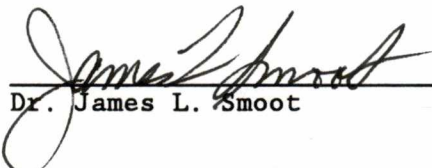


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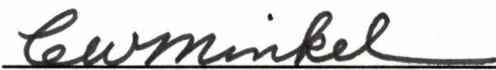

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STATISTICAL CHARACTERIZATION
AND
TREND ANALYSIS
FOR
TENNESSEE AND CLINCH RIVER FLOWS
AT
CHICKAMAUGA AND NORRIS DAMS

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Enrique Gomezdelcampo

August 1991

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ABSTRACT

Long-term linear trends in calculated natural riverflow data and the methods used for their detection were investigated for the Clinch River at Norris Dam and the Tennessee River at Chickamauga Dam.

Riverflow records at Norris Dam, available from 1903 to 1989, were validated against the flow data of two unregulated tributary rivers to Norris Lake.

Step and monotonic trends were sought in the flow record, step trends with the t-test, monotonic trends with linear regression and seasonal Kendall tests.

No statistically significant step or long-term linear trends were found in the annual, monthly, and maximum and minimum annual data sets. Long-term linear decreasing trends were detected in some individual months of record.

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"I am but an aspect of the river, one of its points of consciousness. Even when not in its presence, I feel the river running, I measure its flows, I run my eyes over its stones and its pebbles, I note the glint of its surface, the sound of its water rustling over stones and through the roots of its banks, its waters that connect to all skies, and to oceans everywhere."

Stanley Crawford

CHAPTER 1

INTRODUCTION

1.1 CLIMATE CHANGE

1.1.1 General

Climate has determined the areas where major civilizations have developed in the world. Any change in climate will impose changes in the people's way of life.

Climate can be defined as the synthesis of weather over the whole of a period essentially long enough to establish its statistical ensemble properties (mean values, variances, probabilities of extreme events, etc.) and is largely independent of any instantaneous state (Kite, 1989a). Climate change would then be the differences in the mean values of climatic statistics between successive climatic periods. Changes in the statistics within a climatic period is termed climatic variation.

Climatologists have suggested that climatic change may occur naturally at several time scales, the shortest being around 100 years (Lettenmaier and Burges, 1978). Human-related activities, could however, cause a climate change in less than 100 years. The emission of greenhouse gases is an example of such an activity.

1.1.2 Impacts of Climate Change

Global climatic changes could include historically significant increases or decreases in temperatures, combined with changes in

global and regional precipitation patterns.

One of the most important regional consequences of global climatic changes may be alterations in the availability of freshwater resources, including changes in streamflow and soil moisture. Precipitation changes would affect the amount and timing of streamflow, groundwater recharge, and the frequency of extreme events, such as major storms and droughts. Temperature changes, presumably warming, would increase evapotranspiration, decrease snow accumulation, and change the timing of snowmelt.

The impacts of climate change on water resource management include water supply, water quality, flood protection, hydropower production, navigation, recreation, and environmental resources (i.e. natural ecosystems).

1.2 THE TVA SYSTEM

1.2.1 General

The Tennessee River system has its headwaters in the mountains of western Virginia, North Carolina, eastern Tennessee, and northern Georgia. Two rivers, the Holston and the French Broad, join at Knoxville to form the Tennessee. After Knoxville, the river flows southwest through the state of Tennessee, where the Little Tennessee, the Clinch, and the Hiwassee Rivers join the Tennessee. Then the river continues flowing southwest into Alabama, until it reaches the northeast corner of Mississippi where the river turns north, recrossing the state of Tennessee and continuing up to Paducah, Kentucky, 600 river miles from Knoxville, where it enters the Ohio

River.

The Tennessee River system drainage area covers 40,910 square miles. It is divided into two distinct regions: the first one includes approximately 21,400 square miles upstream of Chattanooga, Tennessee, the second 19,500 square miles west of Chattanooga, upstream from Paducah, Kentucky. The drainage area lies mostly in the state of Tennessee with parts in six other states: Kentucky, Virginia, North Carolina, Georgia, Alabama, and Mississippi.

The eastern half of the valley includes the slopes of the Blue Ridge and Great Smoky Mountains, where an abundant growth of forest covers the ground. The western half of the Valley is less rugged, with substantial areas of flat or rolling land occurring in middle and western Tennessee.

The Tennessee Valley has a mean annual rainfall of about 52 inches, with a low of 36 inches in 1985 and a high of 65 inches in 1973 since records were started 100 years ago (TVA, 1990). The spatial variability of rainfall includes a mean annual rainfall of over 90 inches in portions of mountainous areas along the headwaters of the tributaries, to as low as 40 inches in parts of the French Broad, Clinch, and Holston Valleys.

Valley-wide monthly average rainfall ranges from between 3 and 5.5 inches, as shown in Figure 1. March and July are typically the highest rainfall-producing months and September through November are usually the lowest. The average annual runoff is about 22 inches, roughly 40% of the average annual rainfall over the drainage area.

MONTHLY PRECIPITATION & RUNOFF TENNESSEE RIVER BASIN 1890 - 1990

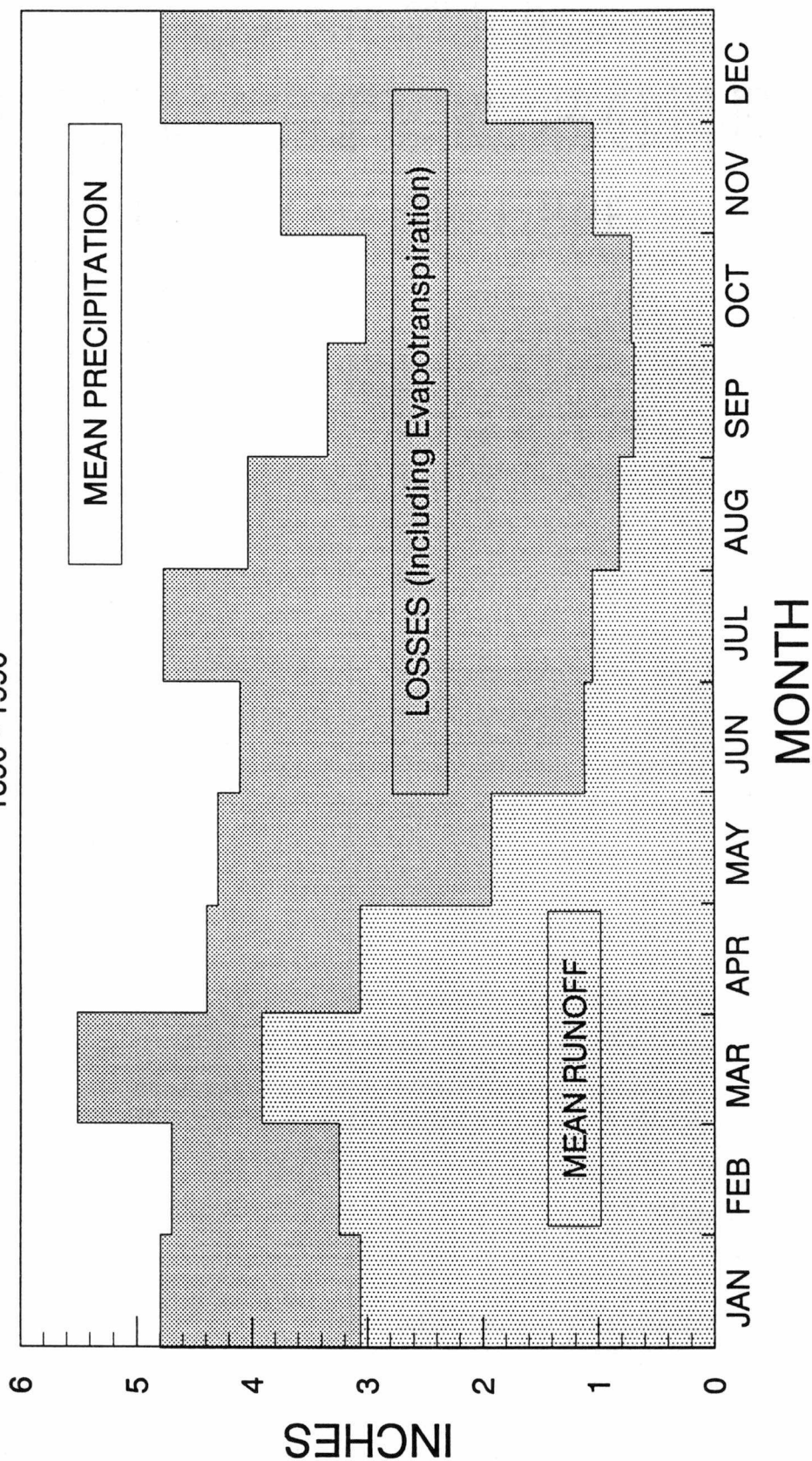


Figure 1. Tennessee River Basin Monthly Rainfall and Runoff (TVA, 1990).

1.2.2 Purpose of TVA

The Tennessee Valley Authority (TVA) was created by Act of Congress in 1933 to develop the resources of the Tennessee River Basin, the principal water control objectives assigned to it were:

- (a) provide 9-foot navigation on the main Tennessee River from its mouth to Knoxville, Tennessee.
- (b) control destructive flood waters in the Tennessee and Mississippi River Basins.
- (c) generate the maximum amount of electric power consistent with flood control and navigation.

In developing the reservoir system these primary purposes have always governed. As one of the major objectives, flood control has been in the forefront in planning, designing, constructing, and operating the dams and reservoirs. But in addition to the three main objectives, mainstream reservoirs have a variety of other functions such as recreation, fishery and wildlife management, water supply, wastewater disposal, and commercial development of various kinds.

1.2.3 Components of the TVA System

The main Tennessee River water control system consists of thirty four major dams. TVA built 25 of these dams and acquired 5 others. Four belong to the Aluminum Company of America and are operated by that company. In addition, TVA has acquired two smaller dams and built a pumped storage project; a system of 4 smaller dams and a floodway for local flood relief, water supply, water quality,

and recreation in the Bear Creek watershed of northwest Alabama; a similar system of 8 dams on Beech River on west Tennessee; and a small 2-dam flood protection project in the eastern end of the Valley above Bristol, Tennessee. TVA has deferred construction of one dam and owns another one in the Cumberland River.

1.3 OBJECTIVES AND IMPORTANCE OF THE STUDY

Four main issues are addressed in this investigation:

- (a) What are the main statistical characteristics of the flow in two selected parts of the Tennessee River System?
- (b) Has there been a significant change in historical flow trends in the Upper Tennessee River Basin?
- (c) Has there been an increase in extreme flow variability?
- (d) Has there been a shift in the seasonality of flows?

The magnitude of the potential climatic impacts combined with the huge investment in TVA's reservoir system and the importance of the benefits it provides, demand that more attention be paid to hydrologic variables. This investigation will allow early identification of changes in flow patterns, which could be useful in the long-range reservoir and power system planning of TVA.

1.4 PLACES OF STUDY

Two major dams were chosen as the places of study for the two rivers investigated in this report: Chickamauga Dam on the Tennessee River at river mile 471.0 and Norris Dam on the Clinch River at river mile 79.8. Chickamauga Dam and Norris Dam are situated in the

vicinity of Chattanooga and Norris, Tennessee, respectively. The locations within the Tennessee Valley of the two dams are shown in Figure 2.

The selection of Chickamauga and Norris Dams was due largely to the availability of streamflow records at these sites. Another factor influencing this decision was the fact that Chickamauga Dam is representative of the upper half of the TVA River System and Norris Dam is often used as a reference site due to the low human-impact around its area.

Chickamauga and Norris Dams are both located in the upper Tennessee River Basin. The topography of the area is very rugged, and the slopes are typically steep. The watershed in the upper basin ranges in elevation about 6,100 feet between the highest peak in the mountains and the site of Chickamauga Dam at about 600 feet above mean sea level. The drainage areas at Chickamauga and Norris dams are 20,790 square miles and 2,912 square miles respectively.

1.5 LIMITS OF THE STUDY

Only riverflow is used in this study, though its relation with precipitation is presented in Appendix A.

