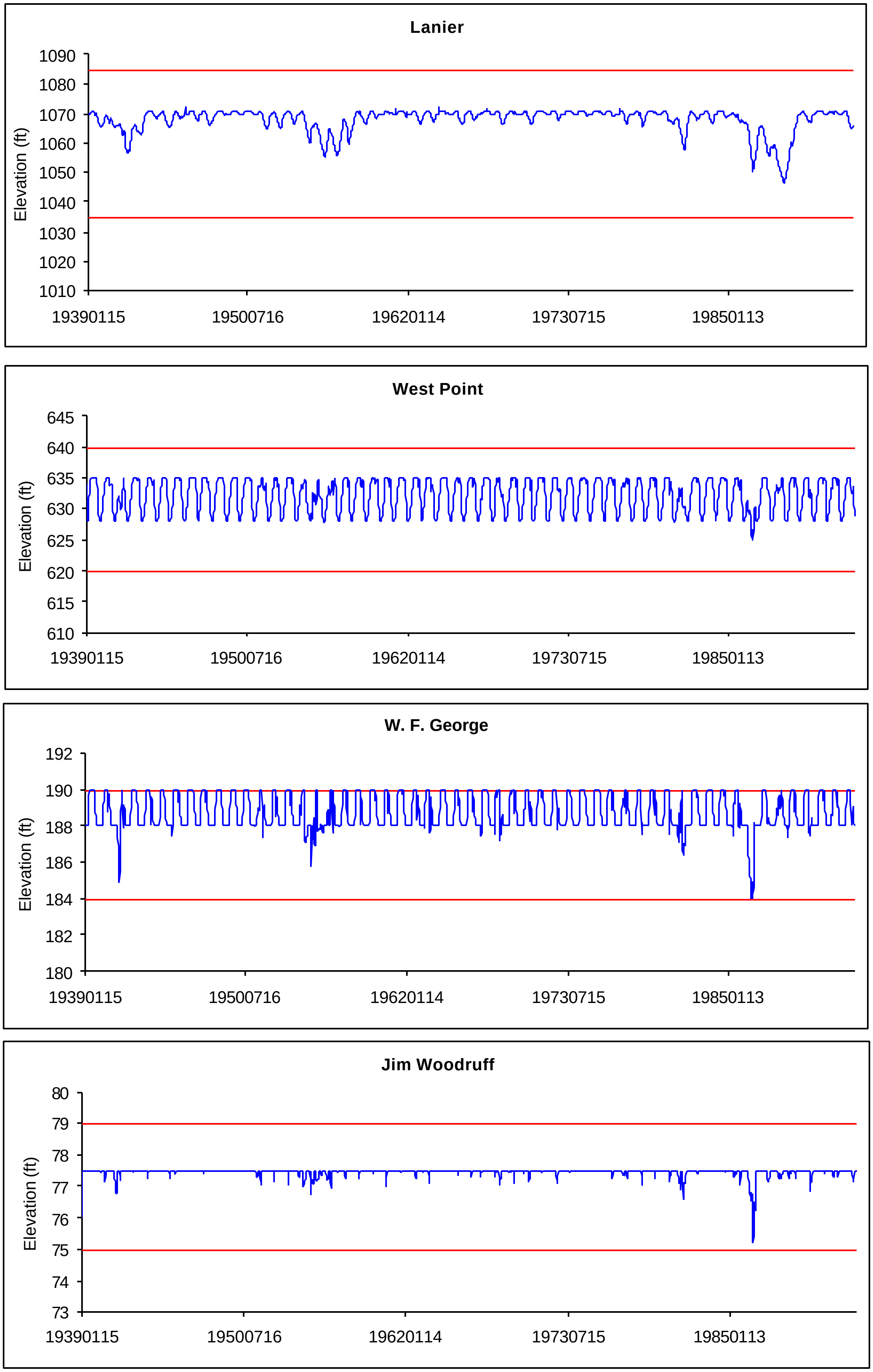



Figure 5.5: Reservoir Level Sequences; Historical Scenario; 1-year Minimum Flow Targets

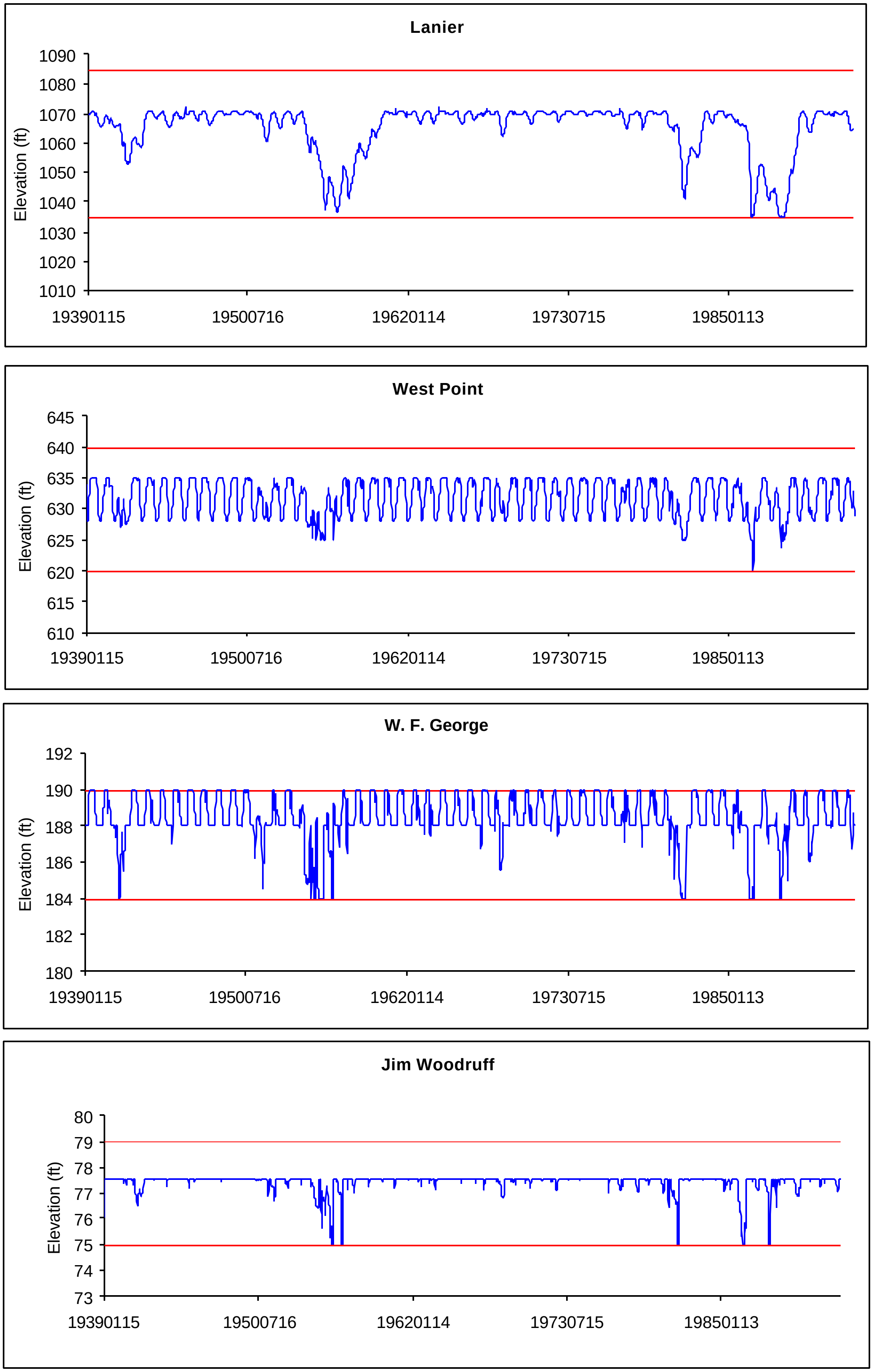



Figure 5.6: Reservoir Level Sequences; Historical Scenario; 5-year Minimum Flow Targets

