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I am submitting herewith a thesis written by Bill Carroll Arnwine entitled "Application of Historical Precipitation Data to Quantitative Precipitation Forecasts for Reservoir System Operations." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental Engineering.

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APPLICATION OF HISTORICAL PRECIPITATION DATA TO QUANTITATIVE PRECIPITATION FORECASTS FOR RESERVOIR SYSTEM OPERATIONS

A Thesis

Presented for the Degree of

Master of Science

The University of Tennessee, Knoxville

Bill C. Arnwine
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DEDICATION

This thesis is dedicated to my wife and best friend

Karen E. Arnwine,

and our sons

Brandon, Keith, Justin, and Nathan Arnwine

for their support as I attempt to achieve my goals

and for their love, patience, and understanding.

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I especially thank my Lord and Savior, Jesus Christ for his love, mercy, and grace and for giving me the knowledge, strength, and perseverance to achieve my goals.

ABSTRACT

The Tennessee Valley Authority (TVA) operates an integrated multi-use reservoir system. Accurate and reliable forecasts of expected precipitation are a critical segment of the decision-making process in the scheduling of daily reservoir operations and for long-term decision-making. TVA receives daily quantitative precipitation forecasts (QPF) for the current day plus the nine following days from a weather forecast vendor. Application of TVA historical precipitation data in conjunction with the vendor forecast could increase the effectiveness of the precipitation forecasts in the long-term (6-10 day period in this context) portion of the forecasts.

Available historical precipitation data consists of 107 years of monthly average precipitation values for the two major divisions of the Tennessee River basin. TVA maintains a data base of this information and also published monthly and annual precipitation reports from 1936 through early 1980. Twenty-seven months of daily forecast and observed values from October 1994 through December 1996 were similarly obtained from the TVA data base. These values consist of forecast (and observed values) for a particular forecast date for each of 5 QPF sub-basins within the Tennessee River basin.

In the first phase of the analysis, the historical data was subjected to statistical smoothing to identify possible long-term trends. Factors such as rain gage spatial distribution, climatic change, topography, etc., which could influence recorded amounts, were also considered. No long-term historical trends were indicated. The second phase of the analysis consisted of a comparison of observed and vendor forecast precipitation values, and various historical forecast precipitation values derived from statistical analysis. Each of the 5 QPF sub-basins were examined for 3 forecast periods. Cumulative precipitation volumes for the forecast periods were compared. Analysis of residuals included an examination for trends and a comparison of the residual values.

Results indicate that the forecast expected rainfall quantities for the short-term forecast cannot be significantly enhanced using the historical data. However, a significant improvement in the forecast of expected rainfall quantities could be realized in the long-term forecasts. The vendor tends to under-forecast precipitation for this period by almost 50 percent. A forecast based on historical data could thus be used to replace or supplement a vendor forecast for this period. Moreover, an apparent variation exists in vendor forecasts for the Southwest QPF sub-basin as compared to comparable forecasts for the 4 other QPF sub-basins. Supplementary analysis of the Southwest QPF sub-basin to determine the cause of the variation is recommended. Additional study is likewise recommended to identify any seasonal trends in the forecast volumes or residuals. Further analysis could also be performed as more precipitation data becomes available.

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GLOSSARY

Area above Chattanooga - The portion of the Tennessee River watershed which lies above Chattanooga, Tennessee.

Area below Chattanooga - The portion of the Tennessee River watershed which lies between Chattanooga, Tennessee and the month of the Tennessee River.

Daily reservoir operating plan - A comprehensive strategy for the operation of the TVA reservoir system. The operating plan covers multiple days and includes forecasts of reservoir inflows, outflows, and pool elevations while considering various goals and objectives.

Drainage basin - The entire area of the surface of the Earth drained by a stream or a system of connecting streams such that all streamflow originating in the area is discharged through a single outlet. Also termed a watershed or simply a basin.

Drainage area - The area of the horizontal projection of a drainage basin.

Expected value QPF - Term applied by TVA to QPF which reflected the most probable quantity of predicted rain.

Gaging station - A particular site where systematic observations of rainfall is obtained.

Inflow - The volume of water which flows into a reservoir over a given time period.

Inflow forecast - A forecast of the projected inflows into a reservoir based on rain which has already fallen or rain which is expected to fall.

Long-term QPF - In the context of this study, a QPF for the last five days of the QPF period (days 6 through 10).

Outflow - The volume of water released from a reservoir over a given time period.

Minimum operating guide (MOG) - Minimum operating levels for a particular reservoir at a particular time.

Multiple purpose project - A TVA water control structure designed and operated to accomplish multiple objectives (such as flood control, recreation, etc.).

Operating guide curve - A graphical representation of desired reservoir operating levels expressed as a function of time.

Peak demand period - A period of time in which the maximum demand for electrical energy occurs within a daily cycle.

Predicted rain inflow forecast - An inflow forecast based on rain which has already fallen and rainfall which is expected to fall.

QPF period - The period of time for which a QPF applies. For this study, the QPF period used is 10 days.

Quantitative precipitation forecast (QPF) - A forecast of expected precipitation volumes over particular time period. Usually expressed in inches of depth averaged over a watershed area.

Rain-on-the-ground inflow forecast - A reservoir inflow forecast based on rain which has already fallen.

Run-of the-river project - A water control structure whose reservoir has limited useful storage volume.

Runoff - The volume of water from rainfall which flows into a stream or reservoir.

Short-term QPF - In the context of this study, a QPF for the first five days of the QPF period (days 1 through 5).

Single purpose project - A TVA water control structure designed and operated for a single objective: the generation of electrical power.

Storage - The volume of water in a reservoir at a particular instant in time.

Streamflow - The discharge that occurs in a natural channel.

Sub-basin - A portion of a larger watershed area.

TAPOCO - A subsidiary company of the Aluminum Company of America (ALCOA) which owns several dams within the Tennessee Valley region

Useful storage - The volume of water in a reservoir above the permissible minimum pool level and below the maximum controlled level at a particular instant in time.

Watershed - See drainage basin.

Weather Rodeo - The term applied by TVA to the evaluation and selection of weather forecast vendors in 1994.

CHAPTER 1

INTRODUCTION

1.1 General Discussion

The Tennessee Valley Authority (TVA) is a unique entity among federal agencies. Its mission began in the early 1930s as an aid to the economic recovery of the depressed Tennessee Valley region. The TVA Act of 1933 was established "to improve the navigability and to provide for the flood control of the Tennessee River..." For over 60 years, the agency has evolved into the nation's largest supplier of electric power while still maintaining its capacity as a steward of the Valley's resources.

In conjunction with these roles, TVA prepares a multi-day operating plan for 40 of 53 reservoirs in the Tennessee Valley region on a daily basis. This operating plan is prepared considering numerous multiple purpose objectives each of which are significant to the region and to the nation as well. In its recent history, multiplying demands on the reservoir system have forced TVA to operate the reservoir system to optimize benefits of the often competing objectives. While navigation, flood control, and power generation were initial objectives, other benefits not envisioned by TVA's founders have developed over the years. These benefits include supporting a healthy recreation industry, improving water quality, and maintaining the unique ecology associated with the reservoir system (TVA, 1991).

Traditionally, operating plans for the reservoir system were prepared for issue to the public using a forecast of inflows to the system based on rainfall already received or "rain-on-the-ground." Contingency plans based on anticipated rain were also prepared but were used only for internal decision making. TVA uses what is known as a quantitative precipitation forecast (QPF) in the development of the reservoir operating plans. These forecasts provide an estimate of the volume of precipitation expected over a certain time frame. Used in conjunction with inflow forecasting models, these forecasts are applied to determine the runoff or inflow into the system. The QPF provide not only the volumes but also account for the distribution of rainfall both spatially and temporally. Within the past few years, with advances in technology of weather forecasts, accuracy of the forecasts has improved. Thus, predicted precipitation is being used more frequently in the development of daily system operating plans. Over the past 5 years, the use of probabilistic quantitative precipitation forecasts that take into account the uncertainties associated with the weather forecasts has been investigated by TVA. This approach has been recently implemented by TVA in their operating strategies (Arnwine and Whitlock, 1994).

1.2 Purpose and Scope of Study

It is assumed that improving the accuracy of the rainfall forecast will thus improve the accuracy of the forecast inflows into the reservoir system. This study considers the development of a rainfall forecast QPF based on historical precipitation data and

application of this forecast in addition to or in place of data provided by the QPF forecast vendor. Reservoir operations has been, for many years, a reactive process in some respects. Recent gains in reservoir modeling and inflow forecasting technology have allowed TVA reservoir forecasts to become more proactive with the ability to examine various strategies simultaneously. Nevertheless, a major source of uncertainty still exists with the weather forecasts, specifically rainfall forecasts. Probabilistic QPF rainfall forecasts attempt to address the uncertainty by assigning probabilities to the QPF. This allows the reservoir operators to weigh risks associated with certain operations in the reservoir forecasts. It permits consideration of different scenarios of expected precipitation based on amounts with varying degrees of confidence (the probabilistic aspects).