All climate variables show considerable natural variability on all time scales, and this variability constitutes the background noise against which a potential signal is to be detected. While atmospheric processes induce randomness into precipitation and temperature series, the storage effect of river basins replaces some of this randomness with autocorrelation in the river flow series, allowing an easier

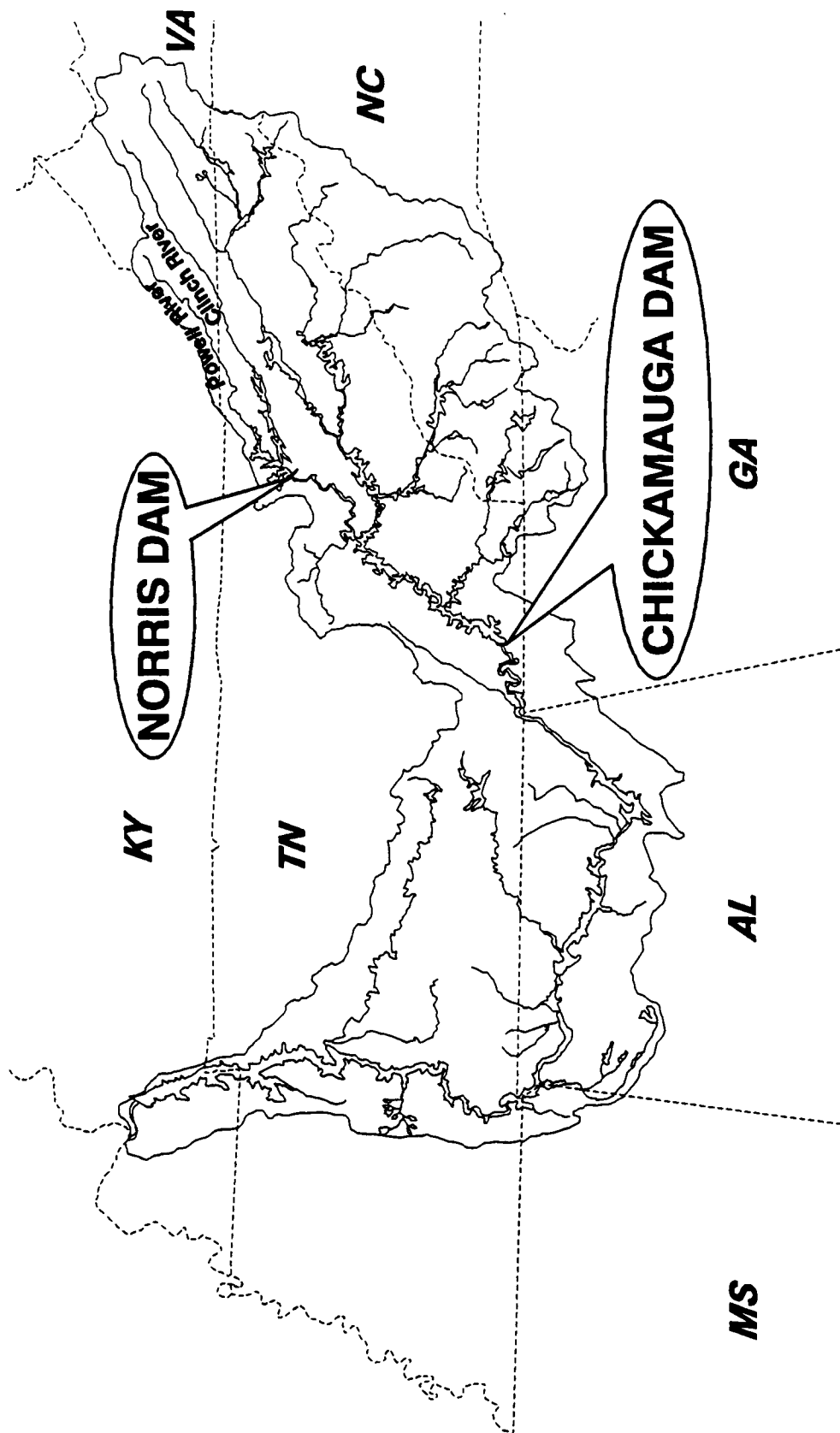


Figure 2. Location of Places of Study.

detection of the signal from the noise. Streamflow has special merit as an indicator of climate, its response is proportionally greater to climate change than is that of precipitation alone (Stockton, 1990).

Mean annual and monthly data are assumed to be adequate for this investigation. Daily data are cumbersome to work with for large periods of time, besides showing high variability.

Although the best data would be that of an unregulated river, none were found with a long enough recording history to try to detect long-term trends. TVA Reservoir Operations calculated natural flow is used in this study.

The two sites chosen, Chickamauga and Norris Dams, are representative of the upper river basin of the TVA system, and as such, the results will only apply to this area.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

There are two primary types of data trends, the step trend and the monotonic trend. The step trend assumes that the data collected before a specific time are from a distinctly different population than the data collected after that time. It should only be used when the records are naturally broken into two distinct periods with a relatively long time gap between them or when there is a known event that occurred at a specific time, and is likely to have resulted in a change. The second type of trend is the monotonic trend, in which the population shifts with no reversals of direction over time, but without specifying how (Hirsch et al., 1991).

This review consists of the description of some approaches used for the statistical investigation of both kinds of trends. They are broadly divided into exploratory and confirmatory data analysis.

2.2 EXPLORATORY DATA ANALYSIS

2.2.1 Smoothing Functions

A scatterplot is one of the most powerful statistical tools for analyzing the relationship between two variables. Trends may be easily discovered from a perusal of a graph, as may be extreme values, interventions, dependencies between observations, seasonality, need for data transformation, nonstationarity, and long term cycles (McLeod

et al., 1983).

A function to smooth the data is often needed to seek a trend in a noisy scatter plot. A variety of techniques can smooth, or filter the noise from a time series. One of the simplest is a running average or running mean. It is based on the assumption that a data point consists of a smooth component plus random error, and then, if several points surrounding a point are averaged, the errors tend to cancel each other out. A running mean provides a simple smoothing which helps clarify long term changes in a variable (Hansen and Lebedeff, 1987); it also helps in damping the high frequency interannual variations that may hide a trend (Katsoulis, 1987).

Usually 5-year, 10-year or 30-year running means are used to analyze the data for trends and periodicities (Hansen and Lebedeff, 1987; Katsoulis and Kambetzidis, 1989). But with some hydrologic time series, like streamflow and precipitation, 11-year or 22-year running means are common, since the periodicity is assumed to be induced by the cycle of sunspots activities, or its double (Yeyjevich and Harmancioglu, 1985; Stockton, 1990; Mitchell, 1990).

Another smoothing function is the running medians. It is a more robust filter when the data do not contain Gaussian (normal) noise (Wilkinson, 1990).

Several other filters are used to detect trends, like the Ormsby filter (Katsoulis, 1987) and LOWESS (Cleveland, 1979; Chambers et al., 1983). LOWESS, or LOcally WEighted Scatterplot Smoothing, determines a functional relation between two variables without

prejudging its shape or monotonicity. It involves a locally weighted regression that is not distorted by a small fraction of outliers. Smoothed values from LOWESS show the middle of the distribution of y as it changes with x .

Despite some limitations and the possible introduction of some cyclicity, known as the "Slutsky effect", smoothed graphs portray the essential features of time series more clearly (Probst and Tardy, 1987; Yevjevich, 1972).

2.2.2 Boxplots

The Tukey boxplot is a simple visual display of a data sample; it shows the level, spread, skewness, tail length, and outliers. Although single plots show the distribution of a single variable, grouped plots display the distribution of a single variable across the levels of a grouping variable. For example, they can describe the changes in the distribution of flows through time. Section 3.4.4 discusses the creation of a boxplot.

Boxplots are suitable display forms for exploratory data analysis because they summarize the body of data without being influenced by outliers and then allow the outliers to stand out as points needing special attention (Hoaglin et al, 1983). In addition to detecting far-out values, boxplots can be used to discover lack of symmetry in the distribution of the data. If the data are approximately symmetrical with respect to the median, they may follow a symmetric distribution such as the normal distribution (McLeod et al., 1983).

Boxplots can also be used in intervention studies of the effects of urbanization, mining activities, forest changes, damming of a river, etc. on hydrology. If the data of the intervention is known, boxplots can be constructed for each period of time before and after the intervention. These two graphs can then be compared to ascertain if the intervention has caused noticeable changes (McLeod et al., 1983; Hipel et al., 1988).

Although the resistance of the boxplot to wild data values or outliers is what makes it attractive for use in exploratory data analysis (Hoaglin et al., 1983), one should be cautious of any peculiarities in the boxplot if few data points are used to determine it (Hipel et al., 1988).

2.2.3 Autocorrelation Functions

Some authors use the autocorrelation function as part of the exploratory data analysis (McLeod et al., 1983; Hipel et al., 1988).

Autocorrelation measures the direction and strength of the statistical relationship between ordered pairs of observations that are part of the same series, but separated by a certain number of time periods. The lag 1 (one) autocorrelation is the ordinary Pearson correlation of a series with itself, shifted by one observation (Wilkinson, 1990). Higher order autocorrelations coefficients describe the correlation between the data series and the same series shifted or lagged by more intervals.

The autocorrelation function is useful for interpreting trends

in the data. If there is large positive correlation at lag 1, a sequence of high values in the series will often be grouped together and low values will often follow other low values (McLeod et al., 1983). When a lag 1 and other lag autocorrelations are significantly different from zero, this indicates the presence of stochastic trends in the data. But this may also indicate long term persistence in data that is serially correlated, particularly for small sample sizes (Lettenmaier, 1988). To work with residuals in that case, may eliminate or reduce the persistence (Hirsch and Slack, 1984).

2.2.4 Residuals

The investigation of residuals is an important part of the exploratory data analysis. The residuals are mainly used to refine and determine the adequacy of a model fitted to the data. Although sometimes they are utilized to detect a trend in the original data (Potter, 1991; Tukey, 1977).

Usually three main aspects are of concern when looking at residuals:

- (a) the size of the residuals
- (b) the change in size of the residuals through time
- (c) the unusual residuals (outliers)

Depending on these, a new model may be chosen, or a new variable introduced in the existing model (Hoaglin et al., 1983; Chambers et al., 1983).

Solow and Broadus (1987), discuss an approach taken by Hansen and Lebedeff, based on scaled residuals to determine the extent to

which 1987 was unusually warm world-wide. The article shows how residuals can be incorporated as part of the trend analysis.

2.3 CONFIRMATORY DATA ANALYSIS

2.3.1 General

Parametric and nonparametric tests can be utilized for hypotheses and significance level testing at the confirmatory data analysis stage.

A parametric test requires the data to have a normal distribution, whereas a nonparametric test does not depend upon the form of the underlying distribution. The characteristics of the sample determine what kind of test to use. But when a parametric test is appropriate, a nonparametric test cannot be as powerful as the most efficient parametric test (Hipel, 1988; Wilkinson, 1990). That is because in order to have a more powerful test of what is occurring many assumptions must be made on the data.

2.3.2 t-Test

From a purely statistical viewpoint, detecting a trend is closely related to detecting a change in the mean (Wigley et al., 1985). The two-sample Student t-test is probably the most frequently used parametric procedure for testing differences between the means of two samples.

Three important assumptions underlie the t-test: 1) samples come from a parent population that is normally distributed, 2) the two-sample groups have equal variances, and 3) sample observations are

independent.

The null hypothesis H_0 for a two sample comparison of means is a statement of no difference in the means while the alternative hypothesis H_1 is a statement of difference. The test statistic is defined by:

$$t = (X_1 - X_2) / S_p (1/n_1 + 1/n_2)^{1/2} \quad (1)$$

where:

t = test statistic

X_1 = mean of group 1

X_2 = mean of group 2

n_1 = sample size of group 1

n_2 = sample size of group 2

$$S_p^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{(n_1 + n_2 - 2)} \quad \text{(pooled variance)} \quad (2)$$

Milton and Arnold (1990) show a procedure to perform a t-test if the variances are unequal, which will reduce the assumptions stated above to two.

With respect to violations in the remaining assumptions, Montgomery and Loftis (1987) state that regarding normality, the two-sample t-test is robust when the groups being compared have similar and non-skewed distributions or equal sample sizes regardless of skewness. It is not robust when comparing a normal group to a non-normal group with small sample size. Relative to the independence factor, the t-test is very sensitive to lag 1 autocorrelation. The true alpha is greater than the nominal value for autocorrelated series

with lag 1 autocorrelation greater than zero. Also the presence of seasonal patterns, which produce an overestimation of the true variance, affects the t-test by reducing its power, the true alpha becoming less than the nominal value.

El-Shaarawi and Damsleth (1988) also investigate the implications of ignoring serial correlations when making inferences about the means. They present a modified t-test that accounts for autocorrelation, but only when the lag 1 autocorrelation is greater than any other and no seasonality exists.

The t-test can be used to evaluate hydrologic changes by selecting different time intervals from the record and comparing them. The periods can be chosen by the use of graphical plots, the knowledge of periods of climatic relevance, or if the dates of suspected changes are known (Buishand, 1984; Karl and Riebsame, 1989; Sharma, 1985).

The nonparametric counterpart to the t-test is the Mann-Whitney test, also called the Wilcoxon test (Conover, 1980). The main assumption of the Mann-Whitney test is independence within each sample and between the two samples. As in the t-test, the null hypothesis H_0 , is a statement of no difference between the two populations, but in this case, the comparison is of the medians rather than the means. The test is based on ranks assigned to the actual data. It is an ordinal comparison.

2.3.3 Linear Regression

A linear trend is a convenient simplification used in the absence of any compelling reasons to suggest otherwise. Linear regression is the method used to fit a linear trend to time series data. After the fit, a t-test is used to evaluate whether the resulting slope is significantly different than zero, that is, the null hypothesis is given by: slope = 0. However, the data must conform to the t-test assumptions of normal distribution, serial independence, and exclusion of seasonal cycles (Butkus, 1990).

The p-value reported for the linear regression represents the probability of the slope being significant. A smaller p-value indicates a greater likelihood of the existence of a linear trend with a slope different than zero. The R-square, or coefficient of determination, is a measure of the fit to the data. It indicates how much of the variance in y (flow) is explained by the regression with x (year). The square root of R-square, or "r" is the correlation coefficient between the two variables of the linear regression (Milton, 1990).

2.3.4 Seasonal Kendall Test

The seasonal Kendall test was developed from the Mann-Kendall univariate test for trend (Bradley, 1968), by Hirsch, et al. (1982) who proposed a seasonal adaptation where each of the seasons is treated as an independent variable. This comparison of data from like seasons minimizes the seasonal effects (Alexander and Smith, 1988). Later Hirsch and Slack (1984) extended the seasonal Kendall test to

the case where correlation between successive seasons within the same year is allowed, but not between the same season in successive years (Lettenmaier, 1988).

Several investigators have recommended the seasonal Kendall test over numerous other trend tests after rigorous statistical comparisons (Butkus, 1990).

The null hypothesis, H_0 , in the seasonal Kendall test, is that for each of the seasons the observations are independent and identically distributed while the alternative hypothesis is that there is a monotonic trend (Hipel et al., 1988). The strength and direction of trend is indicated by tau (τ) and the statistical significance by a p-value.