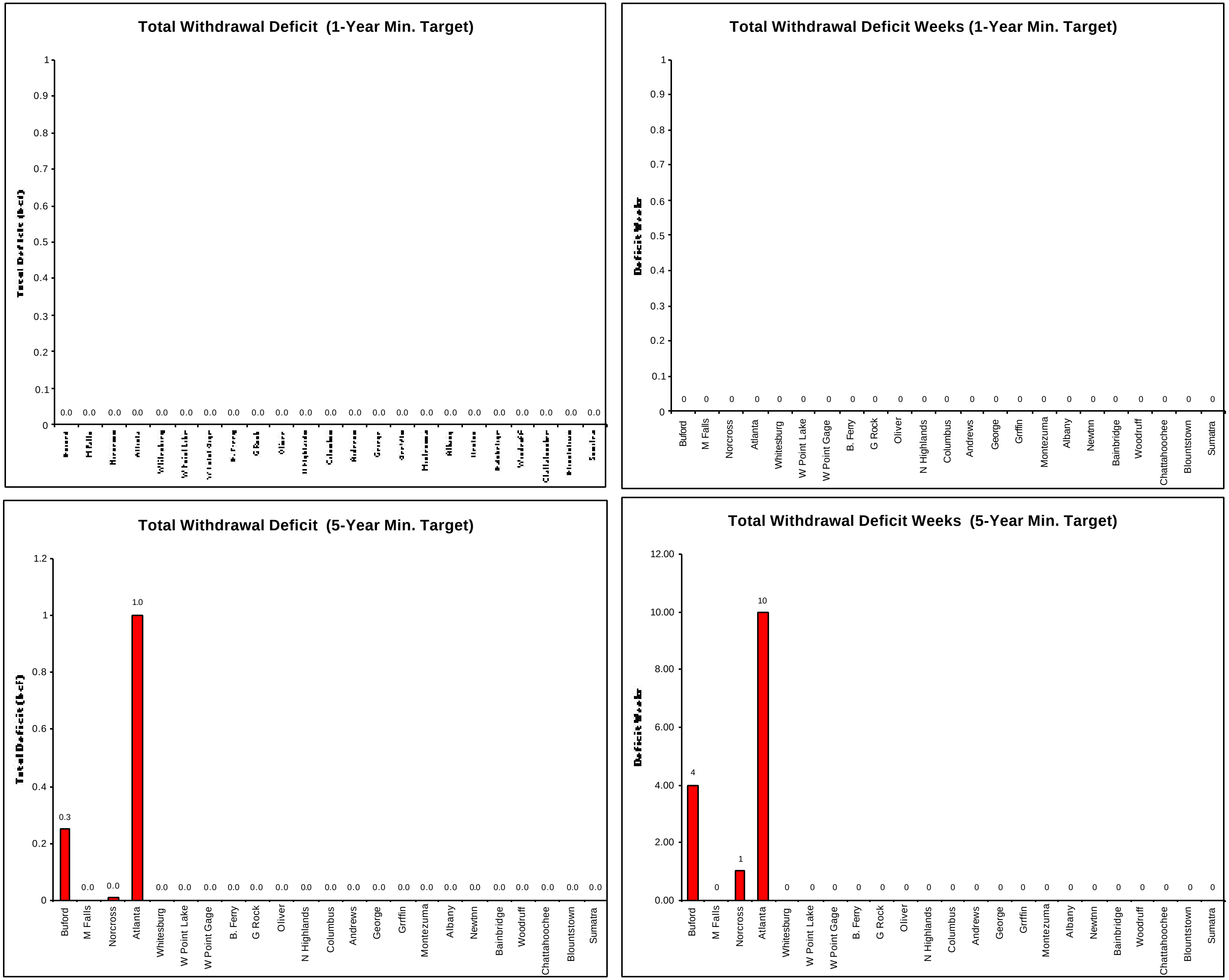
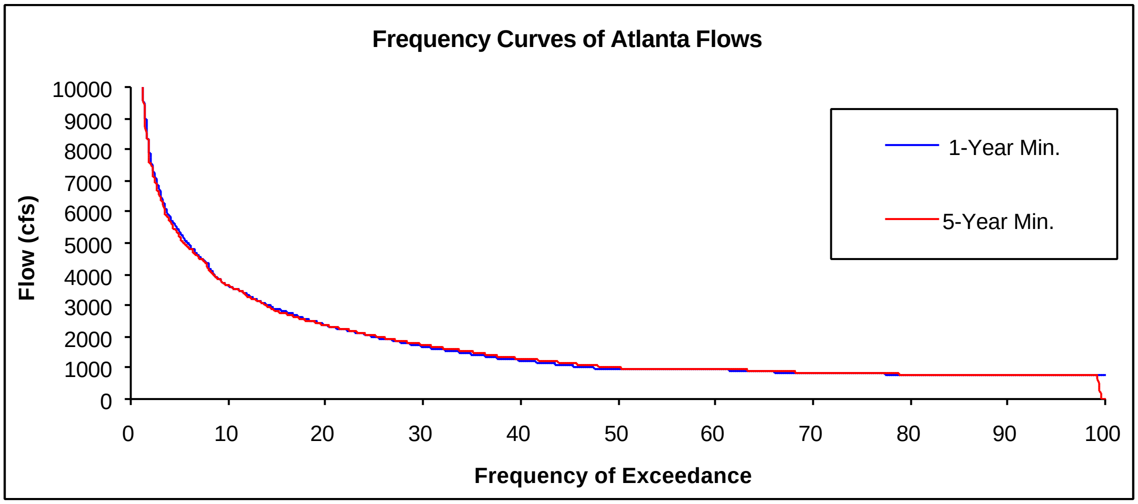
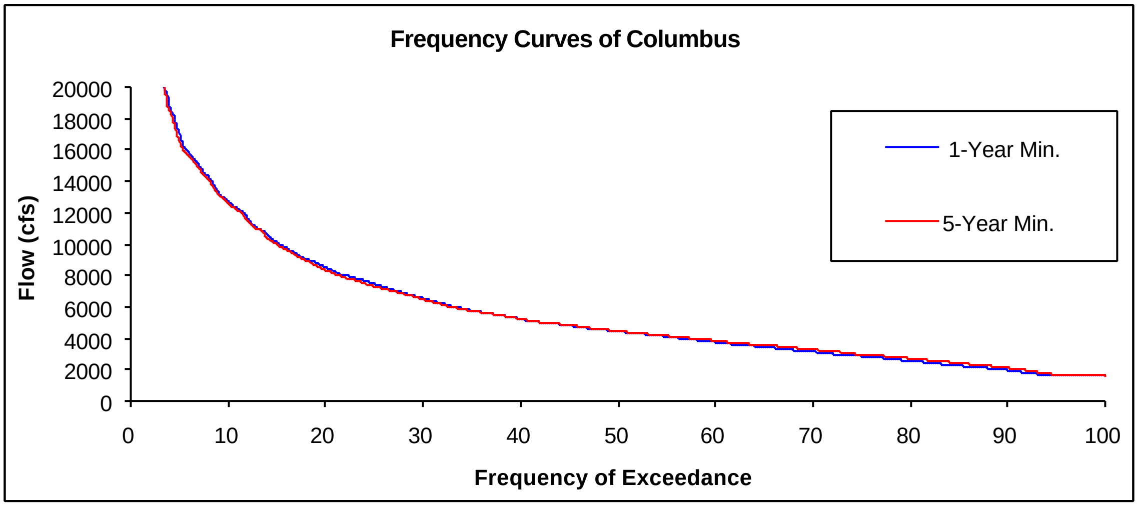