TVA currently contracts with a weather forecast vendor for the QPF rainfall forecasts used in the development of the daily reservoir operating plans. By examination of QPF precipitation and historical data, the following questions arise, namely:

- How would the vendor QPF forecasts compare to a QPF based on historical precipitation data?
- Is historical data considered in the development of the vendor QPF?
- Could the use of the historical data QPF in conjunction with (or instead of) vendor forecasts provide more accurate reservoir inflow forecast results?
- If so, how could the historical QPF be used with the vendor forecasts?

This study attempts to answer (or at least provide a method to answer) most or all of these questions. To support this objective, an examination and analysis will be conducted of observed and forecast rainfall data for a 27-month period, and the historical monthly average precipitation for 107 years of record.

There are numerous benefits from increased reservoir forecast accuracy. Some are difficult to quantify. By increasing lead time of reservoir forecasts during high flow events (i.e., floods), loss of property or of life can be minimized, or in some cases, be eliminated. Additionally, evaluation of multiple scenarios allows increased flexibility of the reservoir system and permits a balance of the operating objectives that are frequently opposing. Planning for expected power generation is critical in the fast approaching deregulated electric power industry. Arranging special operations, such as special flows or planning maintenance activities, is facilitated when expected inflows can be determined with a reasonable or high degree of certainty. Thus, a more accurate forecast would promote the proactive approach and reduce the number of later adjustments or changes.

1.3 TVA Reservoir System

Watershed Characteristics

The watershed of the Tennessee River is located in the southeastern United States and covers an area of 40,910 square miles. An area of 40,200 square miles is regulated above the last dam in the Tennessee River system, Kentucky Dam (refer to Figure 1.1).

Covering most of Tennessee and portions of six other states (Alabama, Georgia, Kentucky, Mississippi, North Carolina, and Virginia) the watershed is the largest tributary basin of the Ohio River basin. It accounts for just over 20 percent of the Ohio River's total drainage area. (Recorded unregulated flood flows have accounted for up to 20 percent of lower Mississippi river flood crests.) Flowing from east to west, the Tennessee River's headwaters originate with streams in the mountains of western Virginia and North Carolina, eastern Tennessee and northern Georgia. Major tributaries include the Clinch, Holston, French Broad, Little Tennessee, and Hiwassee Rivers in the east and the Duck and Elk Rivers in the west. The head of river is located at Knoxville, Tennessee with the confluence of the Holston and French Broad Rivers. From the east at Knoxville, the Tennessee flows southwest for 188 miles through Chattanooga, Tennessee into northern Alabama for 149 miles then makes an abrupt turn northward back into Tennessee. Flowing northward for 166 miles the river then crosses into western Kentucky for the final 49 miles.

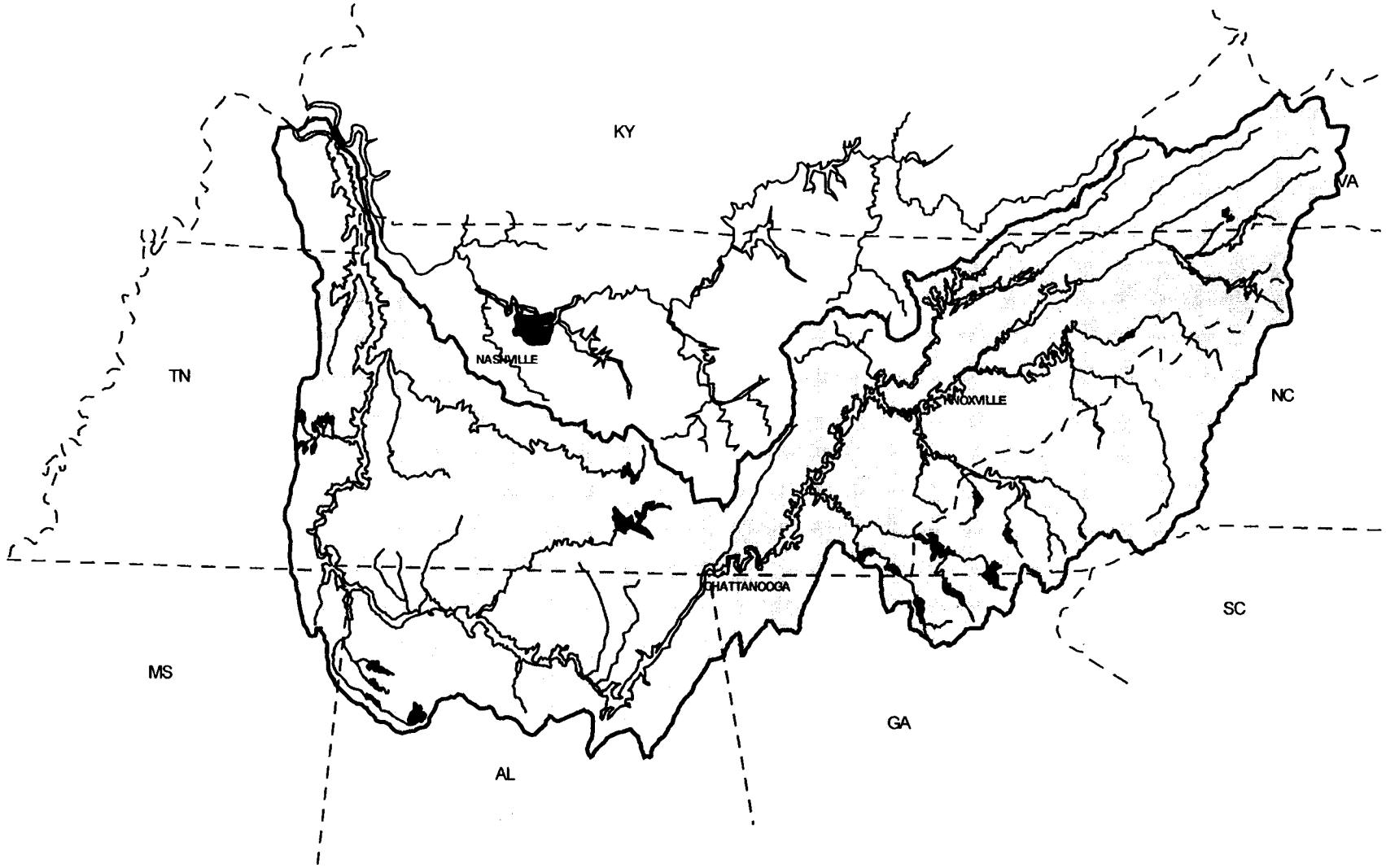


Figure 1.1. Tennessee River Watershed.

The mouth is located in western Kentucky where the river joins the Ohio at Paducah, Kentucky 652 river miles from Knoxville. Average annual flow of the Tennessee River at the month is 67,000 cubic feet per second (cfs).

Topography of the Tennessee River basin varies from the semi-tropical, mountainous east to the relatively flat and rolling west. From Thorpe dam (on the West Fork of the Tuckasegee River, a tributary of the Little Tennessee River) in the southeast to the tailwater at Kentucky dam, the river falls almost 3,200 feet in 714 river miles. On a map, the watershed resembles an hourglass with the two major divisions separated by a narrow river gorge at Chattanooga, Tennessee. The location of Chattanooga in this narrow gorge makes it very susceptible to flooding in extreme high flow periods. One of the principal reasons for the founding of TVA was to alleviate the flooding in this area. The two major divisions east and west of Chattanooga, Tennessee are commonly referred by TVA as the areas "above" and "below" Chattanooga, respectively.

In the area above Chattanooga, the French Broad, Hiwassee, and Little Tennessee River systems have their origins in the Great Smoky Mountains of eastern Tennessee and western North Carolina, and the Blue Ridge Mountains of northern Georgia. Upper reaches of these watersheds typically exhibit low development with large areas of forested lands many within national park boundaries. As one moves downstream, topography of these areas becomes less rugged changing to a more rolling appearance. The Holston and Clinch River systems are located in the Great Valley of the Tennessee

and are characterized by long, parallel wooded ridges alternating with scattered woodlands and cultivated fields. These northern watersheds are elongated along the ridges and valleys in contrast with the fan shaped basins of the southern watersheds.