The seasonal Kendall test is specifically designed to provide a single summary statistic for the entire record and will not indicate when there are trends in opposing directions in different months. If one is interested in trends in specific months, then it would be appropriate to use the test for each of the months (Hirsch et al., 1982).

2.3.5 Other Trend Analysis Methods

A different approach to trend analysis consists on the fit of a time series model to the data and the subsequent analysis of the residuals for trend.

Many different models can be used to represent hydrologic time series (Hipel, 1988), but caution must be applied in the search for

the one reflecting the actual physical process involved. Otherwise the fitting of a model to the data becomes an exercise in mathematics and the results have no physical foundation (Klemes, 1986; Klemes, 1988).

Intervention analysis is other method used to detect hydrologic changes. Its main application is in the analysis of step trends, like the effects of dam construction or forest fire on river flows (McLeod et al., 1983; Sharma, 1985).

Kite (1989a) presents another approach to detection of trends by separating a time series in its components: linear trends, periodicities, autoregression and residual. Evaluating the percentage of the total variance explained by each part, and then trying to ascribe the different components to possible climate change.

CHAPTER 3

EXPLORATORY DATA ANALYSIS

3.1 GENERAL

The purpose of this chapter is to discover important statistical properties of the data by carrying out simple graphical and numerical studies. The origin of the data and its validity are also described in this chapter.

3.2 DATA ORIGIN

The Tennessee and Clinch riverflow time series data extends from January 1903 to December 1989. There are no missing weekly data throughout the period. The data represent adjusted weekly natural streamflows, that is streamflow that would have resulted directly from runoff were there no dams. The adjusted natural flows are calculated using two general methods, one before and the other after the closure of the dam at each site. Prior to dam closure, flows were measured directly based on river gages when available at the site and on the ratio of drainage areas if not. After the dam closure (most TVA dams were completed between 1936 and 1950), the adjusted natural flows were computed based on dam releases and the change in storage at each reservoir by the following equation:

$$I_1 = (S_2 - S_1) + (Q_d - Q_u) \quad (3)$$

where:

I_1 - local inflow

S_1 = storage at beginning of the week

S_2 = storage at the end of the week

Q_d = release from downstream dam

Q_u = release from upstream dam

The above formula calculates the adjusted local inflow at the dam site. The adjusted natural flow is the sum of all the local inflows above the dam of interest. In the case of the uppermost dam, the adjusted natural flow is the local inflow. The released water includes turbine flow, sluicing, overtopping, and leakage. The change in storage is computed using the reservoir storage-elevation curve.

The weekly records, furnished by TVA Reservoir Operations, consist of eighty-seven years each with fifty two flow values. Every week comprises seven days, except for the final week of each year which has eight days. Leap years have one more day on the ninth week.

The monthly and annual records are calculated from the weekly data. The annual average flow is the sum of the weekly flows for the year divided by fifty two. The monthly average flow is a weighted average using the number of days in a week belonging to a certain month.

The adjusted natural flow record for Norris Dam is divided in seven different periods, three before the dam closure in March 4, 1936, and four after it. Chickamauga Dam was closed in January 15, 1940. The records show six periods, four before the closure and two afterwards (see Appendix B for detailed information).

3.3 VALIDITY OF DATA

3.3.1 General

The analysis and conclusions are based on the data set of adjusted natural flows. There is a need to ascertain the validity of the data, particularly for the second part of the record. After the dams commenced operation all of the data is calculated. This method of computing the natural flow creates the possibility of errors due to groundwater seepage, evaporation from the inundated area, and in the releases.

3.3.2 Unregulated Rivers

Flows from two unregulated tributaries of Norris Lake are used to determine if the calculated flow is representative of the natural flow that would have occurred if the dam was not in place.

The two unregulated rivers used to validate the flow record were the Clinch River above Tazewell, and the Powell River near Arthur. The Clinch River at that location and the Powell River near Arthur have drainage areas of 1,474 square miles and 685 square miles respectively. The drainage area of Norris Dam is 2,912 square miles. The drainage areas of both rivers combined comprise 74% of the total drainage area at Norris Dam. The records for these two rivers are shorter than the records from the dam. For the Clinch River data has been collected from 1919 to 1989 and for the Powell River data exists from 1919 to 1982. All records are in the form of monthly flows.

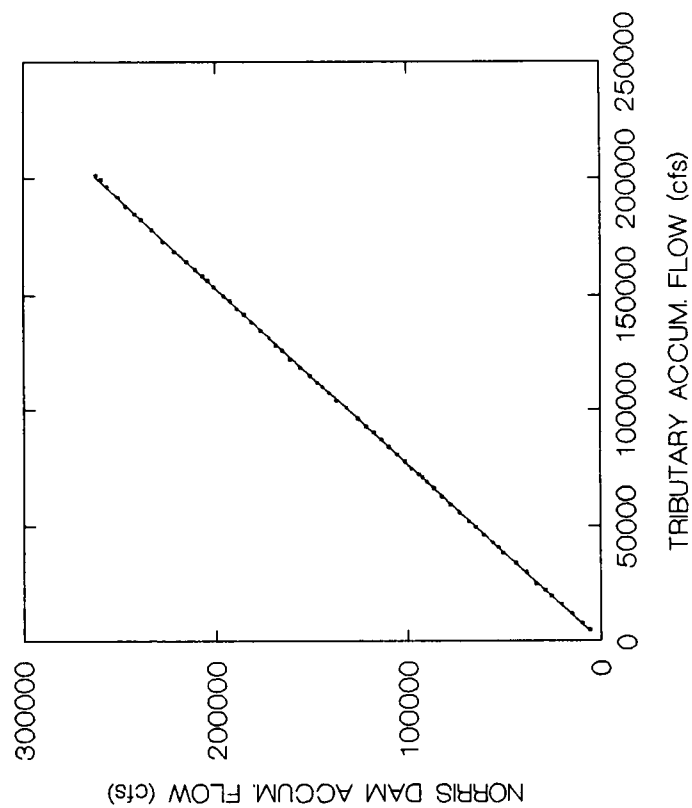
A double mass curve analysis (Linsley et al., 1986) is the first step used to determine the difference between the flow

calculated at Norris Dam and the one recorded by gages in the unregulated rivers for the two tributary periods. The accumulated flow from Norris Dam is plotted against the accumulated flow from the two combined rivers and checked for changes in slope. So long as the relationship between the two flows remains constant, the points will plot in a straight line. A break in this plot would indicate a change in the proportionality between them (Owe, 1985). As seen in Figure 3, the analysis for monthly and annual flows shows no drastic breaks in slope.

Double mass analysis is not conclusive and its results should be substantiated by other tests (Linsley et al., 1986). The second analysis performed to compare the two sets of flows (unregulated and regulated) consists of a regression analysis on the percentage of variance among the data sets. This test is similar to the bivariate test of Potter (1981). The slope of the regression line of the annual residual flow versus time is tested to see if is significantly different from zero (H_0 : slope = 0) at the 0.05 level. If it is not, the two flows track each other. The residual flow is calculated by subtracting the two tributary flows from the flow at Norris Dam. Figure 4 shows the results of this analysis. It is apparent from the slope statistic given in Figure 4 that the Norris Dam flow follows the same pattern as the two unregulated rivers. The p-value obtained was 0.592.

Figure 5 shows a graph of the flows from Norris Dam and the two combined unregulated rivers. Both flows are divided by their

DOUBLE MASS CURVE
ANNUAL FLOW



DOUBLE MASS CURVE
MONTHLY FLOW

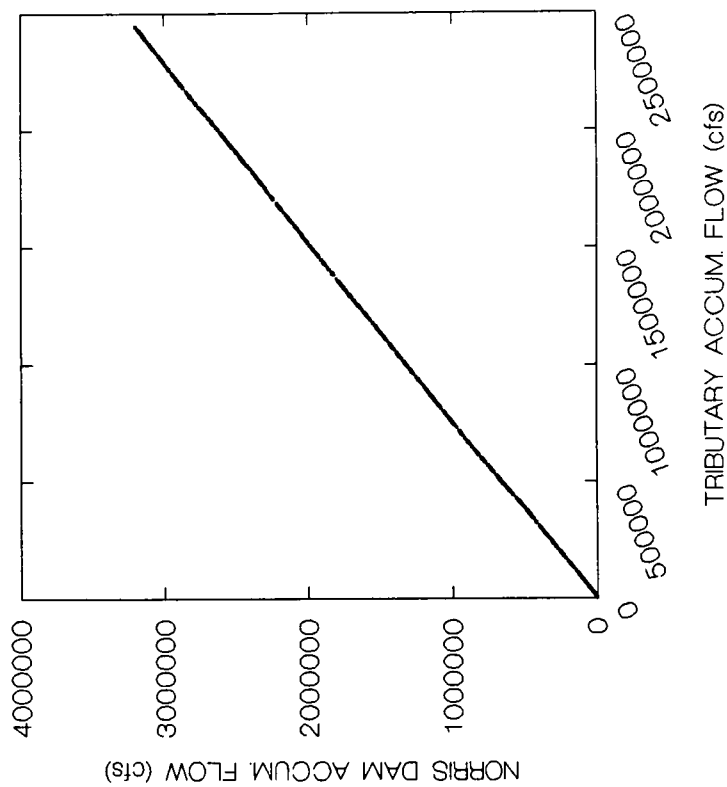


Figure 3. Double Mass Curve of Flows at Norris Dam.

NORRIS DAM AND TRIBUTARIES

LINEAR REGRESSION, ANNUAL FLOW

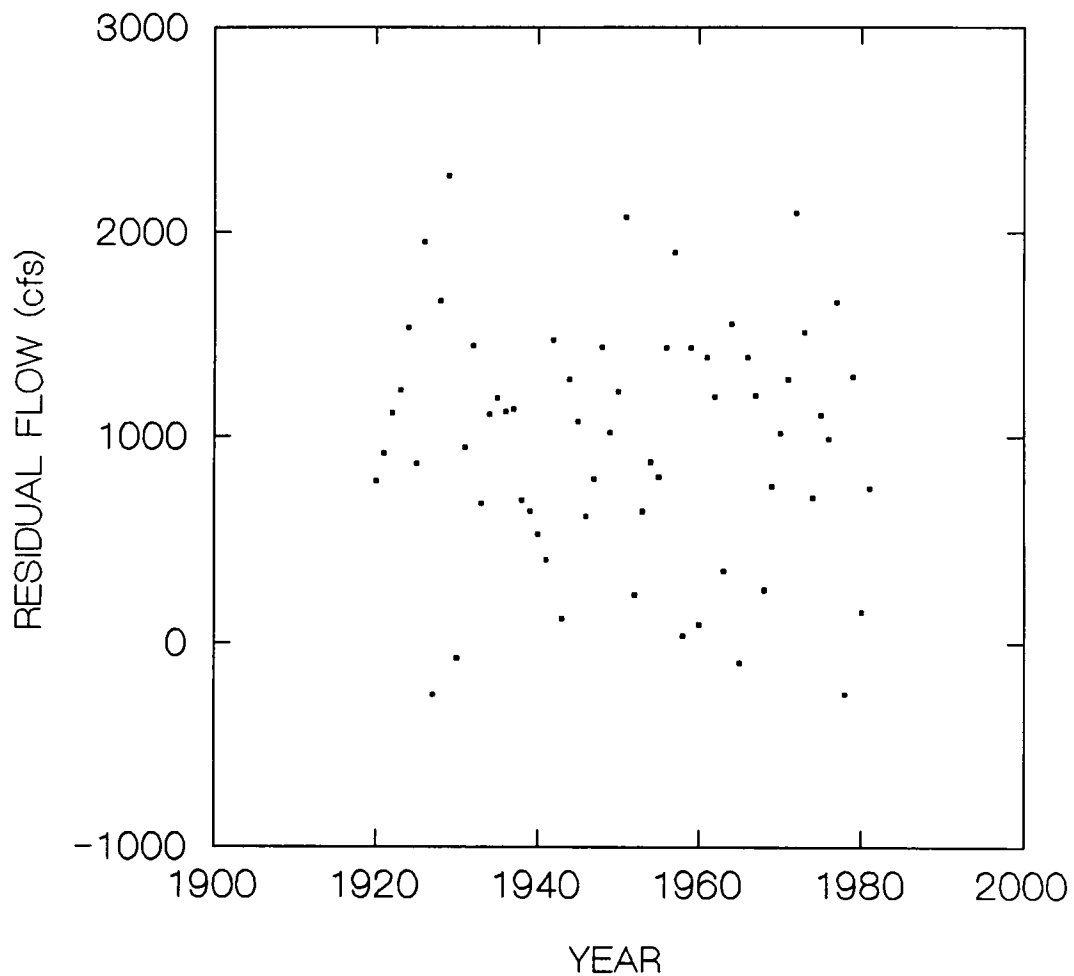
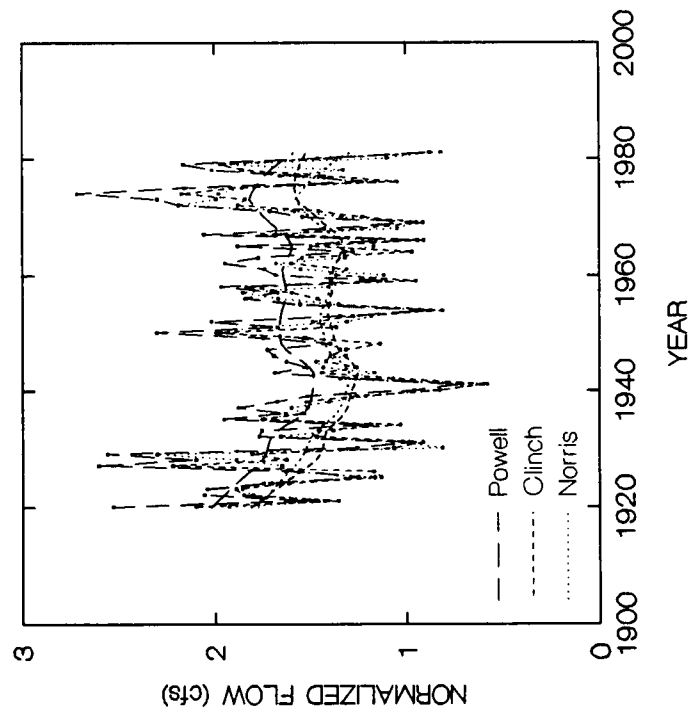


Figure 4. Linear Regression of Residual Flow for Norris Dam and Tributaries.