Figure 5.7: Water Supply Deficits; Historical Scenario



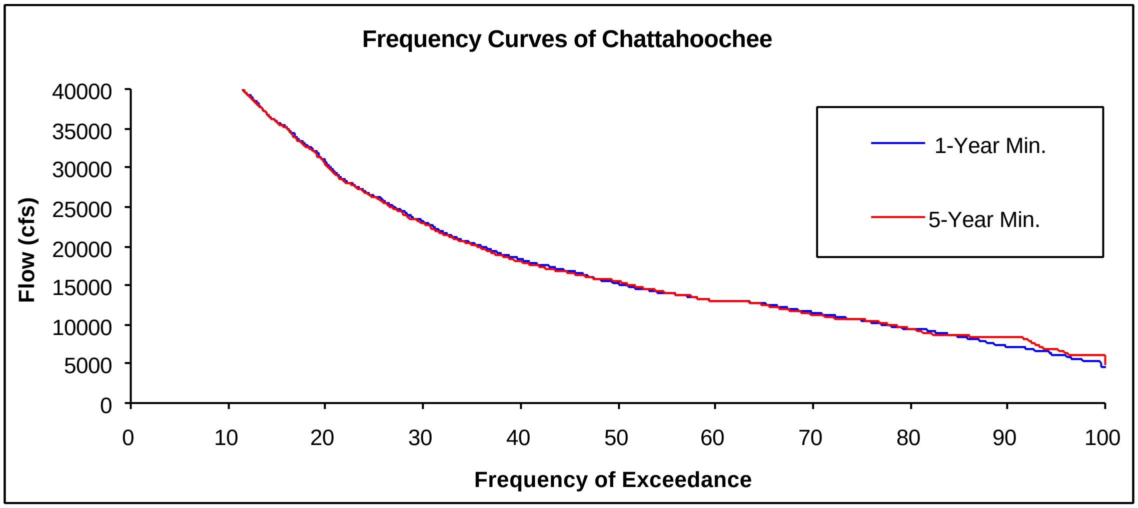




Figure 5.8: Flow Frequency Curves; Historical Scenario

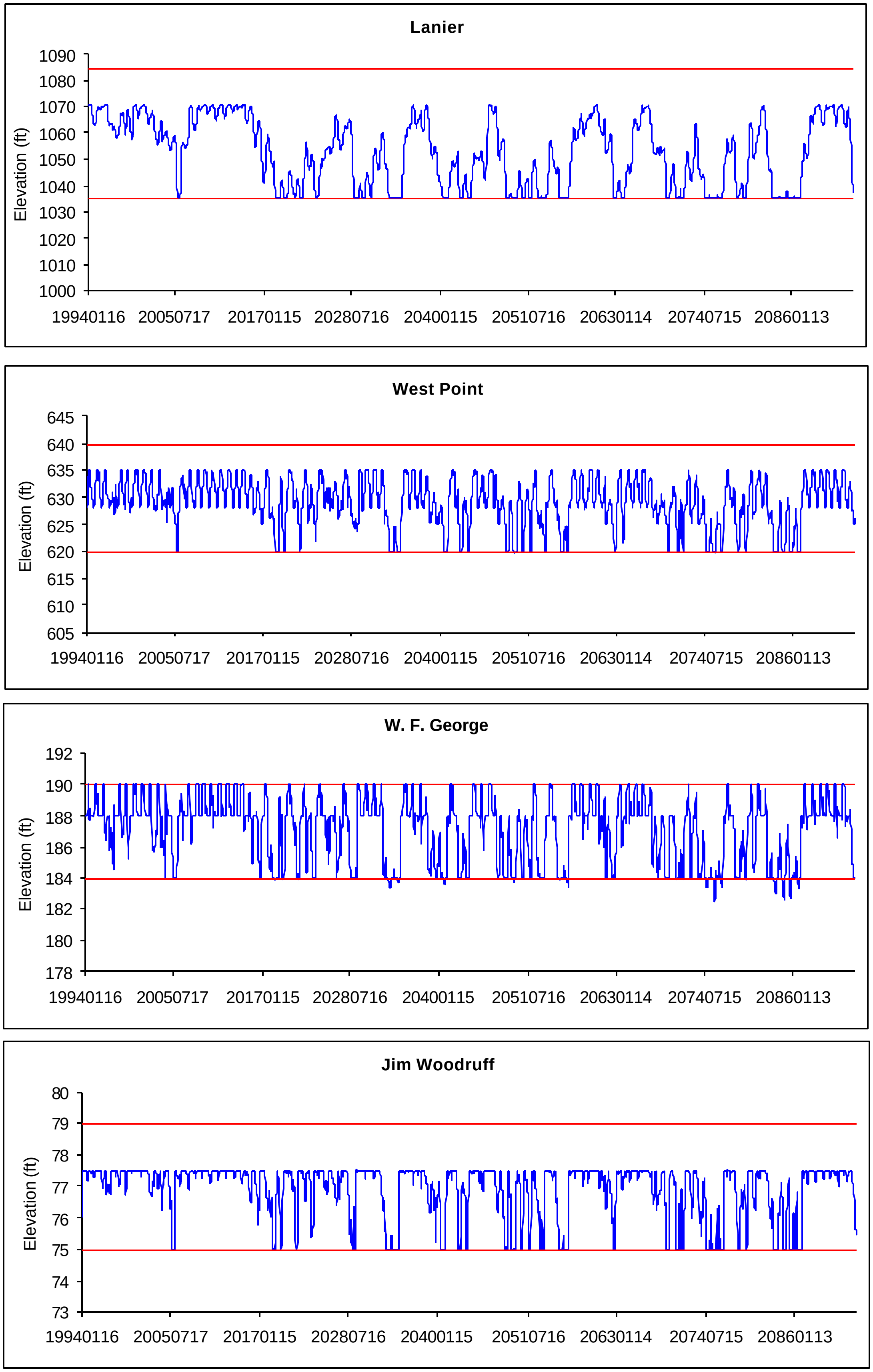



Figure 5.9: Reservoir Level Sequences; Canadian GCM Scenario; 1-year Minimum Flow Target