Topography for the area below Chattanooga is generally less rough with a more rolling demeanor. Major tributaries of the western area include the Duck and Elk rivers. These systems have their origins on the western edge of the Cumberland Plateau and flow generally westward to the Tennessee River (Alavian, 1994). Table 1-1 is a summary of the major tributaries of the Tennessee River and some general information.

Table 1-1. Summary of Major Tributary Characteristics.

Tributary	Average Annual Rainfall (Inches)	Drainage Area (Sq. Mi.)	% Runoff	General Topography
Above Chattanooga (Eastern Valley)	50.6	21,400	45	
Clinch	48.5	4,413	43	Valley and ridge
French Broad	47.4	5,124	42	Mountainous upper; Valley and ridge lower
Hiwassee	55.7	2,700	51	Mountainous upper; Valley and ridge lower
Holston	45.7	3,776	41	Valley and ridge
Little Tennessee	61.2	2,627	50	Mountainous upper; Valley and ridge lower
Below Chattanooga (Western Valley)	52.2	19,510	-	
Elk	52.5	2,249	46	Rolling to flat
Duck	-	3,500	-	Rolling to flat

Adapted from Alavian, 1994.

For the Tennessee Valley, rainfall averages between 51 and 52 inches annually. Annual rainfall ranges from 36 to 65 inches. The area above Chattanooga experiences a wider range of precipitation due to orographic effects of the valley and ridge, and the eastern mountains. Rainfall in the west is essentially uniformly distributed. Basins in the mountains of the southeast receive on average just over 60 inches annually while some portions of the northeast average only about 45 inches annually.

Runoff for the area above Chattanooga ranges from 10 to 37 inches and averages about 22 to 23 inches annually. For the Tennessee Valley, runoff ranges from 11 to 34 inches and averages about 22 to 23 inches annually. Monthly average rainfall varies from a high of about 5 ½ inches in March to a low of about 3 inches in October. Runoff totals experience a much greater seasonal variation ranging from a high of about 4 inches in March to a low of less than 1 inch in September and October (refer to Figures 1.2 and 1.3).

Project Descriptions

With the authorization of the Tennessee Valley Authority Act of 1933, TVA began its 64 year history. Since the early days of TVA the reservoir system has been envisioned as an integrated system of reservoirs with navigation, flood control, and power generation as the primary objectives (TVA, 1936). A system of 53 reservoirs has evolved through

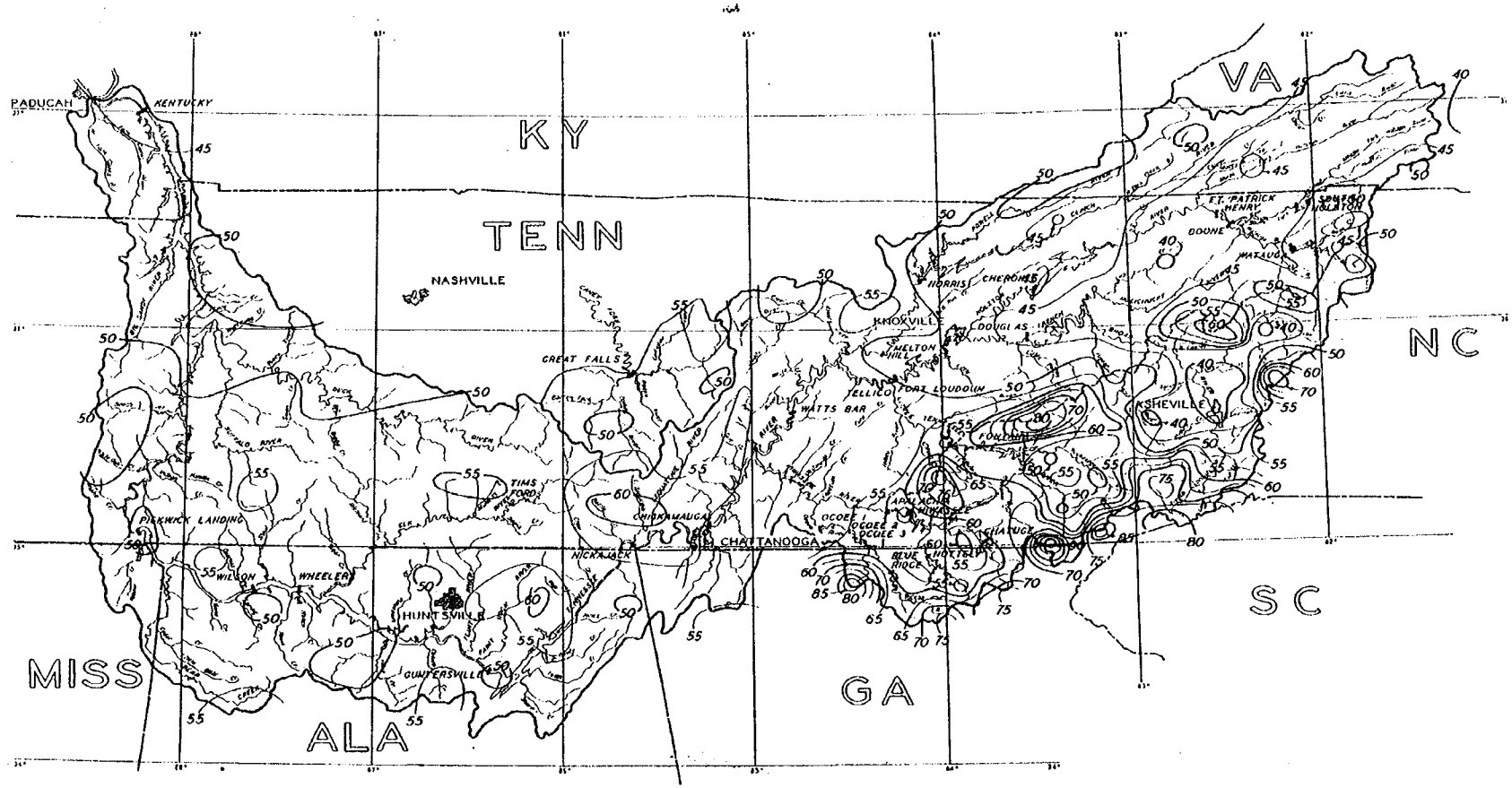


Figure 1.2. Mean Annual Precipitation for the Tennessee River Basin.

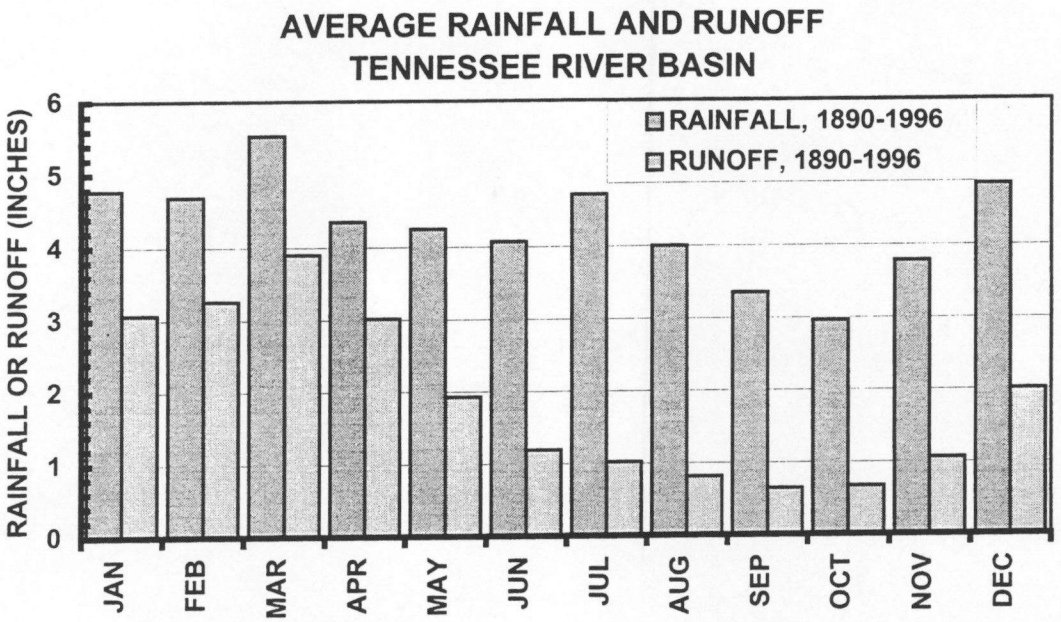


Figure 1.3. Rainfall and Runoff for the Tennessee River Basin.

the 64 years and consists of water control projects both acquired from others and constructed by TVA. It also includes projects owned by other entities (refer to Table 1-2). Of the 53 total projects, 40 projects are scheduled on a daily basis. Thirty-five projects are scheduled for hydropower. Included in this figure is Barkley Reservoir on the Cumberland River. Due to an interconnecting canal, Barkley Reservoir is operated in tandem with Kentucky Reservoir. Ten projects (Beech River and Bristol projects) are small non-power (no facilities for power generation) projects and are self-regulating. Four projects (Thorpe, Nantahala, Woods, and Walters) are owned and operated by others. A single project (Nolichucky) is a decommissioned facility with the reservoir used as a wetlands and wildlife refuge.