NORRIS WATERSHED ANNUAL FLOW



NORRIS WATERSHED ANNUAL FLOW

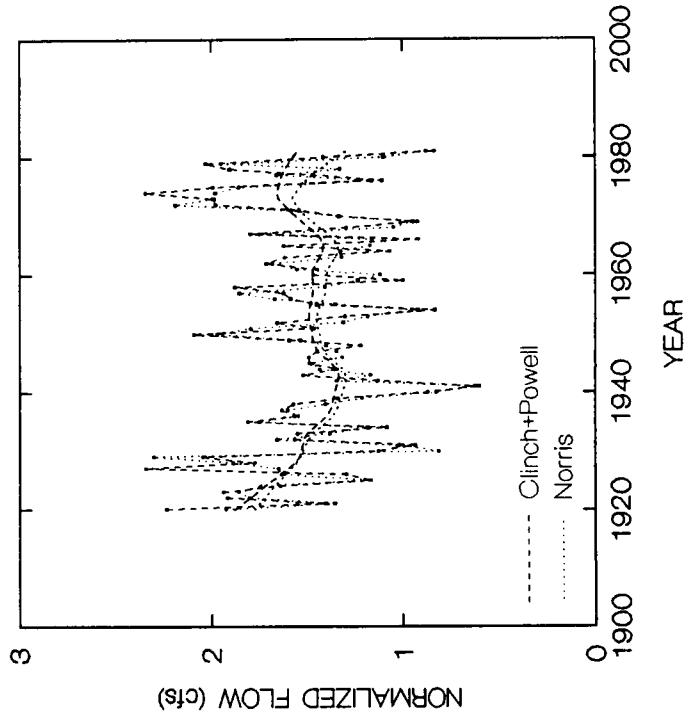


Figure 5. LOWESS Smoothed Scatterplots of Norris Dam and Tributaries Flow.

respective drainage area for comparison purposes. A LOWESS smooth of the flows with a tension factor of 0.5 is superimposed on the graph. The LOWESS smooth was used instead of a running average because LOWESS is more statistically robust to outliers. There are no visually significant differences between the flows.

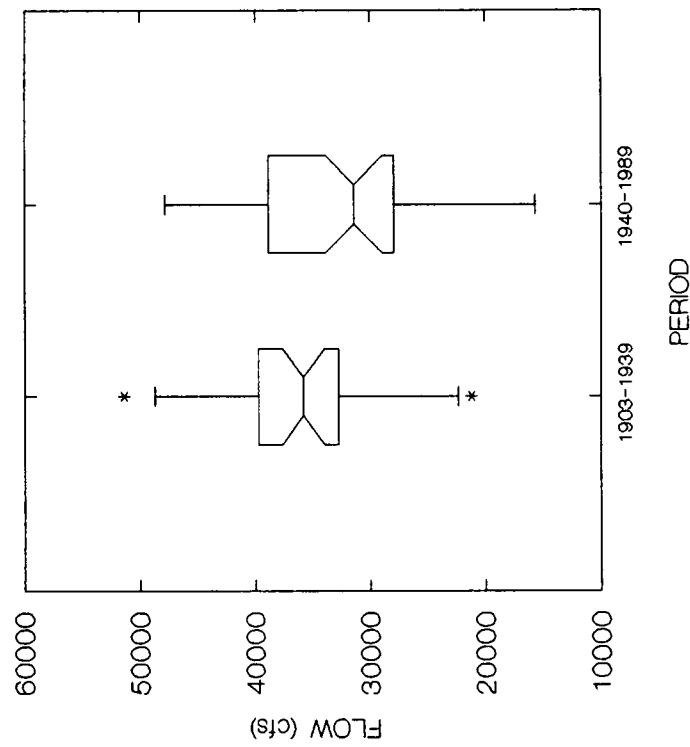
The previous analyses demonstrate that the flow record at Norris Dam is a good representation of the computed river flow in the upper Tennessee Valley area as it would have been naturally without the dams.

3.3.3 Coherence of Data Record

The first exploratory step to detect a shift in the mean of the time series of flows consists of notched boxplots before and after the dams were closed as shown in Figure 6. This is done to determine the coherence of the whole data record. The notched boxplot is a variation of the Tukey boxplot (see Section 3.4.4). The boxplots allow a distinction between the medians of two populations at the 95% confidence level. If the notches or indentations around two medians in the graph do not overlap, the medians are different at the 0.05 significance level (Wilkinson, 1990; Chambers et al., 1983).

For Chickamauga Dam the median annual flow for the two cases shown in Figure 6 is slightly different, as is the interquartile range, or 50% of the data spread. This is a first indication of non-stationarity in the flow median record that needs to be corroborated in the confirmatory analysis. Norris Dam boxplots display the same

CHICKAMAUGA DAM



NORRIS DAM

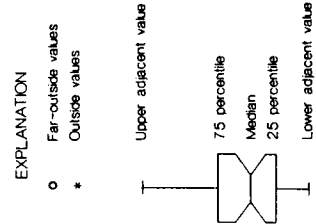
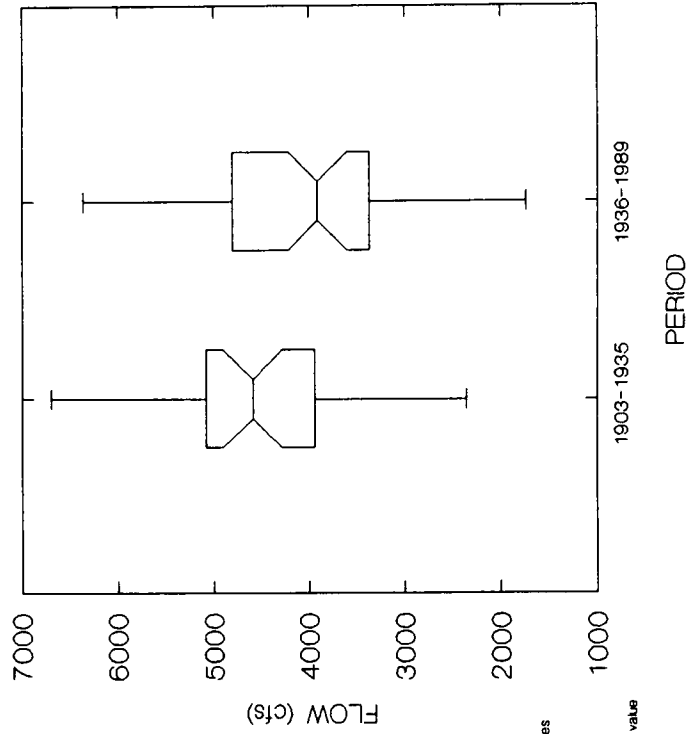


Figure 6. Notched Boxplots Before and After Dam Closure for Chickamauga and Norris Dams.

behavior, that is, a slight difference in medians and shape of interquartile range.

A more detailed view of the Chickamauga record using monthly flows and separating them into six periods, as seen in Figure 7, shows no critical difference in the contiguous medians for all the periods. The two boxplots located in the middle of the Chickamauga graph have a different shape than the rest of the boxplots because those periods have a much smaller data set. The TVA's use of the method to obtain the flow for those periods lasted for only a few months and the corresponding boxplots are distorted due to the lack of data. A similar behavior is present in the Norris Dam graph for the same reason. The plot for Norris Dam shows no significant difference in the contiguous flow medians. The records for period 4 are appended to the ones of period 3 since there are only four values for that time interval. The flows for both cases were computed from the same gage (see Appendix B).

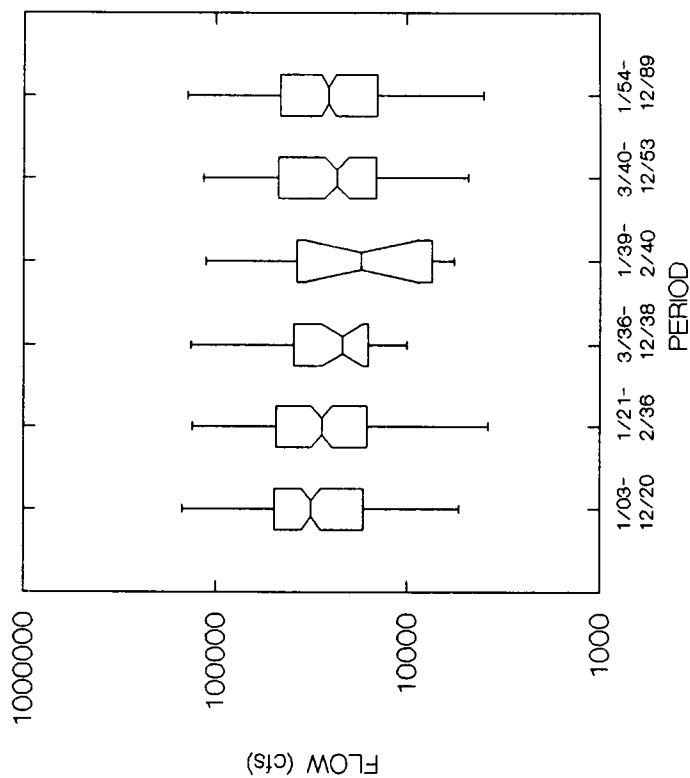
Overall, the data at both dams are coherent throughout the whole record. No difference in medians seems to be related to the methods used to calculate the adjusted natural flow.

3.4 CHARACTERIZATION

3.4.1 General

One of the objectives of this study is to typify the river flow at the two sites as a way to uncover important properties of the data. This is achieved through simple graphical and numerical studies. Four different data sets for each of the two dams are characterized. The

CHICKAMAUGA DAM



NORRIS DAM

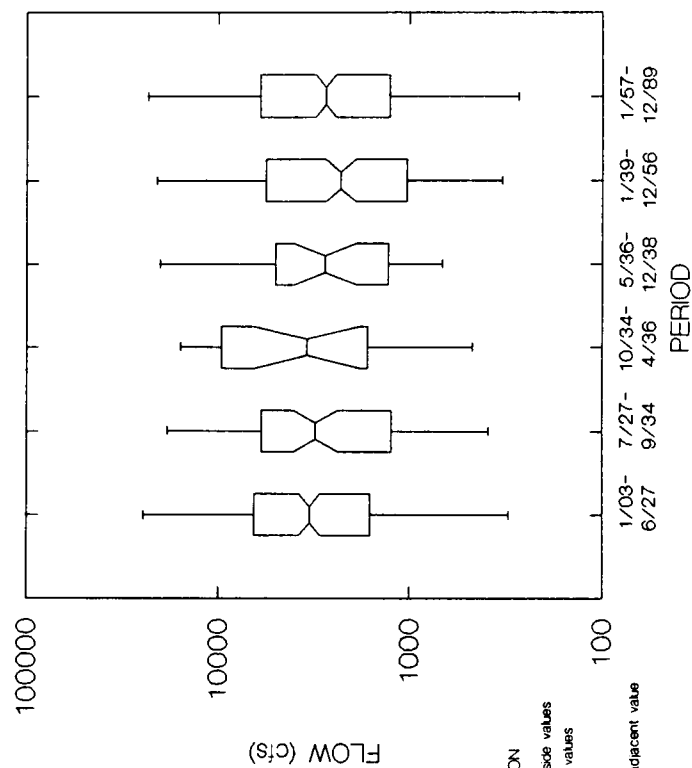


Figure 7. Notched Boxplots for Different Periods of Record for Chickamauga and Norris Dams.

data sets are: annual flows, monthly flows, flows for individual months (Januarys, Februarys, etc.) for the whole record, and extreme flows (maximum and minimum monthly flows for every year).

The flow characterization allows an understanding of the distribution of the set of data values: where they lie along the measurement axis, and what kind of pattern they form. The flow characterization is also a first look at their change in time through the use of scatterplots.

3.4.2 Statistical Moments

Tables 1 through 4 show the first characterization of the flows using its main statistical moments. For the monthly and annual flows, the date of occurrence of maximum and minimum flows is located at the bottom of the Table 1. Tables 2 and 3 show the statistics for all the months of January, February, etc. in record. The extreme flows are presented in Table 4. The Lilliefors probability, which is a measure of the normality of a data sample is also included in the characterization tables. The higher the Lilliefors probability the greater the chance of the data to follow a normal distribution (Wilkinson, 1990).

The tables show the main characteristics of the data as a whole for each time series and are more specific than a graph. The high number of significant digits found in the tables are a result of the computations performed on the adjusted natural flows. Only the first three significant figures are reliable.

Table 1. Summary of Statistical Moments for Chickamauga Dam (Tennessee River) and Norris Dam (Clinch River).