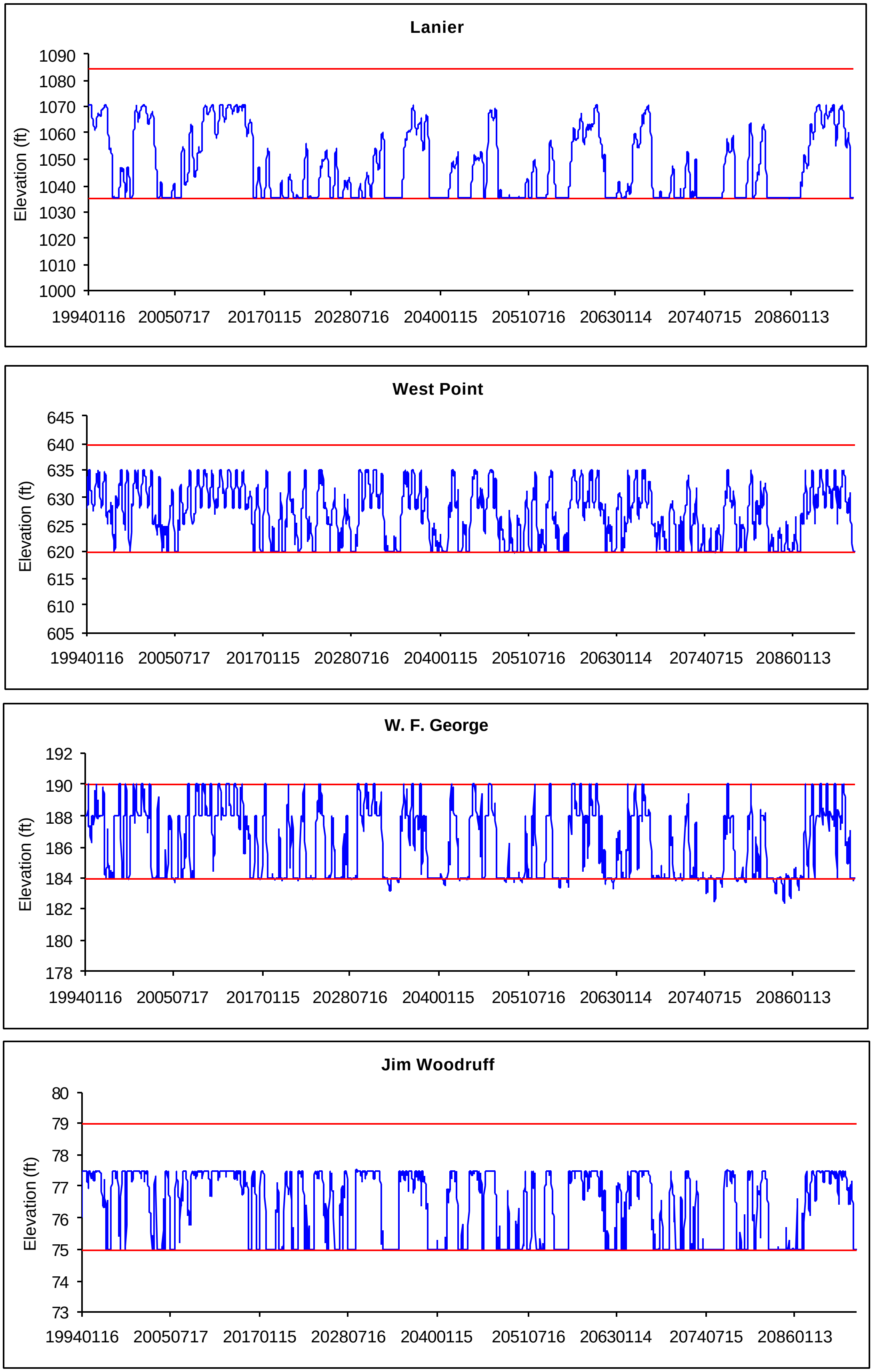



Figure 5.10: Reservoir Level Sequences; Canadian GCM Scenario; 5-year Minimum Flow Target