Table 1-2. Water Control Projects of TVA

RESERVOIR	TYPE	RESERVOIR	TYPE
Clinch Basin		**Bear Creek Basin**	
Norris	1P	Upper Bear Creek	1
Melton Hill	1P	Bear Creek	1
		Little Bear Creek	1
Holston Basin		Cedar Creek	1
South Holston	1P		
Watauga	1P	**Beech River Basin**	
Wilbur	2P	Beech	1
Boone	1P	Cedar	1
Fort Patrick Henry	2P	Dogwood	1
Cherokee	1P	Pine	1
		Pin Oak	1
French Broad Basin		Redbud	1
Nolichucky	4	Sycamore	1
Walters	O	Lost Creek	1
Douglas	1P		
		Bristol Projects	
Little Tennessee Basin		Beaver Creek	1
Thorpe	O	Clear Creek	1
Nantahala	O		
Fontana	1P	**Tennessee River**	
Santeetlah	O	Fort Loudoun	3P
Cheoah	O	Watts Bar	3P
Calderwood	O	Chickamauga	3P
Tellico	3	Raccoon Mountain	PS
		Nickajack	3P
Hiwassee Basin		Guntersville	3P
Chatuge	1P	Wheeler	3P
Nottely	1P	Wilson	3P
Hiwassee	1P,PS	Pickwick Landing	3P
Apalachia	2P	Kentucky	3P
Blue Ridge	2P		
Ocoee No. 3	2P	**Cumberland River**	
Ocoee No. 2	2P	Wolf Creek	C
Ocoee No. 1	2P	Dale Hollow	C
		Cordell Hull	C
Elk Basin		Great Falls	2P
Woods	O	Center Hill	C
Tims Ford	1P	Old Hickory	C
		Cheatham	C
Duck Basin		Barkley	C
Normandy	1		

TVA Projects
1 - Tributary Multiple Purpose
2 - Tributary Single Purpose
3 - Main Channel
P- Power Generation Facilities
PS- Pumped Storage Facility

Other Projects
C-U. S. Army Corps of Engineers
O-Other

Five projects of the 40 scheduled on a daily basis (Cheoah, Calderwood, Chilhowee, Santeetlah, and Barkley) are owned by other entities (4 by TAPOCO and 1 by the U. S. Army Corps of Engineers (USCOE)). Raccoon Mountain pumped-storage facility is operated for power generation only and is not included in the totals above. Water for this project is pumped from the Tennessee River into a mountain reservoir during periods of low hydropower demand. Water is released from the reservoir through the generating units during peak power demand periods. No reservoir inflows or pool levels are forecast, but its operation affects the operations of the Tennessee River. By agreement with the Southeastern Power Administration (SEPA), hydropower from seven additional projects (owned and operated by USCOE) on the Cumberland River is included in TVA's power system.

TVA-owned projects are categorized according to their primary functions and fall into two general categories: multiple purpose and single purpose. Multiple purpose projects perform a variety of functions as their name implies. These functions include supporting navigation, water supply, flood storage, power generation, recreation, etc. Single purpose projects were initially constructed for the express purpose of power generation. These two general categories may be further subdivided into 4 sub-categories as follows: multiple purpose main channel, tributary multiple purpose power, tributary multiple purpose non-power, and tributary single purpose.

Main channel reservoirs (10) are used primarily to provide a minimum 11-foot navigation channel (adequate for barges with a 9-foot draft) from the mouth of the river at Paducah, Kentucky to the head of the navigable channel at Knoxville, Tennessee. Furthermore, these reservoirs provide some flood storage and are used additionally for power generation. Pool levels typically fluctuate only 5 to 6 feet seasonally due to the minimum pool levels required for navigation. Nine of these projects are operated to seasonal guide curves which provide for the minimum navigation levels in the high runoff period from December through March. The remaining project (Nickajack) is operated within a 2-foot range due to its limited amount of useful storage. Two special cases are Tellico Reservoir and Kentucky Reservoir. Tellico is actually located on the Little Tennessee River, but due to an interconnecting canal with Fort Loudoun Reservoir, is operated in tandem with that project. Tellico has no facilities for power generation. Kentucky Reservoir is unique among the TVA reservoirs in that its primary purpose is to provide flood storage for areas outside the Tennessee River watershed.

Multiple purpose power reservoirs (12) were constructed principally as flood storage reservoirs with ancillary functions for power generation, water supply, downstream flow augmentation, and recreation. These projects typically have large storage capacity and their pool levels experience large seasonal fluctuations associated with flood control and power generation functions. Pool elevations may change up to 50 to 60 feet seasonally. Eleven of these projects are located in the eastern watersheds and provide most of the flood storage space for the area above Chattanooga. Four projects are located in the

Holston watershed, three in the Hiwassee, two in the Clinch, and one each in the French Broad and Little Tennessee Basins. The remaining multiple purpose power tributary project (Tims Ford) is located on the Elk River in south central Tennessee.

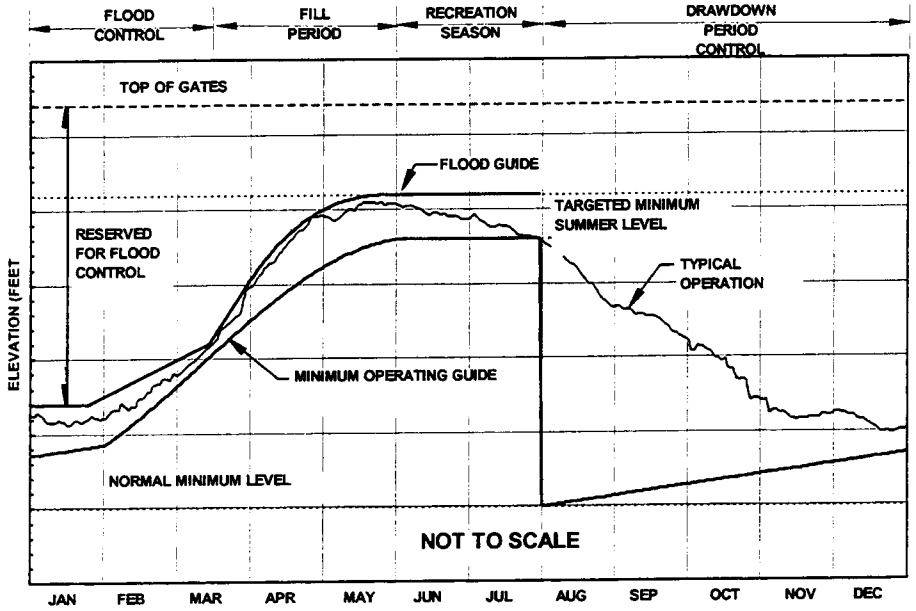
Multiple purpose non-power projects (15) have no power generating facilities and are utilized for flood control, water supply, fisheries, and recreation. Releases for only the largest of these facilities are scheduled on a daily basis: Normandy Reservoir on the Duck River and the 4 Bear Creek projects in northern Alabama. These projects have multiple outlets for controlled and uncontrolled releases. The Beech Projects in western Tennessee and the Bristol projects in northeast Tennessee are self-regulating with uncontrolled spillways.

As stated above, single purpose projects (8) were constructed as power generation facilities. In contrast to the multiple purpose projects, these projects have limited useful storage and generally do not experience the seasonal fluctuations associated with the large storage reservoirs. Blue Ridge Reservoir is an exception to these conditions. Although constructed as a power reservoir, growth of recreation and water quality issues have resulted in its operations being very similar to multiple purpose projects. Single purpose projects are generally operated within ranges of 5-6 feet due to their limited storage capacity. These projects are commonly referred to as "run-of-the-river" projects since their impoundments are narrow and riverine in nature. Only Blue Ridge is operated with a seasonal guide curve.