	Chickamauga Dam	Norris Dam
Average Annual Natural Flow (cfs)		
N OF YEARS OF RECORD	87	87
MINIMUM	15,688 ^a	1,740 ^c
MAXIMUM	51,381 ^b	6,694 ^d
MEAN	34,152	4,185
STANDARD DEV	7,749	1,045
STD. ERROR	831	112
SKEWNESS(G1)	-0.091	-0.067
KURTOSIS(G2)	-0.406	-0.451
C.V.	0.227	0.250
MEDIAN	33,771	4,130
LILLIEFORS	1	0.779
Average Monthly Natural Flow (cfs)		
N OF MONTHS OF RECORD	1,044	1,044
MINIMUM	3,785 ^e	271 ^g
MAXIMUM	148,945 ^f	24,490 ^h
MEAN	34,309	4,210
STANDARD DEV	24,587	3,827
STD. ERROR	761	118
SKEWNESS(G1)	1.297	1.604
KURTOSIS(G2)	1.701	3.021
C.V.	0.717	0.909
MEDIAN	26,750	2,889
LILLIEFORS	< 0.001	< 0.001

Notes: a) 1988; b) 1929; c) 1941; d) 1929;
e) Sep. 1949; f) Mar. 1932;
g) Oct. 1980; h) Mar. 1917

Table 2. Summary of Statistical Moments for Chickamauga Dam (Tennessee River) Natural Flow for Individual Months (cfs).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
N OF YEARS OF RECORD	87	87	87	87	87	87	87	87	87	87	87	87
MINIMUM	9,099	12,787	19,584	13,251	11,469	4,745	6,232	4,539	3,785	4,007	5,390	7,443
MAXIMUM	134,339	131,968	148,945	105,730	103,546	75,997	70,004	70,516	49,487	57,084	69,167	91,726
MEAN	51,549	59,042	63,630	50,696	35,645	25,219	22,360	18,409	14,225	14,647	20,644	35,644
STANDARD DEV	25,471	23,497	27,427	20,081	16,026	12,470	12,268	9,958	8,203	9,134	14,013	20,728
STD. ERROR	2,731	2,519	2,940	2,153	1,718	1,337	1,315	1,068	879	979	1,502	2,222
SKEWNESS(G1)	0.835	0.562	0.966	0.704	1.669	1.683	1.494	2.107	2.283	1.895	1.661	0.884
KURTOSIS(G2)	0.629	0.105	0.851	0.246	4.148	3.823	2.207	7.357	6.094	4.919	2.694	0.042
C.V.	0.494	0.398	0.431	0.396	0.450	0.494	0.549	0.541	0.577	0.624	0.679	0.582
MEDIAN	47,129	56,036	58,771	48,023	31,497	21,879	18,362	16,465	12,192	12,014	16,274	32,640
LILLIEFORS	0.002	0.555	0.001	0.137	0.008	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.002

Table 3. Summary of Statistical Moments for Norris Dam (Clinch River) Natural Flow for Individual Months (cfs).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
N OF YEARS OF RECORD	87	87	87	87	87	87	87	87	87	87	87	87
MINIMUM	659	1,073	2,088	1,281	983	512	358	442	330	271	306	441
MAXIMUM	20,097	19,150	24,490	17,427	14,679	9,122	6,469	7,330	4,699	4,854	9,931	19,626
MEAN	7,201	8,082	8,700	6,257	4,357	2,622	2,115	1,766	1,141	1,310	2,346	4,626
STANDARD DEV	4,106	3,792	4,688	3,156	2,720	1,822	1,355	1,255	783	1,083	2,026	3,277
STD. ERROR	440	407	503	338	292	195	145	135	84	116	217	351
SKWENESS(G1)	0.831	0.673	1.264	1.039	1.483	1.780	1.340	1.928	2.282	1.673	1.579	1.666
KURTOSIS(G2)	0.541	0.175	1.541	1.013	2.392	3.242	1.295	4.722	6.612	2.167	2.307	4.263
C.V.	0.570	0.469	0.539	0.504	0.625	0.695	0.641	0.711	0.687	0.827	0.864	0.708
MEDIAN	6,238	7,748	7,368	5,595	3,728	2,038	1,714	1,423	969	948	1,461	4,151
LILLIEFORS	0.019	0.344	< 0.001	0.008	0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.015

Table 4. Summary of Statistical Moments for Chickamauga and Norris Dams, Maximum and Minimum Flows.

	Chickamauga Dam	Norris Dam
Maximum Natural Flow (cfs)		
N OF YEARS OF RECORD	87	87
MINIMUM	42,076	4,390
MAXIMUM	148,945	24,490
MEAN	84,923	12,061
STANDARD DEV	22,498	4,247
STD. ERROR	2,412	455
SKEWNESS(G1)	0.631	0.663
KURTOSIS(G2)	0.316	0.123
C.V.	0.265	0.352
MEDIAN	83,665	11,189
LILLIEFORS	0.252	0.028
Minimum Natural Flow (cfs)		
N OF YEARS OF RECORD	87	87
MINIMUM	3,785	271
MAXIMUM	27,842	2,364
MEAN	10,245	750
STANDARD DEV	4,237	410
STD. ERROR	454	44
SKEWNESS(G1)	1.461	2.006
KURTOSIS(G2)	3.160	4.867
C.V.	0.414	0.547
MEDIAN	9,362	659
LILLIEFORS	0.001	< 0.001

3.4.3 Histograms

A histogram depicts the frequency distribution of the data using bars constructed so that the area of each bar is proportional to the number of objects in the respective category. If the histogram exhibits a characteristic "bell" shape, the data have a normal distribution (Milton and Arnold, 1990).

Histograms for annual, monthly, and extreme flows are presented in Figures 8 to 10. The scale on the right of the graphs show the number of cases in each bar. The scale on the left is the proportion of the sample in each bar.

From the histograms, and the Lilliefors probability, it can be seen that the annual flows for both sites have a normal distribution, whereas monthly, maximum, and minimum flows do not.

3.4.4 Boxplots

Boxplots give a quick impression of certain prominent features of the data distribution. In the boxplot the upper and lower quartiles of the data (75% and 25% hinges) are portrayed by the top and bottom of the box. The median is portrayed by a horizontal line segment within the box. While the median splits the numbers in half, the hinges split the remaining halves in half again. The end of the lines extending from the upper and lower quartiles (hinges) are the adjacent values. The upper adjacent value is defined to be the largest observation that is less than or equal to the upper inner fence (not shown), which is the upper quartile plus 1.5 times the difference between the upper and lower quartiles or H_{spread} (upper

CHICKAMAUGA DAM

NORRIS DAM

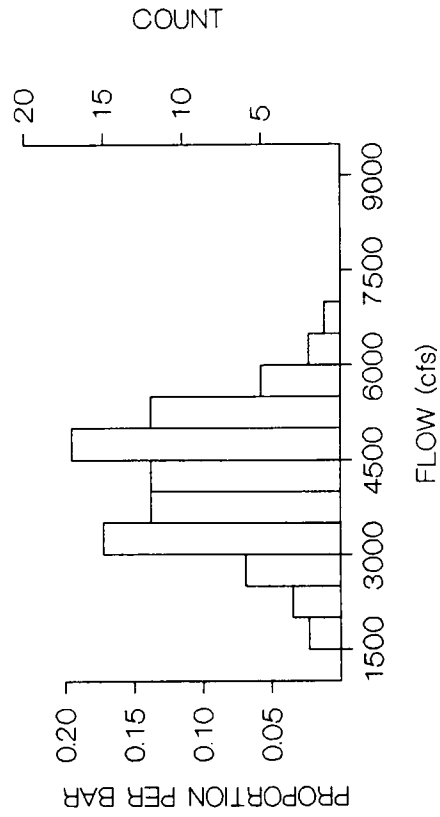
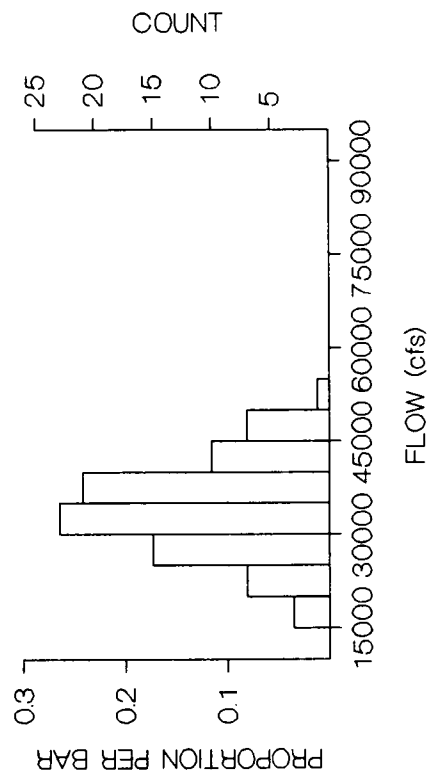
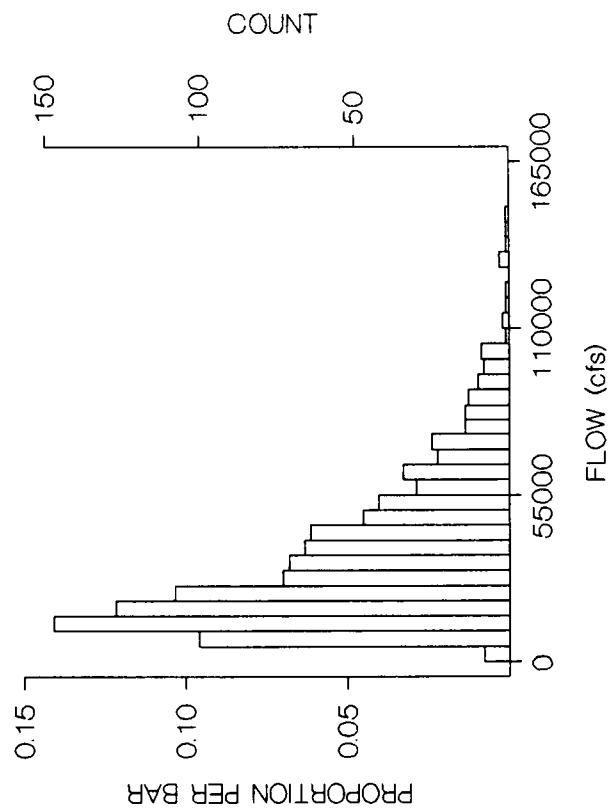


Figure 8. Histograms of Annual Flow Data at Chickamauga and Norris Dams.

CHICKAMAUGA DAM



NORRIS DAM

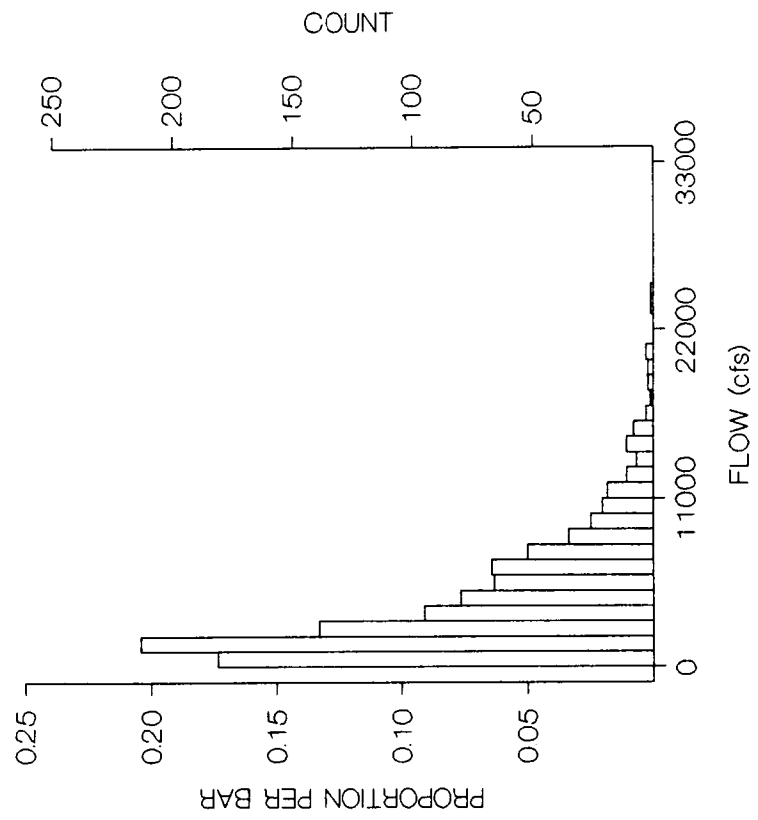
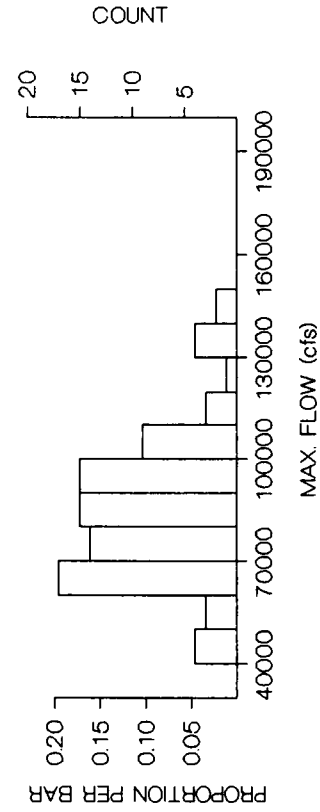


Figure 9. Histograms of Monthly Flow Data at Chickamauga and Norris Dams.