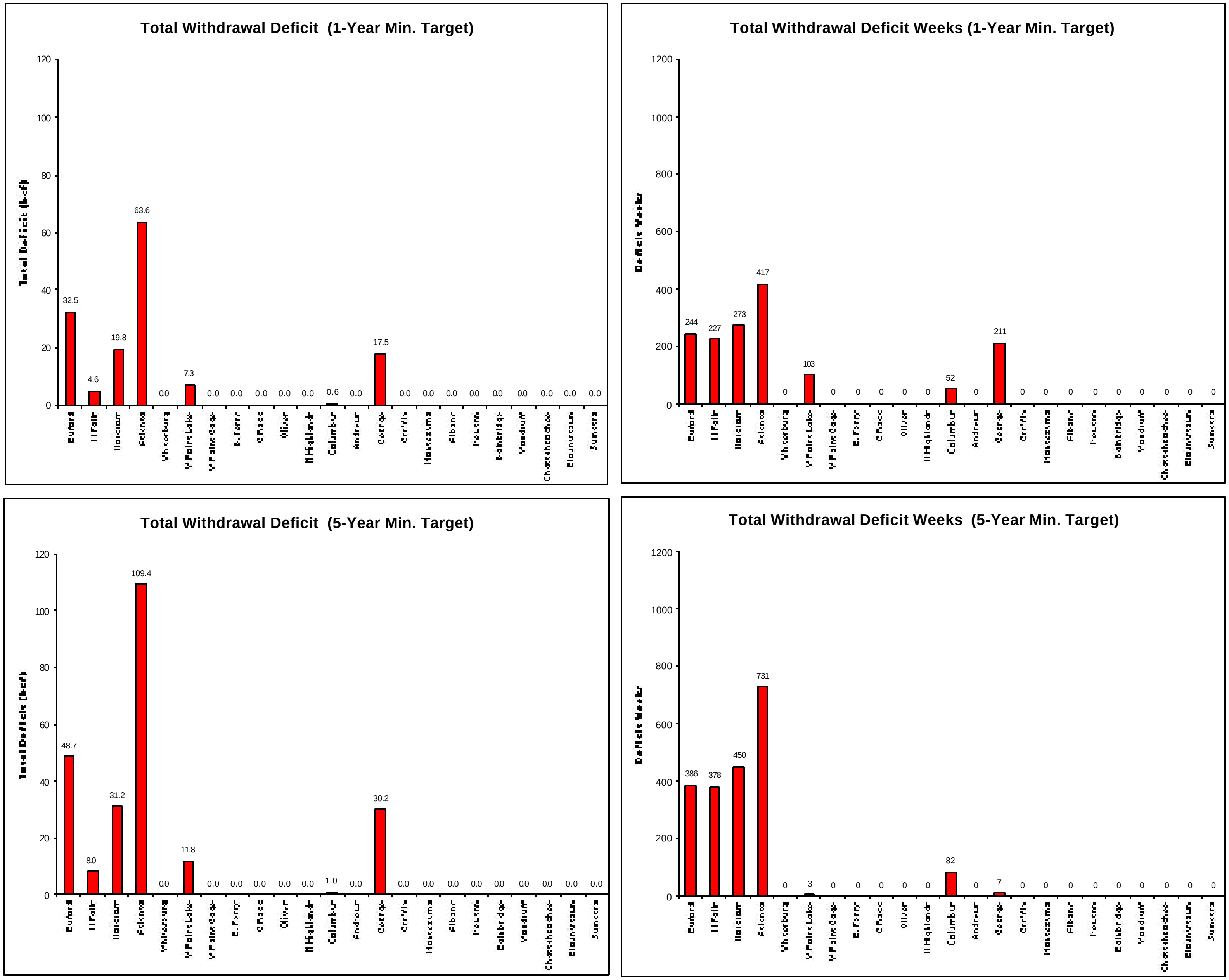



Figure 5.11: Water Supply Deficits; Canadian GCM Scenario

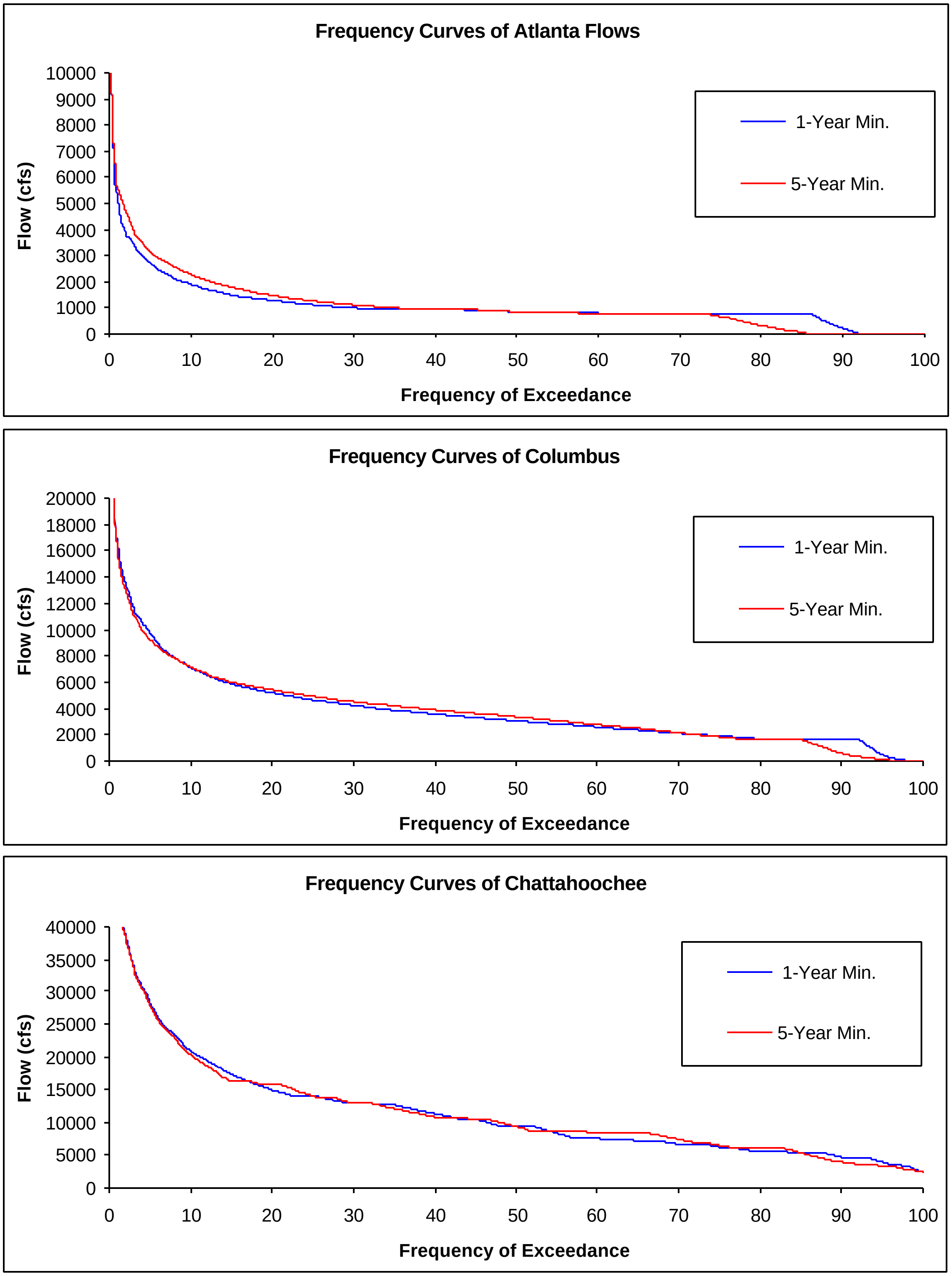
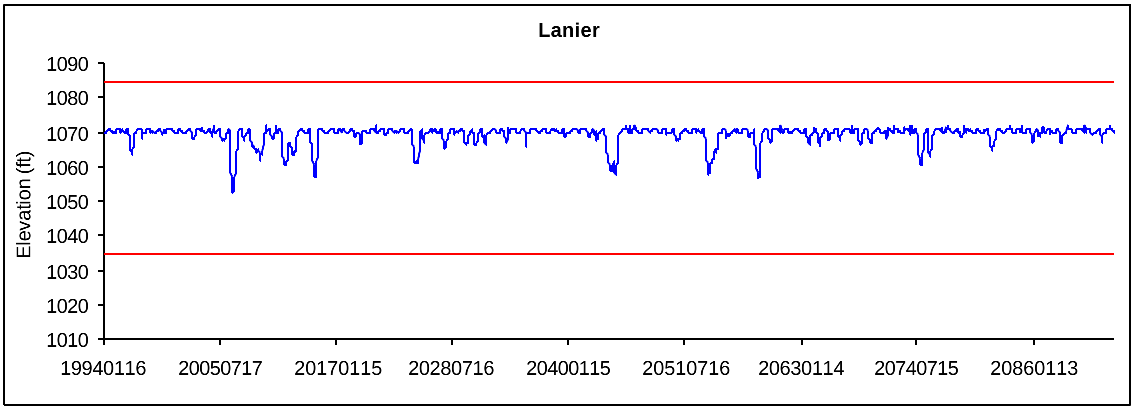
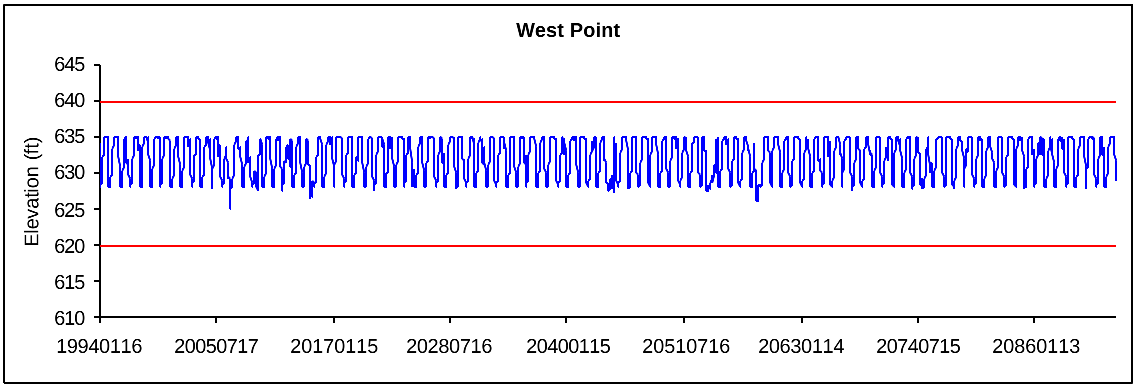
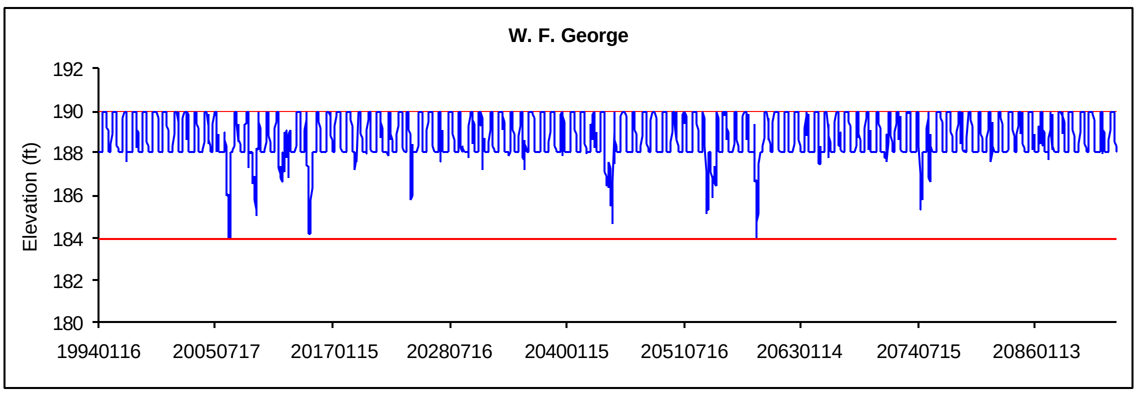



Figure 5.12: Flow Frequency Curves; Canadian GCM Scenario



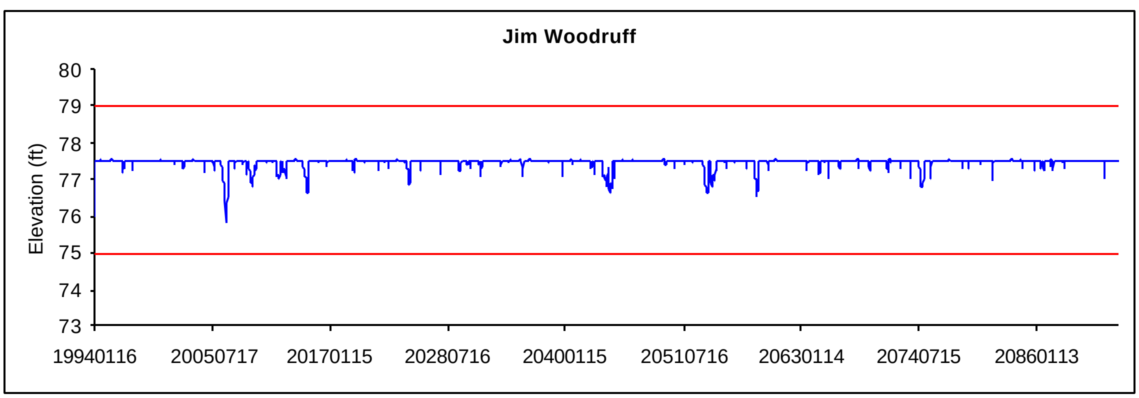




Figure 5.13: Reservoir Level Sequences; Hadley GCM Scenario; 1-year Minimum Flow Target