Typical reservoir operating guide curves are shown in Figure 1.4. Generally, reservoirs are filled in the high runoff periods from December through March with drawdowns occurring late in the year in preparation of the next year's cycle. This type of operation lends itself to hydropower operations since fill periods are typically periods of low power demand and drawdown periods are typically periods of moderate to high power demand. Normal summer pool elevations are routinely met for reservoirs on the main channel. However, minimum summer pool levels for tributary storage reservoirs are expected to be achieved only 90 percent of the time (TVA, 1991). Drawdowns below the minimum operating guide (MOG) levels are scheduled only during periods of extreme drought, high power demand, or maintenance.

Over the past twenty to thirty years, recreation and water quality aspects as well as the aesthetic benefits of the reservoirs have become increasingly more important at all projects. TVA performed an extensive study in the late 1980s to examine alternate operating schemes (TVA, 1991) for the reservoir system. Input was collected from the general public and other interested parties to develop criteria for operations. The study provided guaranteed minimum pool elevations (MOG) for the major tributary reservoirs during the summer recreation season. It also includes provisions for improvements to the quality and quantity (aeration, minimum flows) of releases from many of its tributary and main channel reservoirs.

TRIBUTARY



MAIN CHANNEL

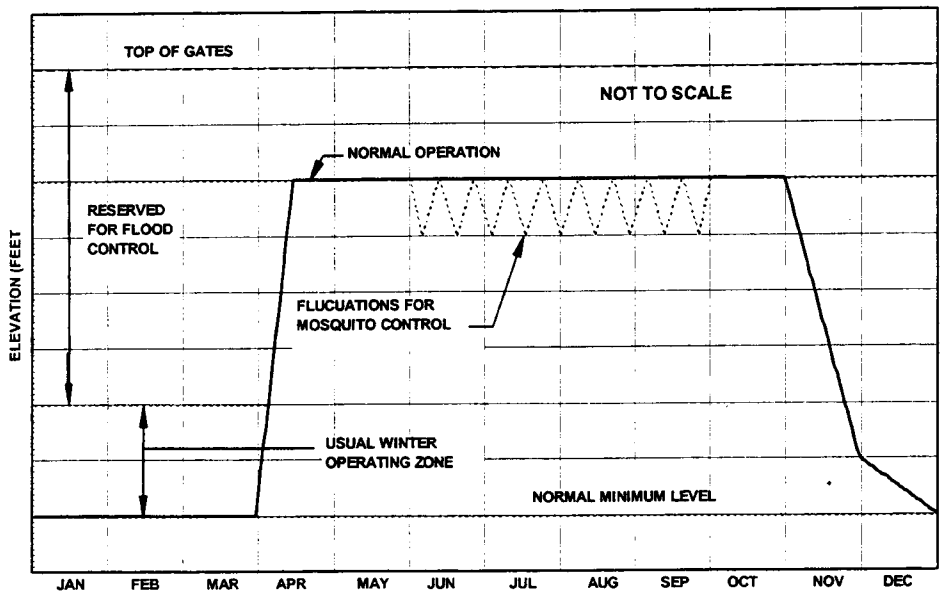


Figure 1.4. Typical Tributary and Main Channel Operating Guide Curves.

Daily Reservoir Regulation

Regulation of the reservoir system is accomplished with development of daily reservoir operating plans from a central facility. The operating plan consists of expected reservoir inflows and outflows. Also, reservoir pool forecasts are furnished based on the expected reservoir inflows and outflows. Additionally, daily hydropower generation totals are provided for those projects with such capability. Preparation of the operating plans involves a five step process:

1. Data collection and verification,
2. Reservoir inflow forecasting,
3. Reservoir release scheduling,
4. Operating plan dissemination,
5. Coordination and monitoring.

Data collection and verification involves telemetered and manual collection of rainfall, streamflow, and hydroproject pool elevations and releases. Rainfall data collected in step 1 is used in step 2, the inflow forecast segment. Projected reservoir inflows (computed with 6-hour time steps) for each sub-basin are then fed into the reservoir scheduling models. It is here that reservoir releases and pool levels are determined consistent with current and projected operating objectives. After the plan is finalized, the information is transmitted to the TVA power supply organization which supplies the daily generation schedules (i.e., reservoir releases) to the individual plants. When

releases larger than hydropower plant capacity are necessary, this information is coordinated with the individual plants directly. For the non-power projects, release information is also coordinated directly to field personnel. The system is monitored continuously for changes or adjustments prior to the issue of the next day's schedule. During high flow periods, the process is accomplished several times each day.

Inflow Model

An extensive data collection network is used to provide the inputs for the reservoir inflow forecasting models. For the "rain-on-the-ground" or observed rain reservoir inflow forecasts, information is received from 304 rain gages, 60 stream gages and the 46 projects owned by TVA. Data collection is continuous throughout the day at varying time intervals. Data transmissions are achieved through telephone link, satellite, and the TVA wide-area network. Data verification is accomplished utilizing automated and manual methods prior to data input into inflow forecasting models.

Reservoir inflows are computed from streamflow, reservoir pool level, and reservoir discharge data. For tributary projects, the computation involves a simple mass balance equation where the inflow into the reservoir is the sum of the reservoir discharge and the change in reservoir storage (flat pool assumption). For the main stem projects, slope-storage effect must be considered in the computations due to the length of these reservoirs. All inflows are computed for 6-hour and 24-hour time steps.

To compute forecast inflows, observed station precipitation is averaged over sub-basins using the Thiessen polygon method. This method allows for an accounting of non-uniform rain gage distribution within a watershed (Lindsey et al., 1975). Theoretically, the area average precipitation of a basin is equal to the integral of a continuous isohyetal field over the basin, divided by the basin area. Expressed practically, the area average precipitation is approximated by a weighted sum of the observed rain at gaged locations within or near the basin (Krzysztofowicz, 1993).

Weather forecast data (QPF) is received from the weather forecast vendor. This data is received electronically as a synopsis and quantitative basin-averaged rainfall amounts for the next 48 hours, 3-5 day, and 6-10 day periods. The probabilistic aspects of the forecast are specified as the maximum (10 percent exceedance probability), most likely (50 percent exceedance probability), and minimum (90 percent exceedance probability) expected values.

Reservoir inflows are determined empirically from inflow models for 98 sub-basins using multi-axial rainfall-runoff relations. These empirical relations are established from the antecedent precipitation (an indication of existing soil moisture conditions based on previous rainfall to an area), relative location within the Valley, time of year (season), and observed or forecast rainfall (area average). Proposed in the early 1950s by the U. S. Weather Bureau (Kohler and Lindsey, 1951), the multi-axial approach has been used essentially unchanged over the past 40 years. TVA has however adjusted the technique

for its reservoir system (Cooper, 1972). The model uses 6-hour unit hydrographs to distribute runoff over time for each sub-basin. Model results are analyzed and can be manually adjusted to match observed streamflow hydrographs through interactive computer processes by inflow forecast personnel. Precipitation from QPFs is loaded into the inflow model in 6-hour time steps for the first 48-hour period for each QPF sub-basin. Daily average values are loaded for the following 8 days of the forecast period. The model computes runoff from these values for the 98 sub-basins using the same multi-axial approach as with the observed rain.

CHAPTER 2

QUANTITATIVE PRECIPITATION FORECASTS

2.1 Purpose of QPF in Reservoir Forecasting

It is apparent from the previous discussion that the TVA reservoir system is a complex system with often competing constraints. Operation of this system without consideration of expected meteorological events would result in waste or deficiency of water resources, and frequent or constant adjustments to system operating plans. For example, if a reservoir is operated near the top of its storage range based on inflows from "rain-on-the-ground" only, spill operations might be needed with additional rainfall. Spilling water means lost hydropower generation not only at a single project, but also at several successive projects. A valuable resource would thus be wasted or lost. Conversely, if the weather turns dry and a reservoir is near the bottom of its operating range, discharges would have to be severely curtailed. The result would be lost hydropower generation and reduced flows for water quality, water supply, and recreation.

TVA is particularly interested in the volume of expected precipitation for its reservoir forecasts. Although a necessary component of the precipitation forecast, the timing of the precipitation (when the it is expected to occur) is not as critical in the reservoir system projects as with unregulated streams. Generally speaking, the larger the size of

the reservoir, the longer their reaction time. Use of the quantitative precipitation forecast (QPF) allows operating contingencies to be developed based on the amount of the expected precipitation. The QPF takes the weather forecast beyond a simple knowledge of whether it will rain or not. As described above, the QPF provides numerical quantities for discrete time periods and locations that can be converted to reservoir inflow by the inflow forecasting models. The same relationships are used as with the observed rain inflow forecast. Multiple rainfall scenarios may also be examined using current high speed computers.