CHICKAMAUGA DAM



NORRIS DAM

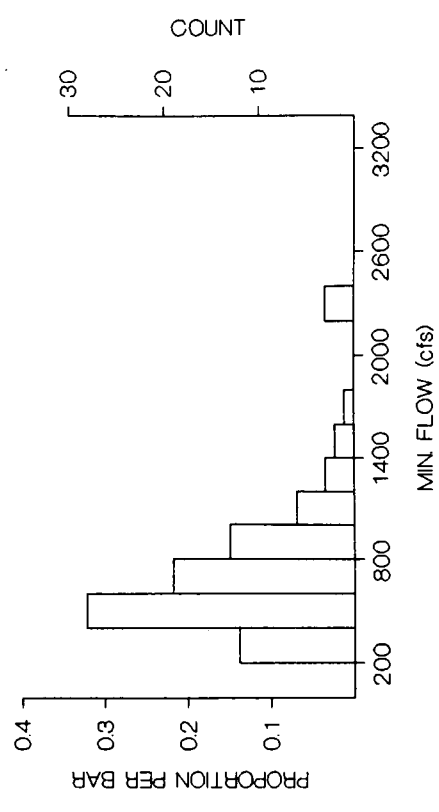
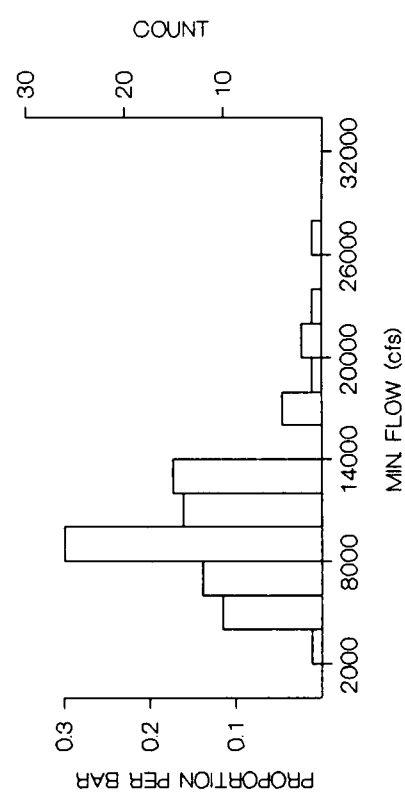
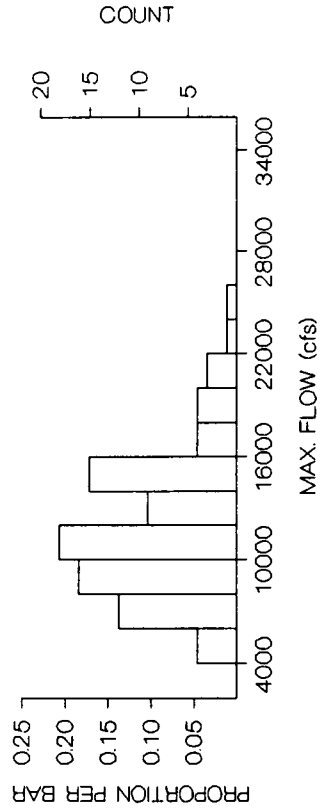


Figure 10. Histograms of Maximum and Minimum Flow Data at Chickamauga and Norris Dams.

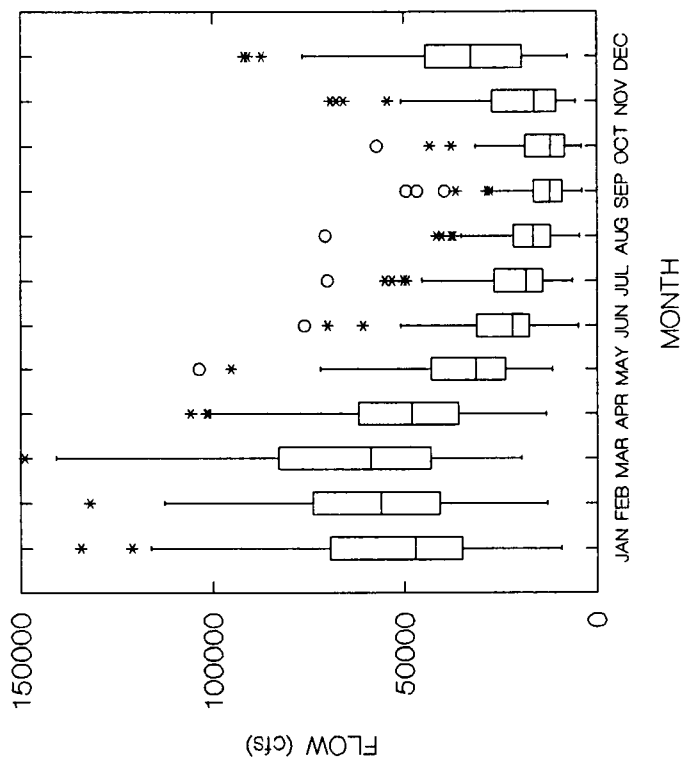
fence = upper hinge + (1.5*Hspread)). The lower adjacent value is defined to be the smallest observation that is greater than or equal to the lower inner fence (not shown) which is the lower quartile minus 1.5 times the difference between the upper and lower quartiles (lower fence = lower hinge - (1.5*Hspread)). Asterisks indicate values which are outside the adjacent values but inside the outer fences. The outer fences (not shown) are defined as plus or minus 3.0 times the Hspread. Open circles indicate outliers that are outside the outer fences.

Figure 11 shows boxplots for every month in the year for Chickamauga and Norris Dams. Each boxplot represents the flow distribution for that particular month from 1903 to 1989. As can be seen from the graphs, and Lilliefors probabilities, all the distributions are not normal. Also, the graph shows very clearly the seasonality of the flow, how it changes throughout the year.

3.4.5 Autocorrelations

Table 5 shows the autocorrelations from lag 1 to lag 6 for all the data sets. Only the monthly flows for both sites have significant autocorrelation. This is due to the seasonality existing in the series. The same pattern present in the boxplots of monthly distribution in Figure 11, exists in the monthly flow absolute value autocorrelations, though only half the seasons are shown in Table 5. The individual months, maximum, and minimum flows do not show any significant correlation at any lag. The annual flows present a small

CHICKAMAUGA DAM



NORRIS DAM

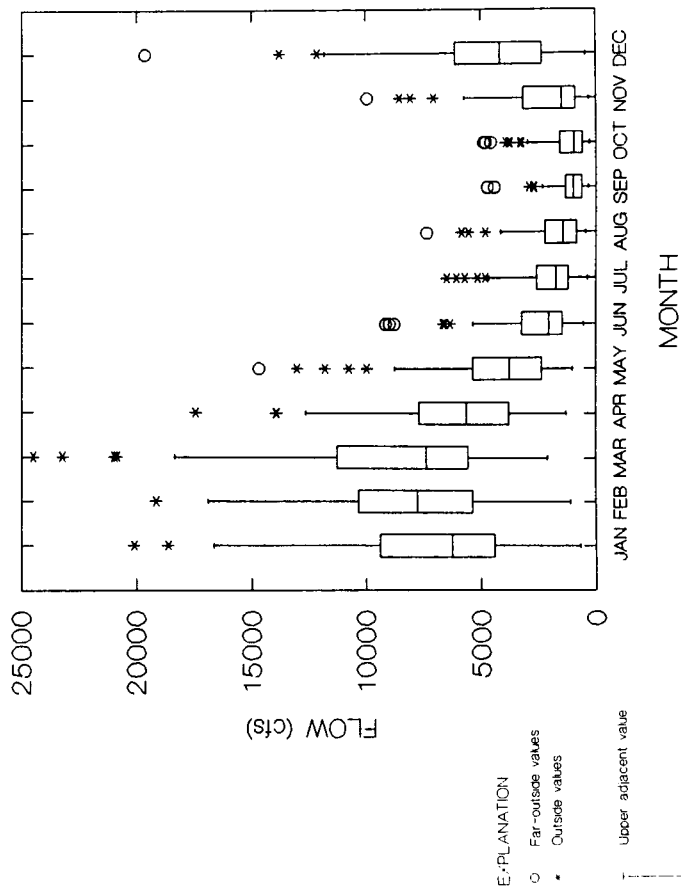


Figure 11. Boxplots for Individual Months Flow Data at Chickamauga and Norris Dams.

Table 5. Riverflow Autocorrelations.

Time Series	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5	Lag 6
Chickamauga (Annual)	.219	-.016	-.040	-.118	-.010	-.021
Norris (Annual)	.254	.068	-.013	-.059	.152	.082
Chickamauga (Monthly)	.577	.313	.019	-.196	-.344	-.380
Norris (Monthly)	.529	.276	-.014	-.207	-.340	-.378
Chickamauga (Every Month)						
Jan	.018	.102	.023	-.008	-.104	.096
Feb	-.020	.040	-.170	-.147	-.015	-.025
Mar	-.010	.044	.102	.017	.029	-.114
Apr	.028	-.038	.120	-.047	.003	.019
May	-.117	.145	.032	-.156	-.049	-.105
Jun	-.176	.105	.088	-.049	.045	.002
Jul	-.074	.082	.016	-.144	-.039	-.005
Aug	-.086	.109	-.025	-.026	-.040	.024
Sep	-.089	.014	-.020	-.003	.254	-.105
Oct	-.098	-.021	.119	-.031	.181	-.059
Nov	.098	-.059	-.132	.017	.027	.072
Dec	.135	-.022	.092	-.090	-.257	-.075
Norris (Every Month)						
Jan	.089	.094	.031	.075	-.069	-.172
Feb	.043	-.071	-.147	-.025	.152	.176
Mar	.109	-.068	-.144	-.064	.052	-.040
Apr	-.113	-.040	.007	.038	-.034	-.093
May	.101	-.100	-.037	-.060	.123	.015
Jun	.073	-.036	-.017	.040	.059	-.006
Jul	.084	-.086	-.065	-.029	-.062	.114
Aug	.078	-.006	.025	.159	.090	-.043
Sep	.026	-.039	-.012	.048	-.021	-.019
Oct	.101	-.061	-.088	.096	.186	-.013
Nov	.026	-.059	-.018	.065	-.040	-.036
Dec	.024	-.079	-.000	-.076	.185	.209
Chickamauga Maximum	-.018	.074	.006	.169	.092	.017
Chickamauga Minimum	-.004	.141	.169	-.043	.133	-.128
Norris Maximum	.063	.122	-.021	-.136	.067	-.031
Norris Minimum	.008	.023	.016	.002	-.064	-.008

correlation at lag 1 only.

3.4.6 Scatterplots

Figures 12 to 15 are scatterplots of the four data sets for the two sites. All the graphs have a LOWESS smooth with a tension factor of 0.5 superimposed on them as a first attempt to detect the long term behavior of the time series of flows.

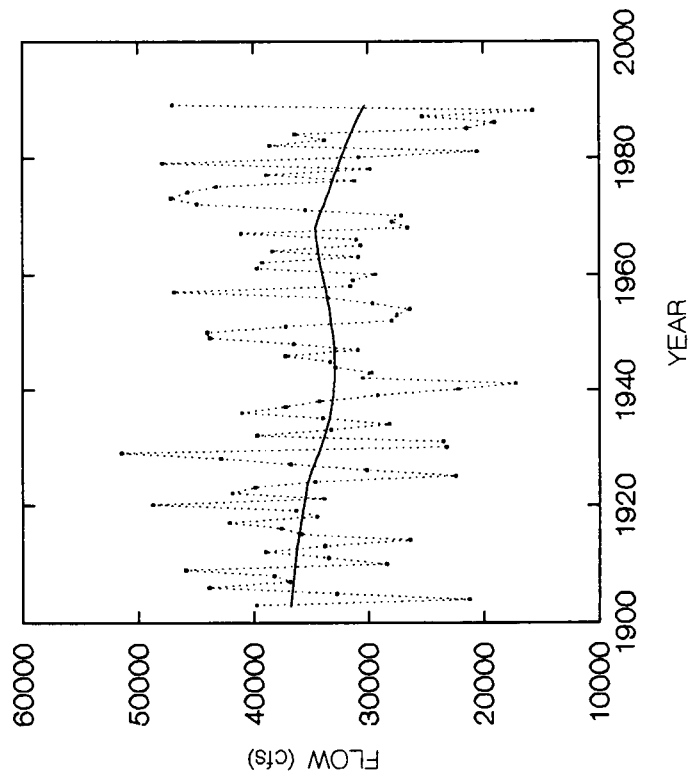
The annual flow series for Chickamauga and Norris dams in Figure 12 show the same pattern between them, except for the first 25 years, when Norris has an upward trend in flow and Chickamauga a slight decrease. This difference in the Norris Dam data could be due to a gaging station used in the flow computations for it until 1927 (see Appendix B). After that period, there is a decrease in flow until the 40s, then an increase up to the early 70s, and a decrease since then. These are in agreement with the changes in temperature for the Northern Hemisphere detected by Wigley et al. (1985) and in streamflow by Probst and Tardy (1987). Overall there is a tendency toward lower flow.

Figure 13 the monthly series of flow, shows that same trends as before (annual flow) are present for both sites.

A whole range of patterns exist in the flow for every month at Chickamauga and Norris dams. There is not a predominant one, as can be seen in Figure 14.