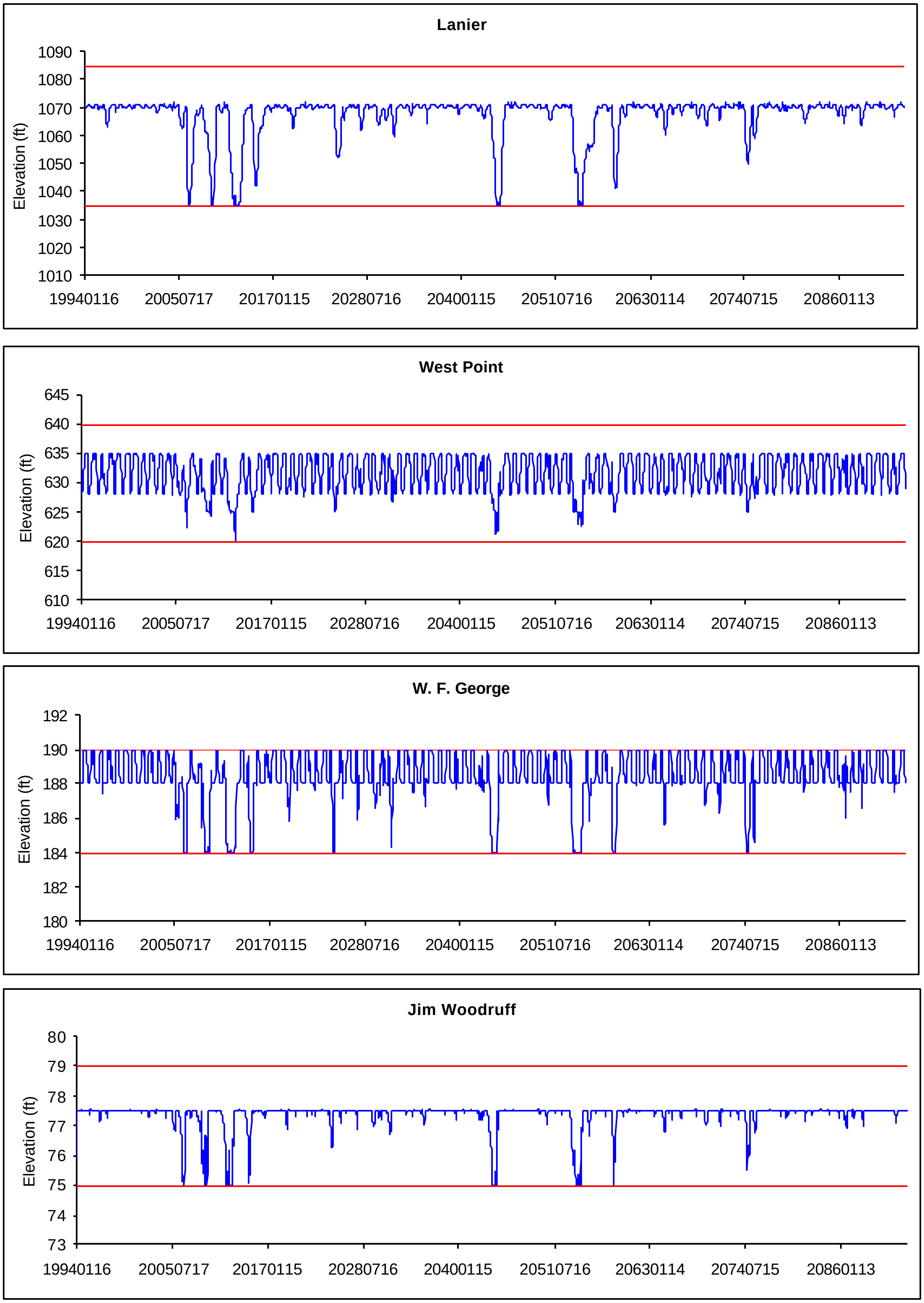



Figure 5.14: Reservoir Level Sequences; Hadley GCM Scenario; 5-year Minimum Flow Target