2.2 Benefits of QPF and Accurate Reservoir Forecasts

Reservoir pool forecasts based on inflows from observed rain were issued for many years by TVA. Prior to the mid 1970s, the forecast periods used by TVA were relatively short since computations were mostly performed by hand. A 3-day forecast would be prepared each day with a 5-day forecast once a week. The no-additional-rainfall scenario worked well for this short timeframe. Uncertainty of expected rainfall was captured by scheduling reservoir pool levels higher or lower depending on the subjective judgment of the reservoir forecaster. As faster and higher capacity computer technology was developed, computational forecast periods were increased to as much as two weeks. It is unrealistic to assume that no additional rainfall would occur within a such a relatively long forecast period. The problem with using forecast rain in the reservoir

operation forecast was with the uncertainty associated with it. Until recently, no means has been available to appropriately address this issue.

Inclusion of the QPF in the reservoir operation forecast attempts to maximize the benefits of the reservoir system within the bounds of each of several demands. Benefits of the inclusion of QPFs in the reservoir forecast for the Ohio River have been documented by the National Weather Service in regards to flood forecasts (Eiben and Philips, 1993) and commercial navigation (Eiben and Yess, 1993). Demands on the reservoir system from power, recreation, water supply, navigation, and other interests, in addition to requirements for flood control dictate an accurate reservoir forecast that can encompass all of these objectives.

Power Generation Benefit

The TVA power system serves nearly 8 million customers in a seven state region (refer to Figure 2.1). Hydropower production represents approximately 20 percent of total TVA power generation (16 percent conventional hydropower and 4 percent pumped storage). Due to its high degree of flexibility, hydropower is used during peak demand periods. Unlike steam generating plants, hydropower units can be brought into service almost instantaneously. During high flow periods, this flexibility is lost because units must be scheduled to run more hours each day to maintain pool elevations. During periods of excess generation, power can also be marketed to outside utilities.

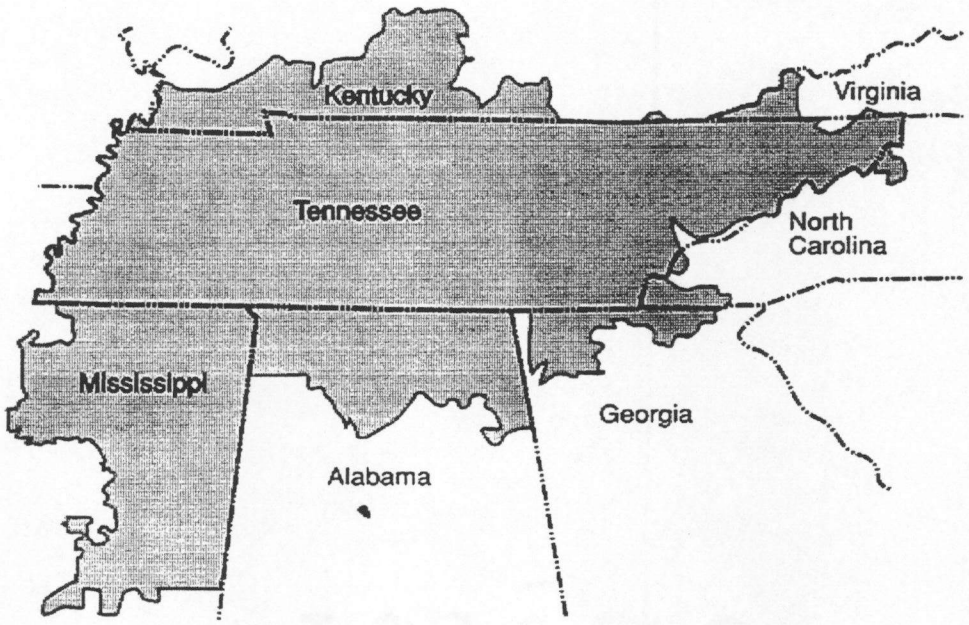


Figure 2.1. TVA Power Service Area.

Use of the QPF in the reservoir forecasts provides the knowledge of when to expect these periods and allows the power supply decision-makers the flexibility to make informed judgments on the buying and selling of electric power.

Recreation Benefit

Reservoir impoundments have created a booming recreation industry for the Tennessee River and its tributaries. Often referred to as the "Great Lakes of the South," the reservoirs are excellent resources for boating, fishing, camping, swimming, etc. Recreation and tourism are key components of several local economies. Visitors to TVA lakes and facilities contribute $1.25 billion annually to the local economies. Ensuring minimum summer reservoir levels and providing minimum reservoir releases are two

aspects of TVA's commitment to this industry. Reservoir releases cannot be scheduled to support this industry without an adequate knowledge of expected inflows into the reservoirs. The QPF used in conjunction with the reservoir inflow models provides additional knowledge of the expected inflows so that reservoir releases can be scheduled appropriately.

Navigation Benefit

With 800 miles of deep channel navigable waterways, the Tennessee River system is a major pipeline for the transportation of bulk commodities into and outside the Tennessee Valley. An average of 34,000 barges each year use the Tennessee River system to move 48 million tons of cargo. Savings over alternative methods of transportation are estimated at $250 million each year. Supporting this industry is one of TVA's major objectives. The inclusion of the QPF in the reservoir forecasts allows TVA to provide additional lead time to shippers during high flow periods. Preparations for high velocity river flows and rising pools that significantly affect navigation operations can therefore be accomplished with greater expediency.

Flood Control Benefit

Flood control for the Tennessee Valley still stands as one of the primary missions of TVA. Since 1933, over $4 billion in damages have been averted for the city of Chattanooga alone. Flood control is accomplished through the restriction of flows through the river system by means of the tributary and to a lesser degree the main

channel reservoirs. Water is stored temporarily in these projects to dampen flood elevation crests. It is then released at a later date. Use of the QPF provides a more accurate rainfall (and thus reservoir inflow) forecast. Pool levels can therefore be drawn down in advance of flood events to provide the maximum amount of flood storage. When reservoir pools are expected to exceed flood levels, advance notice can be given sooner to maximize lead time for evacuations of property and personnel.

Other Benefit

Other demands on the system such as water supply, fisheries, etc. are no less important. The Tennessee River system provides fresh water to 4 million people across the valley. Thus there are numerous benefits from a reservoir forecast made more accurate using the QPF. Having an accurate forecast affects many industries and people both inside and outside the Tennessee Valley.

2.3 History of the QPF at TVA

General

In the late 1930s and early 1940s, TVA recognized its need for QPF forecasts in the operation of its then fledgling reservoir system. A mutual agreement was reached between TVA and the U. S. Weather Bureau in 1940 to exchange meteorologic and hydrologic data as a means to avoid duplication (Cooper, 1969). The Weather Bureau

also provided meteorological forecast services to TVA under this agreement. These services included providing at least daily (and more frequently as necessary) forecasts of:

- General weather conditions (i.e., Hot, wet, rainy, etc.)
- Quantitative precipitation for the Tennessee Valley;
- Temperature and light intensity (sky conditions) at selected locations;
- Expected precipitation and temperatures for the current and succeeding four days.

Additional services relating to TVA's power generation functions were also included, as well as information dissemination and forecasts on unregulated streams within the Tennessee River watershed. Furthermore, the Tennessee and Cumberland watersheds were divided into nine QPF sub-basin areas (refer to Figure 2.2). Weather forecasts were issued with a descriptive synopsis of the current weather conditions along with expected developments. Additionally, the forecast provided expected precipitation totals within each of the nine QPF sub-basins for the next two twelve hour periods, the following 24-hour period, and the following 3-day period for a total of 5 forecast days (Cooper, 1969).

The specific time when this arrangement with the Weather Bureau ended and private weather forecast vendors began providing the forecast services is unclear. Based on available documentation within TVA, this would seem to be in the early 1970s. Since the 1970s, a number of different weather forecast vendors have been utilized.