The maximum flow in Figure 15 shows a different behavior for the two sites. In Norris Dam the maximum flow increases until 1925 (may be due to a recording error detected previously in this chapter)

CHICKAMAUGA DAM



NORRIS DAM

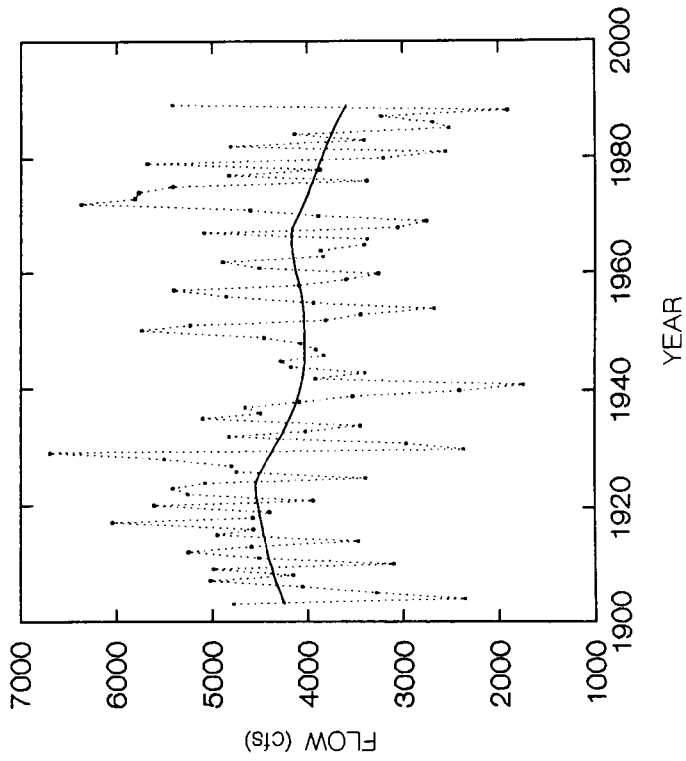
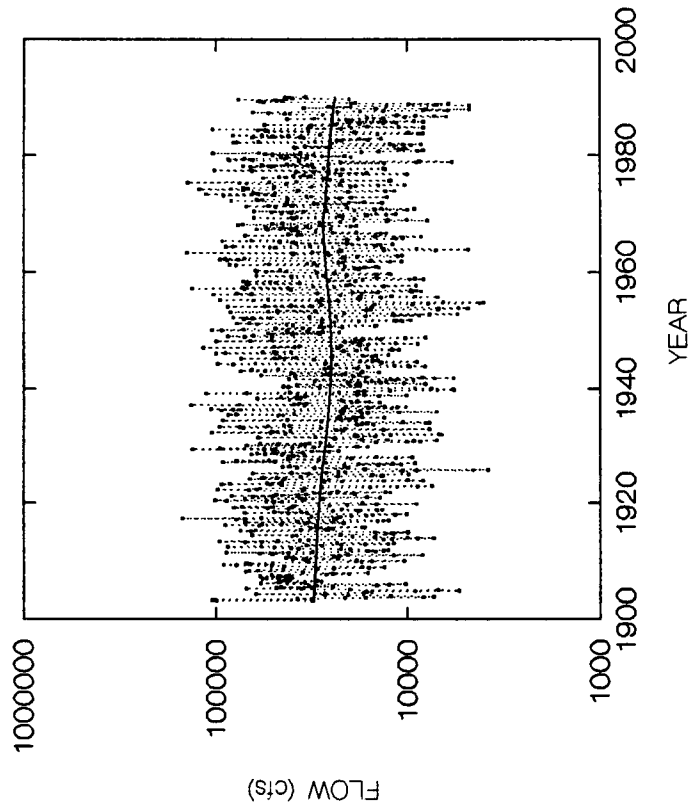


Figure 12. LOWESS Smoothed Scatterplot of Annual Flow Data at Chickamauga and Norris Dams.

CHICKAMAUGA DAM



NORRIS DAM

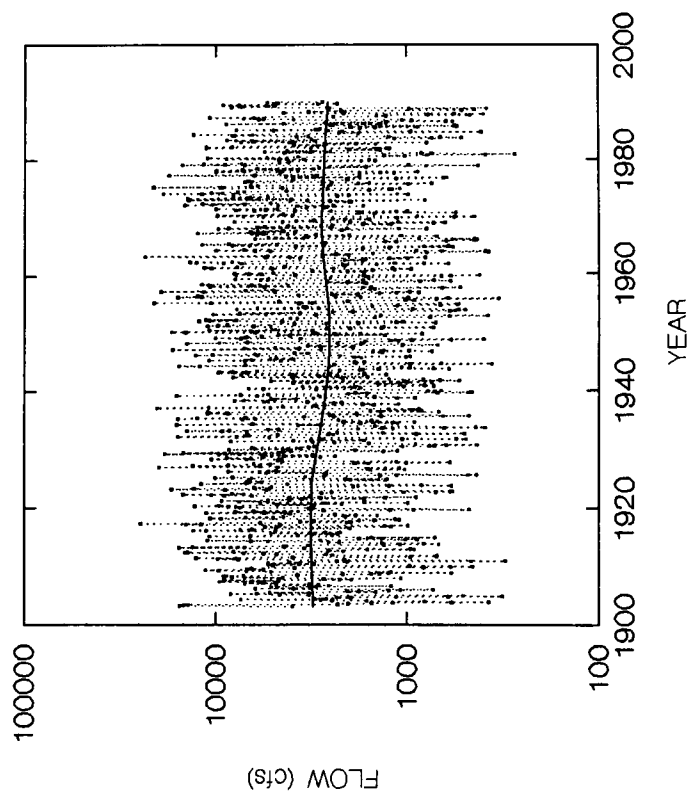
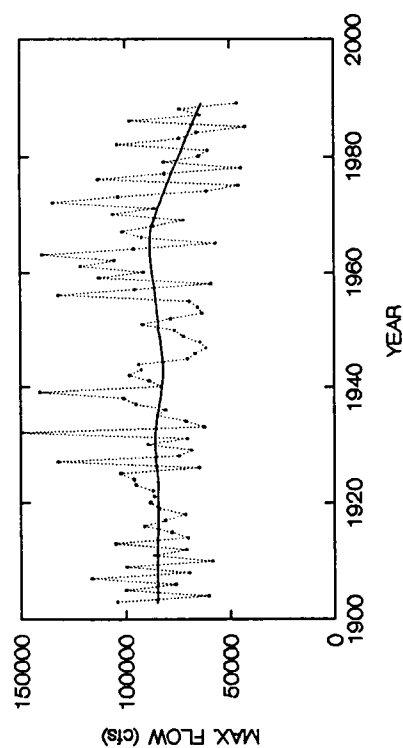


Figure 13. LOWESS Smoothed Scatterplot of Monthly Flow Data at Chickamauga and Norris Dams.

CHICKAMAUGA DAM



NORRIS DAM

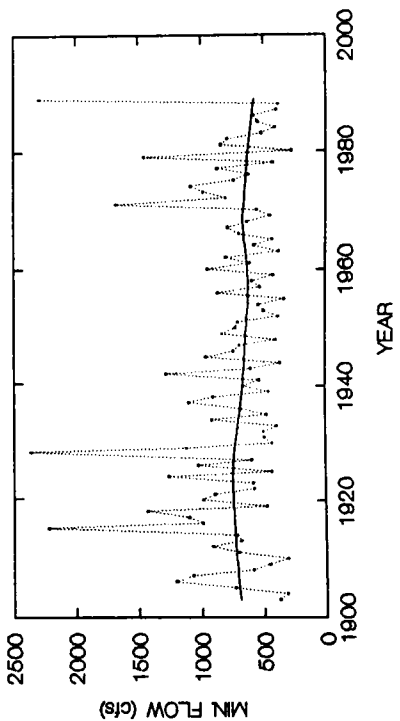
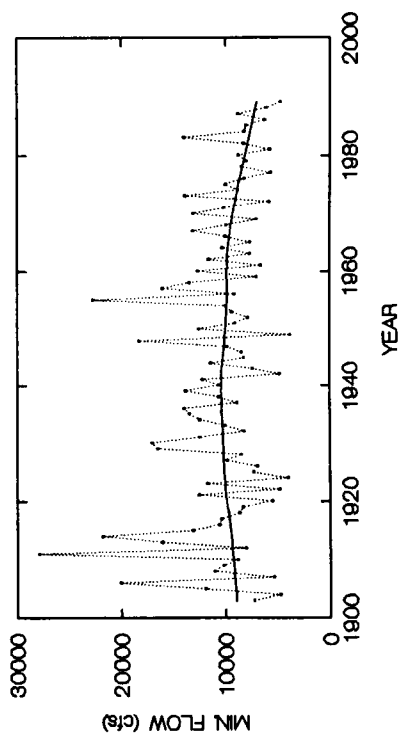
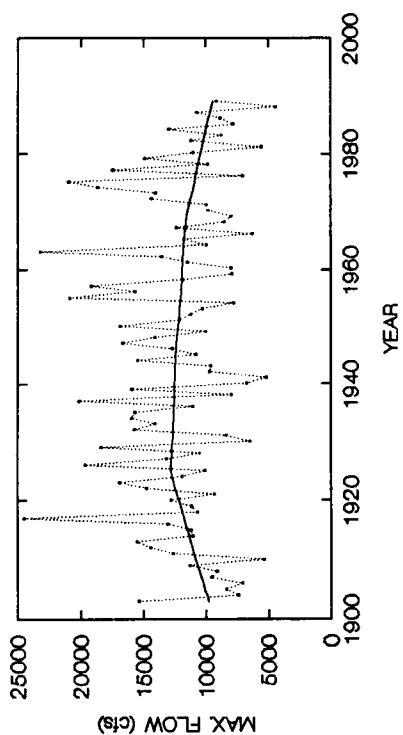


Figure 15. LOWESS Smoothed Scatterplot of Maximum and Minimum Flow Data at Chickamauga and Norris Dams.

and then decreases for the rest of the period of record, with a more pronounced decline since the early 70s. The Chickamauga Dam maximum flow is stable for the first 40 years of record, then it goes up, reaching a peak in the early 70s, to decrease again until the present. The Norris Dam minimum flow follows the same pattern as the annual flow. The minimum flow at Chickamauga Dam has a similar behavior as that of the maximum flow at Norris Dam; increase in the first part of the record and then a decline for the rest of the period.

CHAPTER 4

CONFIRMATORY DATA ANALYSIS AND RESULTS

4.1 GENERAL

The purpose of this chapter is to statistically confirm in a rigorous fashion the presence or absence of trends in the data, to determine if there is a significant change in the mean levels of the riverflow time series.

The detection of a trend should be approached with caution. An alpha level of 0.05 was deemed to be correct for the purposes of this investigation. In this way, the probability of detecting a trend when there is none present would only be 0.05. P-values are shown in the tables. The p-value is the smallest level at which alpha could be preset and still be able to reject H_0 (Milton and Arnold, 1990). If the p-value is less or equal to 0.05 for this investigation, H_0 is rejected.

4.2 t-TEST

A t-test was applied to the Norris and Chickamauga annual flow data to determine if there had been a change in flow since the dams were put in place. That is, if the closure of the dams affected the calculated flow records. The results are presented in Table 6.

Since the p-value is greater than 0.05, the means for the two periods tested for each dam are not significantly different.

Even though the populations for the two sites do not have a

very high degree of normality and do have some lag 1 autocorrelation, the t-test is still statistically robust and can be applied (Montgomery and Loftis, 1987).

Table 6. t-Test on Annual Riverflows Before and After the Closure of the Dams

Site	Periods	P-value
Chickamauga Dam	1903-1939/1940-1989	.189
Norris Dam	1903-1935/1936-1989	.053

The Mann-Whitney nonparametric U test was also used, yielding similar results as the t-test for both sites. There is no statistical evidence of a step trend occurring before and after the dams were closed at Chickamauga and Norris. Although the notched boxplots of Figure 6 show a step trend, the parametric and nonparametric tests applied do not confirm it. The boxplots in Figure 6 almost overlap.

The Mann-Whitney test was also utilized to try to detect the trends found by Wigley et al. (1985) and confirmed by the smoothed scatterplots of Chapter 3. The results of the test appear in Table 7.

Table 7. Mann-Whitney Test of Annual Riverflows for Different Periods.

Site	Periods	P-value
Chickamauga	1903-1949/1950-1970	.279
Chickamauga	1950-1970/1971-1989	.507
Norris	1903-1949/1950-1970	.235
Norris	1950-1970/1971-1989	.755

The Mann-Whitney test was used due to the small sample sizes (around 20 points) and the non-normality of one sample in the Chickamauga and Norris dams annual flow data. For all cases, no significant step trends at the 0.05 level for any of the periods tested was found.

4.3 LINEAR REGRESSION

For Chickamauga and Norris dams a linear regression was calculated for the following data sets: annual flows, flows for individual months, and maximum and minimum flows. Except for the annual flows, the other two data sets were altered by a logarithmic transformation to reduce the skewness and improve the symmetry of the distribution. No linear regression was performed on the monthly flows due to the seasonality present in them.

The results of the linear regression are shown in Table 8. The slope for the annual series is in cfs/year and for the other series in $\log(\text{cfs})/\text{year}$.

All the slopes found are negative which indicates a downward trend in flows, but the statistical significance of those slopes is very small, except for the January and February individual months for Chickamauga Dam and July and August for Norris Dam. The maximum and minimum flows for both sites show no significant trend.

4.4 SEASONAL KENDALL TEST

The seasonal Kendall Test was applied to the monthly data using a coefficient of 12 for the number of seasons and to the individual

Table 8. Linear Regression of Flow Series.