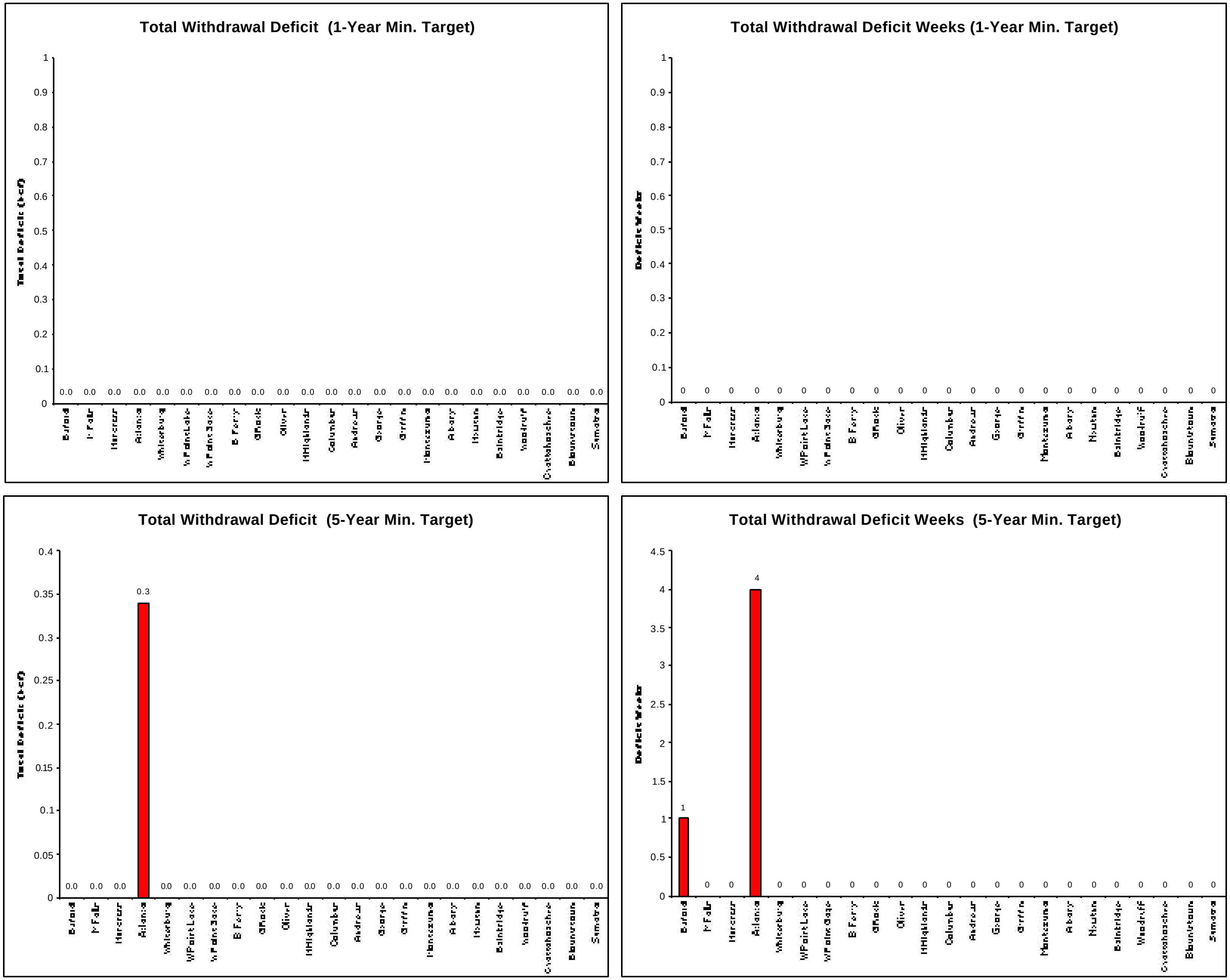



Figure 5.15: Water Supply Deficits; Hadley GCM Scenario

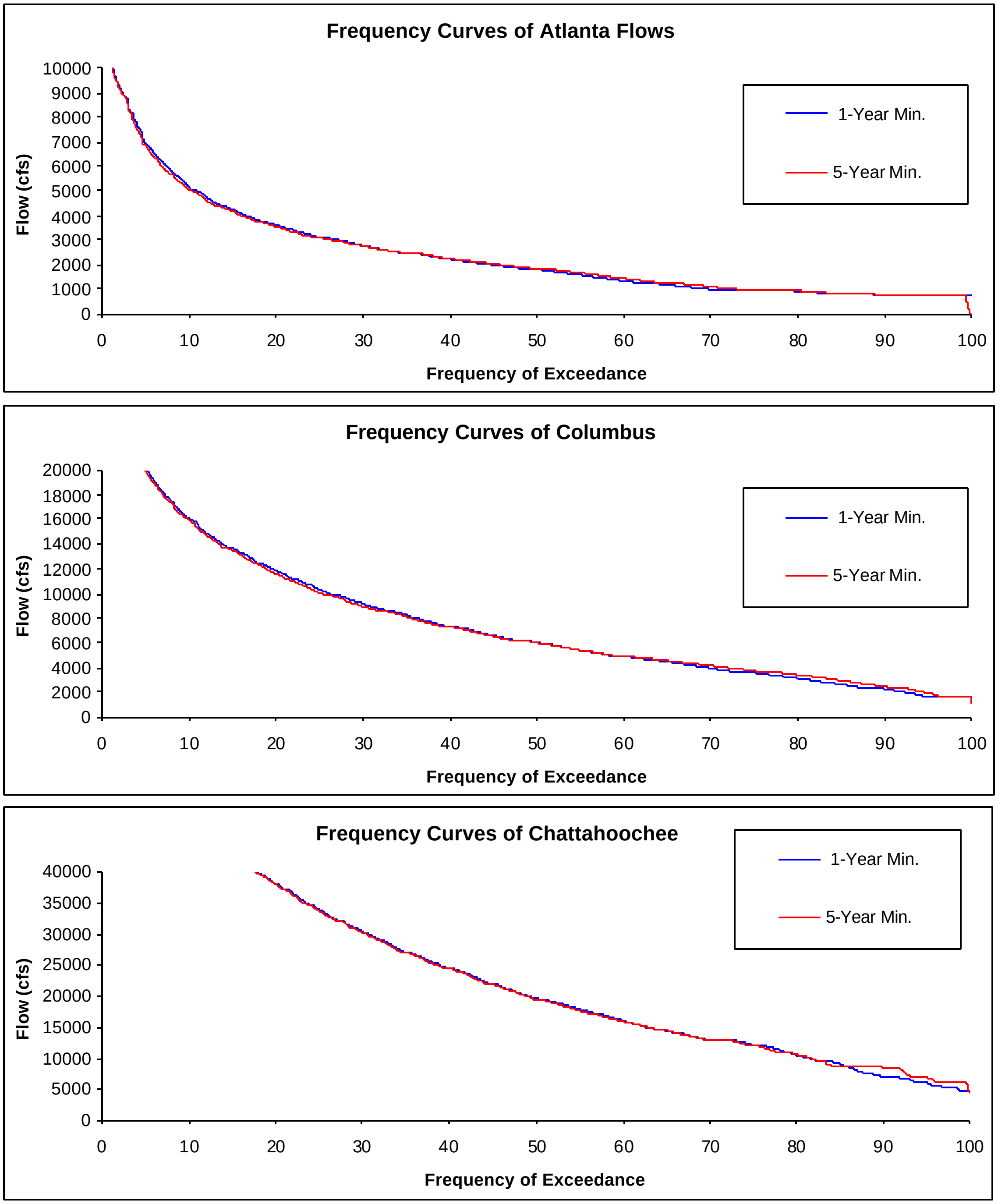



Figure 5.16: Flow Frequency Curves; Hadley GCM Scenario

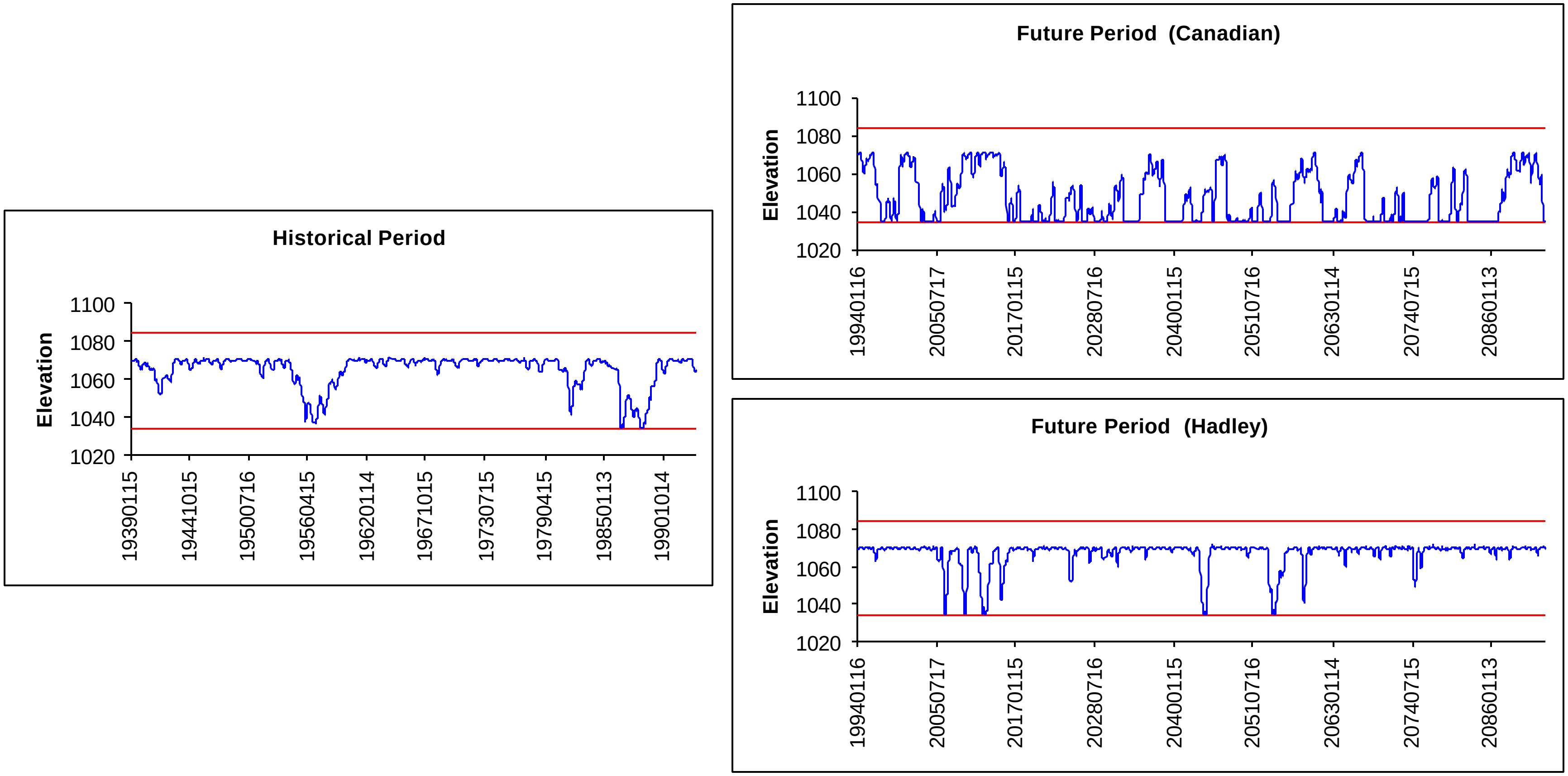



Figure 5.17: Historical and Potential Future Lake Lanier Level Sequences

## Table 5.1a: Energy Generation Statistics; Historical Scenario; Federal Reservoirs

| Min. Target | Energy (GWH) | Buford | West Point | George | Woodruff | System |
|---|---|---|---|---|---|---|
| 1-Year | Primary | 27.36 | 21.53 | 37.75 | 8.05 | 94.69 |
| | Secondary | 136.99 | 183.95 | 416.64 | 214.9 | 952.48 |
| | Sum | 164.35 | 205.48 | 454.39 | 222.95 | 1047.17 |
| | Reliability (%) | 100 | 100 | 100 | 100 | 100 |
| 5-Year | Primary | 26.89 | 21.52 | 37.76 | 8.04 | 94.21 |
| | Secondary | 135.55 | 183.78 | 417.14 | 216.65 | 953.12 |
| | Sum | 162.44 | 205.3 | 454.9 | 224.69 | 1047.33 |
| | Reliability (%) | 99.86 | 100 | 100 | 100 | 99.86 |