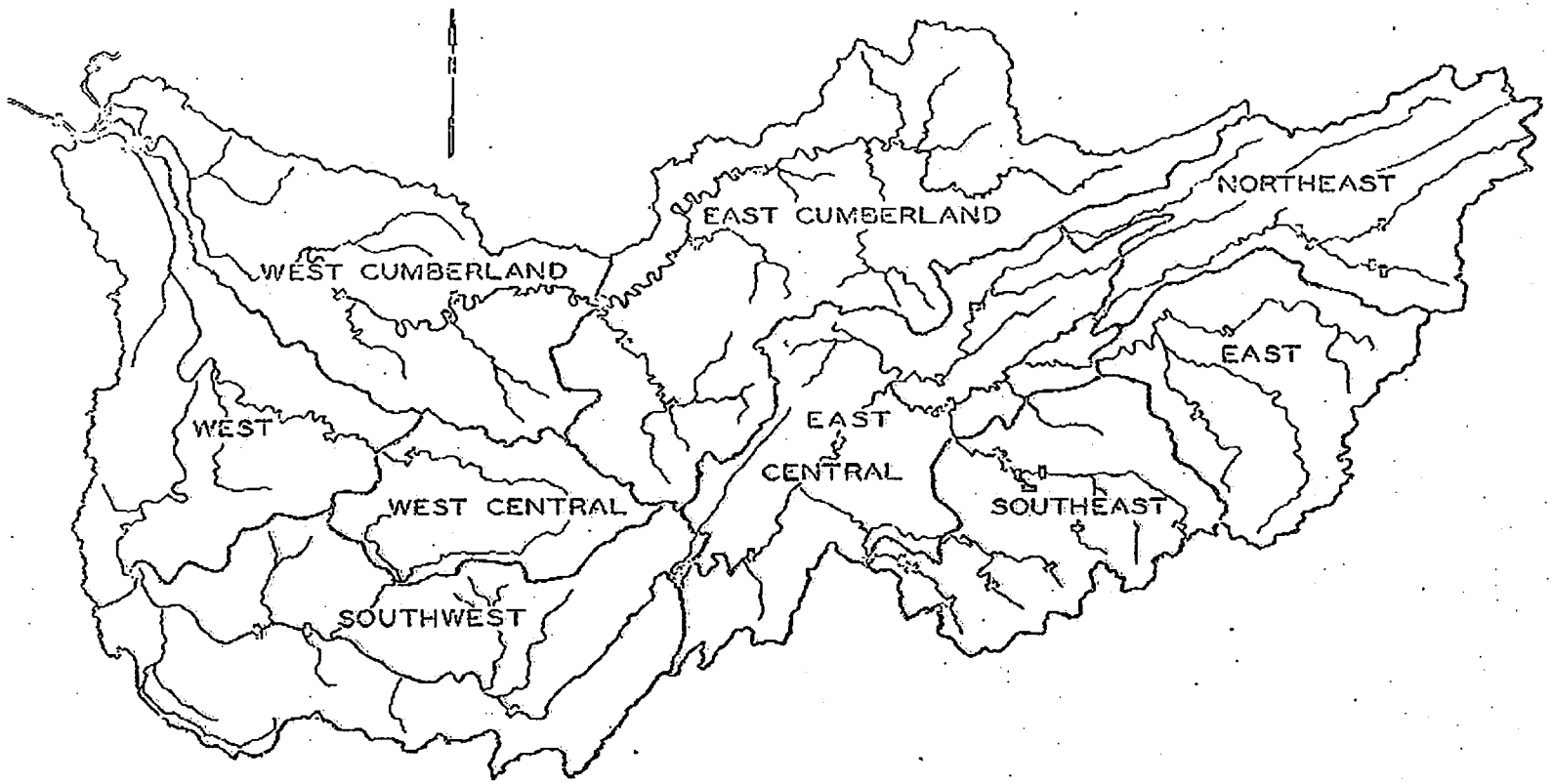


Figure 2.2. Original Quantitative Precipitation Forecast Sub-basins for the Tennessee and Cumberland River Basins.

Weather forecast services provided during this period by these vendors were essentially unchanged from those services rendered in previous years.

Introduction of Probabilistic Criteria

Weather forecasting is an inherently complicated process. The complex nature of the atmosphere has caused forecasting to be likened to balancing a pencil on its point and predicting in which direction it will fall (Lijas and Murphy, 1994). Typical QPFs had no means to account for the uncertainties associated with the rainfall forecasts. These uncertainties have been attributed to three factors: 1) A very large number of elements must be observed to determine the state of the atmosphere; 2) The basic instability of the atmosphere must be considered (the "pencil on its point"); 3) The problem of calculating future states of the atmosphere even from a well-defined initial state (Lijas and Murphy, 1994).

By the early 1990s, increasing interest emerged (both within and outside of TVA) for probabilistic precipitation forecasts to account for the uncertainties associated with the complex nature of the atmosphere. Since the mid 1980s Wilks, Murphy, Krzysztofowicz and others have investigated probabilistic applications to QPFs. Krzysztofowicz has conducted a large amount of research on the subject of probabilistic QPF in conjunction

with river basin streamflow forecasts issued by the National Weather Service. His rationale for quantifying the uncertainty includes the following benefits:

- Aiding the forecaster in making unbiased judgments;
- Providing the inputs necessary for making probabilistic river stage forecasts (or at TVA, the reservoir inflow and reservoir pool level forecasts);
- Through the use of the probabilistic stage forecasts, providing flood watches and warnings in a quantitative, probabilistic format (Krzysztofowicz et al., 1993).

Additionally, surveys in the power utility industry indicated an increased demand for climatic information of which probabilistic QPFs are a part (Changnon et al., 1995). In early 1993, TVA began tracking the vendor precipitation forecast against the amounts actually observed to arrive at "expected value QPFs" of precipitation to be used in the reservoir inflow forecasting models. Concurrently, several TVA process improvement teams also determined the need for accurate weather forecasts in several key areas of TVA operations (Morris, 1994). With the current forecast vendor's contract nearing an end, an opportunity to develop new criteria based on the probabilistic approach was available.

The 1994 "TVA Weather Rodeo"

Increasing demands on the reservoir system have caused TVA to recognize the need to account for the uncertainties in precipitation forecasts. The "expected value QPFs" used

by TVA in 1993 were a step toward this end. During late 1993, TVA advertised for a weather forecasting services (QPF and temperature forecasts) vendor. In what was termed the "TVA Weather Rodeo," a four-month evaluation of six prospective weather forecast vendors ensued. The evaluation included consideration of technical as well as business factors. A list of these factors is shown in Table 2-1. By May 1994, two vendors were selected to provide the daily forecasts for QPF and temperature during a one year (later extended to two years) evaluation period. Ultimately in mid-1996, one of the vendors was selected as the sole forecast vendor.

Table 2-1. TVA "Weather Rodeo" Evaluation Criteria.

Primary Item	Secondary Item	Maximum Points
Staff Available	Forecasters	13
	Other	7
Hardware Available	Computers	5
	Communications	5
Data Access	NWS	5
	Commercial	5
Experience	TVA Region	13
	Utility	7
Technical Capability	QPF	8
	Temperature	8
	Probabilistic	4
Business	Dunn & Bradstreet	5
	TVA Region	2
	Other	3
Cost	Base Year	10
Total		100

Source: "Report from the Weather Forecasting Services Evaluation Team," (TVA,1994).

2.4 Details of the Vendor QPF

The vendor forecasts are similar in content as those received previously from other forecast vendors and the Weather Bureau. Included in the forecasts are the synoptic discussion and information on forecast temperature, wind speed and direction, humidity, and sky conditions, as well as the QPF. The forecast is transmitted electronically in a text file to TVA three times a day. Specifications of the vendor forecasts relating to the QPF aspects both prior to and after the selection include the following:

- The vendor provides three forecasts each day at 5:30 a.m., 10:30 a.m., and 2:00 p.m. Eastern Time;
- TVA evaluations of the forecasts are conducted on the 5:30 a.m. forecast;
- The forecast period consists of the current day plus 9 additional days (two twelve hour periods - 6:00 a.m. to 6:00 p.m., Central Time and 6:00 p.m. to 6:00 a.m., Central Time, followed by a 24-hour period, a 3-day period, and a 5-day period for a total of 10 days);
- Forecasts are provided for five QPF sub-basins within the Tennessee and Cumberland River basins. The five forecast sub-basin are the Central, East, Northeast, Northwest, and Southwest. The number of QPF sub-basins was reduced from the nine used in earlier QPFs to five for simplicity at the request of the vendor (refer to Figure 2.3);
- Probabilistic aspects are captured in the QPF through the inclusion of a triangular frequency distribution. This distribution includes 3 expected values: the minimum