Time Series	Slope	P-value	R-square
Chickamauga (Annual)	-37.8 cfs/yr	.256	.015
Norris (Annual)	-6.5 cfs/yr	.149	.024
Chickamauga (Individual Month)			
Jan	-.005 log(cfs)/yr	.049	.045
Feb	-.004 log(cfs)/yr	.042	.048
Mar	-.003 log(cfs)/yr	.126	.027
Apr		.343	
May		.575	
Jun	-.003 log(cfs)/yr	.198	.019
Jul	-.004 log(cfs)/yr	.079	.036
Aug		.506	
Sep	-.002 log(cfs)/yr	.256	.015
Oct		.530	
Nov		.861	
Dec		.464	
Norris (Individual Month)			
Jan		.314	
Feb		.506	
Mar	-.003 log(cfs)/yr	.157	.023
Apr		.515	
May		.831	
Jun		.318	
Jul	-.007 log(cfs)/yr	.006	.087
Aug	-.007 log(cfs)/yr	.006	.085
Sep	-.004 log(cfs)/yr	.084	.035
Oct		.909	
Nov	-.006 log(cfs)/yr	.088	.034
Dec		.973	
Chickamauga Maximum	-.002 log(cfs)/yr	.114	.029
Chickamauga Minimum	-.003 log(cfs)/yr	.089	.034
Norris Maximum		.400	
Norris Minimum		.390	

Note: Bold print indicates p-value below or equal to 0.05.

months data using 1. The results are presented in Table 9.

The results from the Seasonal Kendall test for the monthly data show that even when seasonality is taken into account a significant long-term trend cannot be found, though there is a tendency toward lower flows, but not very strong. This is shown by the small and negative r_s . All the individual months exhibit decreasing flow trends, except for November at Norris Dam. The p-value of the trend is only significant at the 0.05 level for July at Chickamauga Dam and July, August, and September at Norris Dam.

Table 9. Seasonal Kendall Test of Flow Series.

Time Series	τ	P-value
Chickamauga (Monthly)	-.06	.256
Norris (Monthly)	-.07	.096
Chickamauga (Individual Month)		
Jan	-.13	.077
Feb	-.12	.096
Mar	-.09	.238
Apr		.572
May		.329
Jun	-.10	.180
Jul	-.14	.050
Aug		.623
Sep	-.08	.289
Oct		.628
Nov		.883
Dec		.533
Norris (Individual Month)		
Jan		.420
Feb		.463
Mar	-.09	.231
Apr		.687
May		.673
Jun		.401
Jul	-.20	.006
Aug	-.18	.015
Sep	-.14	.049
Oct		.764
Nov	.13	.079
Dec		.947

Note: Bold print indicates p-value below or equal to 0.05.

CHAPTER 5

DISCUSSION AND CONCLUSION

5.1 SIGNIFICANCE OF RESULTS

The calculated natural flow records of the Tennessee River at Chickamauga Dam, and the Clinch River at Norris Dam were investigated in order to detect possible trends and to statistically characterize their flow.

The annual and monthly riverflow for Chickamauga and Norris dams do not present a statistically significant long term linear monotonic trend at the 0.05 level. The high variability existing in all the natural variables, including flow, does not permit the detection of a trend with the 87-year record used. A longer record is needed to determine the existence of a trend at this significance level. Karl et al., 1991 discuss a method to determine the length of the record needed for precipitation and temperature data.

The maximum and minimum flows at the two sites show a decreasing long-term trend, though it is not significant yet. There has not been an increase in extreme flow variability, since the difference between the maximum and minimum flow for Chickamauga and Norris dams has remained constant. The maximum and minimum flows have the same order of magnitude downward slopes.

The trend in individual months was utilized for the detection of a shift in the seasonality of flows. If one month shows a decreasing flow and the next an increasing flow, that would indicate a

possible change in the flow season.

All the individual months show decreasing trends at Chickamauga Dam, either by the linear regression or the seasonal Kendall test. January and February have significant trends in the linear regression, though not in the seasonal Kendall test. Nonetheless, the p-value in the seasonal Kendall test is low. This is the first indication that a change in flow patterns is occurring. It is not big enough to be detected in the annual or monthly records. The trend is probably due to a change in precipitation (see Appendix A), since the other important natural factors in which the riverflow depend, like evaporation and land use such as vegetation cover, do not have a strong presence during the winter months. The area does not have much agriculture or development to account for the losses. Besides, if that were the case, trends should also have a greater level of significance in the low flow months of the year.

For Norris Dam, the individual months show decreasing trends except for November, which has a positive r in the seasonal Kendall test, but it is not significant at the 0.05 level. The months displaying statistically significant trends are for the linear regression July and August, and for the seasonal Kendall test July, August, and September. This trend in the summer months although not detectable at Chickamauga yet, can be due to a decrease in precipitation, or to an increase in forestry reported by the TVA Natural Resources Office. Since 1937, the forest resources in the Tennessee Valley area have doubled (Smith, 1991). This increase in

forestation would reduce the amount of rainfall available for runoff.

In any case, for Chickamauga and Norris dams, no shift in the seasonality of flows was found.

5.2 CAVEATS

The results are based on data that do not come from unregulated rivers, and as such should be accepted cautiously. Although the validity of the calculated natural flow was investigated and found to be sound, there were some problems in the records, like the shift in the monthly distribution of minimum flows at Norris Dam reported in Appendix C.

If a climate of a region changes with time, the change may be reflected in a general tendency for the values of streamflow and rainfall either to increase or to decrease with time. Only flow was used in this study. In order to relate the changes in streamflow to climate change an investigation of the time series of precipitation for the area along with its relation to streamflow is needed.

Other kinds of trends besides the long term linear trends researched in this investigation may be present in the data. An example of those are cyclical trends, which need to be investigated.

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APPENDIXES

APPENDIX A
(Correlation of Precipitation and Flow)

Correlation of Precipitation and Flow

A simple Pearson correlation was performed on precipitation and flow data. The precipitation data consists of annual records for the area above Chattanooga, that is, for the upper Tennessee River basin. The flow record is the annual calculated natural flow at Chickamauga Dam.

The correlation coefficient r , found is 0.886. By squaring the correlation, the percentage of variance in flow due to the variance in precipitation is determined (Milton and Arnold, 1990). The value found is 0.786 (R^2). This means 78.6% of the changes in flow are statistically accounted for by changes in precipitation.

APPENDIX B
(Calculated Flow History)

Calculated Flow History

Chickamauga Dam (drainage area: 20,790 square miles)

- 1/10/3-12/31/20 Flows were computed from USGS records at Chattanooga in proportion to drainage area. Drainage area: 21,400 sq. mi.
- 1/1/21-3/4/36 Flow estimated from USGS gage records at Chattanooga (drainage area: 21,400 sq. mi.) and Hales Bar (drainage area: 21,800 sq. mi.) in proportion to drainage areas, except May 28 to October 14, 1925, when the gage flows were reduced by a graduated percentage to correct for the influence of Hales Bar Reservoir.
- 3/5/36-12/31/38 Flows corrected for storage changes in Norris Reservoir (reservoir closure March 5, 1936); Ocoee No. 1 reservoir after January 1, 1936, and Chickamauga Reservoir after January 1, 1938.
- 1/1/39-3/10/40 Flows were computed by reducing USGS records of the At Chattanooga, Tennessee, gage by the local inflow between Chickamuaga Dam and Chattanooga using as an index South Chickamauga Creek near Chickamauga, Tennessee, and then correcting these reduced Chattanooga flows for storage changes in the following reservoirs: Blue Ridge, Ocoee No. 1, Norris, Cheoah, Santeelah, Calderwood, Walters, Chickamauga, Hiwassee (beginning 10/1/39).
- 3/11/40-12/31/53 Discharges for Chickamauga Dam, reported by the TVA Division of Power Operations were used and corrected for storage changes in the above reservoirs and additional reservoirs beginning with the date indicated: February 12, 1941, Thorpe; October 1, 1941, Watts Bar; December 5, 1941, Cherokee; January 24, 1942, Nottely; January 30, 1942, Nantahala; February 12, 1942, Chatuge; August 15, 1942, Ocoee No. 3; February 14, 1943, Apalachia; February 19, 1943, Douglas; August 2, 1943, Fort Loudoun; November 4, 1944, Fontana; December 1, 1948, Watauga; November 20, 1950, South Holston; December 16, 1952, Boone; October 27, 1943, Fort Patrick Henry.
- 1/1/54-current Flows were computed by correcting Chickamauga Dam discharges, reported by TVA Division of Power

Systems Operations, for storage changes in Chickamauga, Ocoee No. 1, Ocoee No. 3, Blue Ridge, Apalachia, Hiwassee, Nottely, and Chatuge Reservoirs in addition to storage changes in the reservoirs listed for Watts Bar Dam. Additional corrections for storage changes were made as follows: John Sevier Steam Plant water supply reservoir; 6/4/57-12/31/57.

Norris Dam (drainage area: 2,912 square miles)

1/1/03-7/2/27	Flow computed from Clinton gage records by ratio of drainage areas (2,912/3,056 sq. mi.).
7/3/27-10/7/34	Flow computed from records at Coal Creek.
10/8/34-12/31/35	Flow computed from records at Coal Creek adjusted for storage changes in Norris Reservoir.
1/1/36-4/15/36	Same as above, with additional corrections made for rainfall on reservoir, evaporation from reservoir, and runoff which would have occurred from inundated area.
4/16/36-12/31/38	Same as above, except using flow records below Norris Dam.
1/1/39-12/31/56	Flows were computed from USGS records of the Below Norris Dam, Tennessee, gage, drainage area 2,913 sq. mi., corrected for storage changes in Norris Reservoir.
1/1/57-current	Flows were computed by correcting discharges reported by the TVA Division of Power System Operations for Norris Dam, for storage in Norris Reservoir.

APPENDIX C

(Distribution of Extreme Flow)

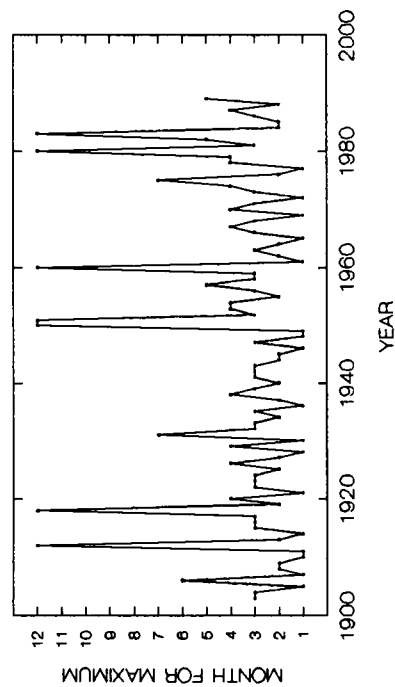
Distribution of Extreme Flow

Figure C1 represents the monthly distribution of the minimum and maximum flow for Chickamauga and Norris dams, that is, in which months the minimum and maximum flows occurred for the 87 years of record.

The Norris Dam minimum flow graph shows a step trend around the year 1927. This same period, from the beginning of the record to 1927, is the one reported in Chapter 3.4.6 as having possible problems in gaging station measurement. Any inferences about this part of the Norris record should be taken cautiously.

No problems were found for the Chickamauga distribution of minimum flow, or for the distribution of maximum flow at any of the two sites.

CHICKAMAUGA DAM



NORRIS DAM

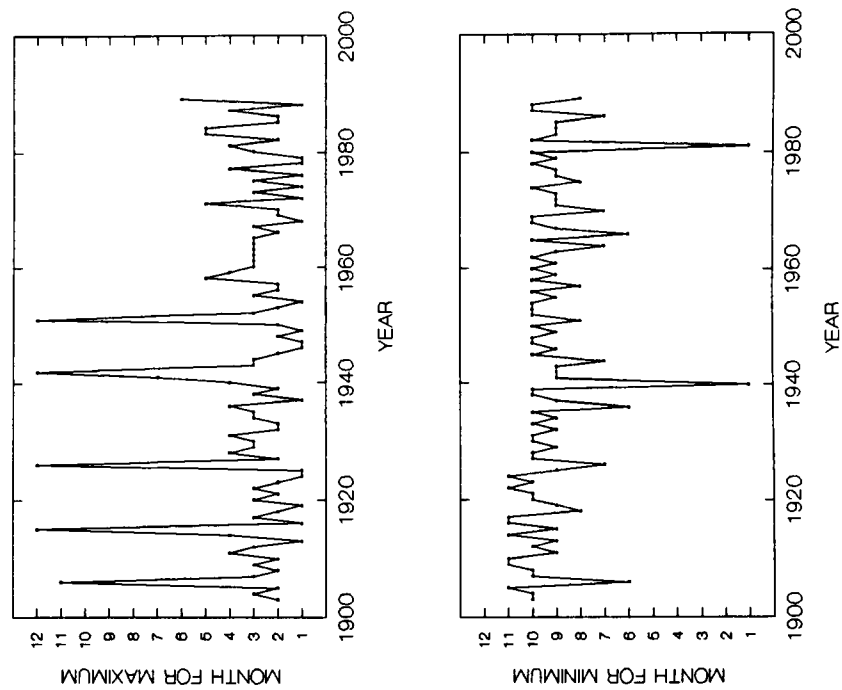


Figure C1. Monthly Distribution of Maximum and Minimum Flow at Chickamauga and Norris Dams.

VITA

Born and raised in Mexico City, Enrique Gomezdelcampo got his B.S. in engineering physics from the Universidad Iberoamericana. During summers he worked as a counselor in a camp in North Carolina. He started his own computer consulting company which he directed for three years, until he was driven mad by the biggest city in the world. Just about that time, a friend convinced him to go back to school and study something that he was truly interested in. He attended the University of Tennessee, Knoxville, across the mountains from the summer camp he used to work, and completed his Master of Science degree in environmental engineering in August of 1991. During his master's program he worked as a research assistant at the Tennessee Valley Authority Engineering Laboratory, where he got interested in global and conservation projects. Now, after a short trip to Europe to visit some good friends, he will be studying at the University of Washington in Seattle towards a Ph.D. in environmental engineering. He hopes to some day get out of school and work in conservation programs in underdeveloped countries with an international organization.