## Table 5.1b: Energy Generation Statistics; Historical Scenario; Private Reservoirs

| Min. Target | M. Falls | B. Ferry | G. Rock | Oliver | N. Hlands | System |
|---|---|---|---|---|---|---|
| 1-Year | 60.89 | 449.36 | 227.49 | 310.64 | 155.25 | 1203.63 |
| 5-Year | 61.22 | 450.28 | 228.08 | 313.32 | 156.61 | 1209.51 |

## Table 5.2a: Energy Generation Statistics; Canadian Scenario; Federal Reservoirs

| Min. Target | Energy (GWH) | Buford | West Point | George | Woodruff | System |
|---|---|---|---|---|---|---|
| 1-year | Primary | 23 | 19.89 | 35.76 | 8.61 | 87.26 |
| | Secondary | 83.15 | 111.7 | 248.66 | 182.76 | 626.27 |
| | Sum | 106.15 | 131.59 | 284.42 | 191.37 | 713.53 |
| | Reliability (%) | 95.09 | 94.86 | 95.88 | 100 | 94.86 |
| 5-Year | Primary | 19.63 | 18.27 | 33.87 | 8.41 | 80.18 |
| | Secondary | 82.79 | 111.08 | 249.91 | 181.7 | 625.48 |
| | Sum | 102.42 | 129.35 | 283.78 | 190.11 | 705.66 |
| | Reliability (%) | 92.16 | 90.14 | 92.27 | 100 | 90.14 |

## Table 5.2b: Energy Generation Statistics; Canadian Scenario; Private Reservoirs

| Min. Target | M. Falls | B. Ferry | G. Rock | Oliver | N. Hlands | System |
|---|---|---|---|---|---|---|
| 1-Year | 42.98 | 288.97 | 211.26 | 224.66 | 112.49 | 880.36 |
| 5-Year | 42.84 | 290.76 | 200.81 | 227.95 | 114.15 | 876.51 |

## Table 5.3a: Energy Generation Statistics; Hadley Scenario; Federal Reservoirs

| Min. Target | Energy (GWH) | Buford | West Point | George | Woodruff | System |
|---|---|---|---|---|---|---|
| 1-year | Primary | 27.37 | 21.53 | 37.75 | 7.6 | 94.25 |
| | Secondary | 202.29 | 238.07 | 520.43 | 209.29 | 1170.08 |
| | Sum | 229.66 | 259.6 | 558.18 | 216.89 | 1264.33 |
| | Reliability (%) | 100 | 100 | 100 | 100 | 100 |
| 5-Year | Primary | 27.06 | 21.51 | 37.75 | 7.57 | 93.89 |
| | Secondary | 199.91 | 237.46 | 520.93 | 211.12 | 1169.42 |
| | Sum | 226.97 | 258.97 | 558.68 | 218.69 | 1263.31 |
| | Reliability (%) | 99.98 | 100 | 100 | 100 | 99.98 |

## Table 5.3b: Energy Generation Statistics; Hadley Scenario; Private Reservoirs

| Min. Target | M. Falls | B. Ferry | G. Rock | Oliver | N. Hlands | System |
|---|---|---|---|---|---|---|
| 1-Year | 78.8 | 568.9 | 228.14 | 363.78 | 181.14 | 1420.76 |
| 5-Year | 79.25 | 569.37 | 228.82 | 368.13 | 183.34 | 1428.91 |

# 6. Conclusions

This work was conducted as part of the National Climate Variability and Change Water Sector Assessment, and aimed to quantify the potential climate change impacts for selected Southeastern U.S. basins. The assessment necessitated the development of new modeling tools and focused on watershed hydrology as well as on river basin management. A summary of the general conclusions follows:

- Compared to the historical (baseline) response, under the Canadian Climate Scenario, all basins experience less precipitation, increased evapotranspiration, less runoff, and smaller runoff coefficients. By contrast, these trends are reversed under the Hadley Climate Scenario.

- Soil moisture exhibits a sharp decline under the Canadian climate scenario, and a mild increase under the Hadley scenario. Both scenarios indicate that soil moisture variability will increase, either because of worse than historical droughts (Canadian GCM) or because of wetter extremes (Hadley GCM).

- Frequent and very severe reservoir drawdowns occur under the Canadian GCM climate scenario throughout the ACF basin. At some locations, water supply deficits increase multi-fold relative to the historical climate. Instream flows shift toward substantively drier regimes and could be devastating to the ecology and the environment. Energy generation decreases by a significant margin. By contrast, under the Hadley climate scenario, reservoir levels are comparable to those of the historical climate. No appreciable water supply deficits occur, instream flow regimes shift toward wetter (than the historical) conditions, and energy generation increases.

- The significant uncertainty associated with future climate scenarios necessitates that water allocation agreements, management strategies, and institutional processes be *flexible and adaptive.*

- From the standpoint of future assessment efforts, there is a compelling need to understand and quantify the uncertainty of GCM climate models, especially relative to climate features critical for water resources planning and management. Thus, in addition to *annual* atmospheric forcing mean and variability trends, it is important to understand and develop the GCM ability to capture potential *inter-annual and decadal* changes in drought and flood patterns.

# References


Alley, W.M. (1984) On the treatment of evapotranspiration, soil moisture accounting, and aquifer recharge in monthly water balance models, Water Resources Research, 20(8), 1137-1149.

Canadian Centre for Climate Modeling and Analysis (CCCMA). (1997) The First Generation Coupled General Circulation Model (CGCM1). WWW page available on-line at http://www.cccma.bc.ec.gc.ca/models/cgcm1.html

Georgakakos, A.P., and H. Yao. (1999) A Decision support system for the Apalachicola-Chattahoochee-Flint river basin. *Technical Report* No. GWRI-01-99, Georgia Water Resources Institute and Georgia Institute of Technology, Atlanta, Georgia.

Georgakakos, K.P., and O.W. Baumer. (1996) Measurement and utilization of on-site soil moisture data, *Journal of Hydrology*, 184(1-2), 131-152.

Kittel, T.G.F., Royle, J.A., Daly, C., Rosenbloom, N.A., Gibson, W.P., Fisher, H.H., Schimel, D.S., Berliner, L.M., and VEMAP2 Participants. (1997) A gridded historical (1895-1993) bioclimate dataset for the conterminous United States. *Proceedings of the 10th Conference on Applied Climatology, 20-24 October 1997, Reno, NV.* American Meteorological Society, Boston.

Mohseni, O., and H.G. Stefan, (1998) A monthly streamflow model, *Water Resources Research*, 34(5), 1287-1298.

Palmer, W.C. (1965) Meteorologic drought, *Res. Pap. U.S. Weather Bur.*, 45, 58 pp.

Thornthwaite, C.W. (1948) An approach toward a rational classification of climate, *Geogr. Rev.*, 38(1), 55-94.

Thornthwaite, C.W., and J.R. Mather. (1955) The water balance, *Publ. Climatol. Lab. Climatol. Drexel Inst. Technol.*, 8(1), 1-104.

Torak, L.J., Davis, G.S., Strain, G.A., and Hemdon J.G. (1996) Geohydrology and stream-aquifer relations in the Apalachicola-Chattahoochee-Flint river basin, southeastern Alabama, northeastern Florida, and southwestern Georgia, *US Geological Survey Water Supply Paper* 2460, 94 p.

U.K. Meterological Office (UKMO). (2000) The Hadley Centre's Second Generation Coupled Ocean-Atmosphere GCM: HadCM2. WWW page available on-line at http://www.cru.uea.ac.uk/link/experiments/1b_experi_contents.html

Yao, H., and A.P. Georgakakos, (2000) Assessment of Folsom Lake Response to Historical and Potential Future Climate Scenarios, 2, Reservoir Management, *Journal of Hydrology,* in review.