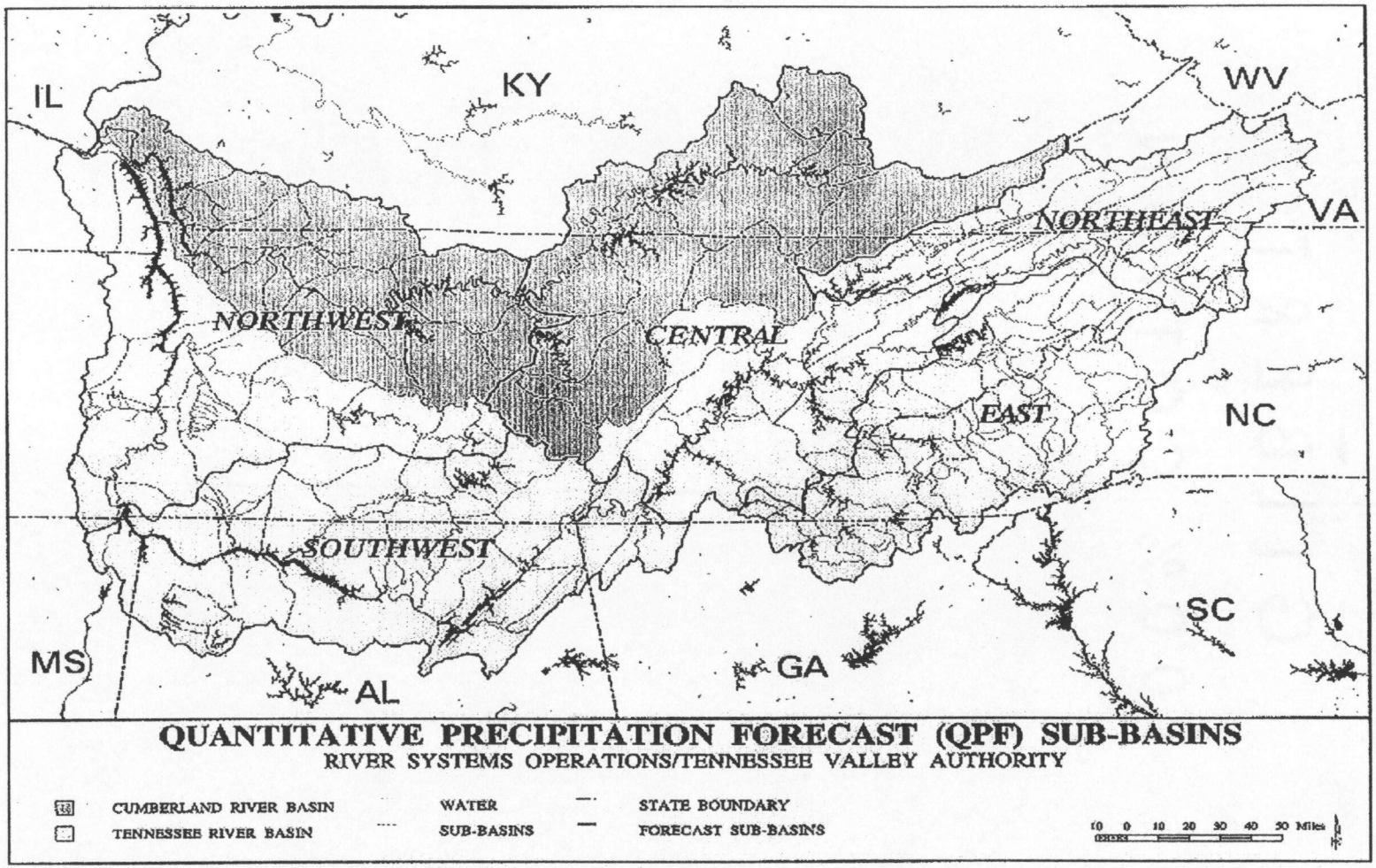


Figure 2.3. Current Quantitative Precipitation Forecast Sub-basins for the Tennessee and Cumberland River Basins.

(90% exceedance probability), the most likely (50% exceedance probability), and maximum (10% exceedance probability) values for each forecast time period and each QPF sub-basin. Observed values are expected to fall within the maximum and minimum values 80 percent of the time;

- The forecast is transmitted in two formats: a concise version and a detailed version. The short forecast provides a synoptic discussion along with a summary of QPF, sky conditions, temperature, wind and other meteorological forecast data. The long forecast furnishes additional detail information on QPF and temperature for later evaluation by TVA.

A status report prepared by the vendor in 1996 gives some insight into the preparation of the vendor QPF. Methods used by the vendor to develop the forecast include examination of domestic and European weather forecast model outputs. Model output is used for the entire ten-day forecast period. Forecasts for the first 48-hour period rely heavily on this model output. Persistence (the short term trend) is weighed more heavily in the periods beyond the first 48 hours. The 3 to 5-day period uses a compromise of model output and persistence. Model output is used as an initial indication of the forecast with persistence factored in on subsequent trials. The 6 to 10-day period also relies on model output for an initial trial. Persistence along with comparisons to similar recent weather patterns is factored in for the final forecast. The status report indicated no use of long-term historical data in any of the forecast periods (Yuknis,1996).

CHAPTER 3

ANALYSIS

3.1 Description of Available Data

Due to the evaluation of the QPF vendor forecasts from the "TVA Weather Rodeo" (refer to discussion in Chapter 2), a large data base of information was collected from the vendor weather forecasts and from the TVA system of rainfall gages. The period from October 1, 1994, to December 31, 1996, is used for this study. The beginning date of this period is based on data availability while the cut-off date was selected arbitrarily. The data is classified in three ways:

- Observed data consists of daily, Thiessen-weighted, area-average precipitation totals for each of the 5 QPF forecast sub-basin areas. This data is further grouped into the 3 forecast periods, i.e. days 1 through 2, days 3 through 5, and days 6 through 10. For the purposes of this study, amounts for days 1 through 2 and days 3 through 5 are lumped into a single period: days 1 through 5;
- Forecast data is the vendor's "most likely" or 50 percent exceedance value for each of the 5 QPF forecast sub-basins. These are also grouped into the forecast periods with values for days 1 through 2 lumped with days 3 through 5;
- TVA has monthly area-average precipitation amounts for the two major watershed divisions (above and below Chattanooga) for 107 years. The period from 1890-1996

is used for analysis of the historical data. Because the study period is from 1994-1996, the period from 1890-1993 is used to develop the historical QPF values.

3.2 Assumptions

Assumptions used in the analysis for this study are based on limitations of the available data. These assumptions are:

1. All data is considered to be provisional. Extensive verification has not been performed on the observed or forecast precipitation data used in the "Weather Rodeo" weather forecast evaluation. Data is available on an electronic data base and has not been published.

   Historical data (1890-1996) has had some verification but, because of its discontinuous nature, is considered unverified in this study. TVA published annual precipitation reports for the Tennessee Valley from 1936 through 1979. Prior to the creation of TVA, rainfall data was collected by the U. S. Weather Bureau and the U. S. Army Signal Corps. Data after 1979 was collected by and is maintained by TVA. All historical data is available in an electronic data base;

2. Historical area-average precipitation data for each of the five QPF sub-basin areas does not exist. Therefore, the historical data for the area above Chattanooga is used

in the analysis to determine average precipitation for those QPF sub-basin areas that lie within this region, namely the Central, East, and Northeast sub-basins. For the Northwest and Southwest sub-basins, the historical data for the area below Chattanooga is used;

3. Observed and forecast area-average precipitation data for the Central and Northwest QPF sub-basins includes areas of the Cumberland basin. Data for the Tennessee River Watershed portions of these QPF areas is not available;

4. It is not known how the station precipitation data was averaged for each year of the historical data. Within the past 12 years the Thiessen polygon method has been used. The method is assumed to be consistent for all years.

3.3 Historical Data Analysis for Trends

Due to the long period of record for the historical data, the data was subjected to an examination in an attempt to discover any trends and possible reasons for these trends, if present. Changes in the location and concentration of rainfall gaging stations could bias results. Additionally, land-use changes could have occurred, such as increased urban development and deforestation over the past 107 years, which could affect evapo-

transpiration rates and formation of rainfall-producing clouds. Long-term climatic changes could influence precipitation and would be evident in the trend analysis.

The first step of the analysis was to review the published annual precipitation reports to investigate the spatial distribution of the rainfall gages. Reports from 1936, 1937, 1940, 1950, 1960, and 1970 included watershed maps with the gage locations plotted. Only two months were published for 1980 but the watershed map was still available. No maps were available for the period prior to 1936. Recent (1994) maps have been developed showing the current gage distribution and are periodically updated as necessary. Figure 3.1 is an example (1940) of the maps from the published precipitation reports. Figure 3.2 is the current (1994) map. For additional maps, the reader is referred to Appendix A.1 through A.7.

In examining these maps, the first thing that becomes apparent is the difference in the concentration of gages in the upper and lower watershed divisions. The eastern basin exhibits a significantly higher concentration of gages more than the western basin. This difference is assumed to be due to the presence of orographic effects on rainfall in the eastern watershed. In such an area of diverse topography, precipitation variations can be large and, therefore, require a higher concentration of rainfall gages. Such a wide variation in rainfall totals was noted in Figure 1.2 over the mountainous regions of this watershed. Contrastingly, with its relatively flat topography, the western area receives a

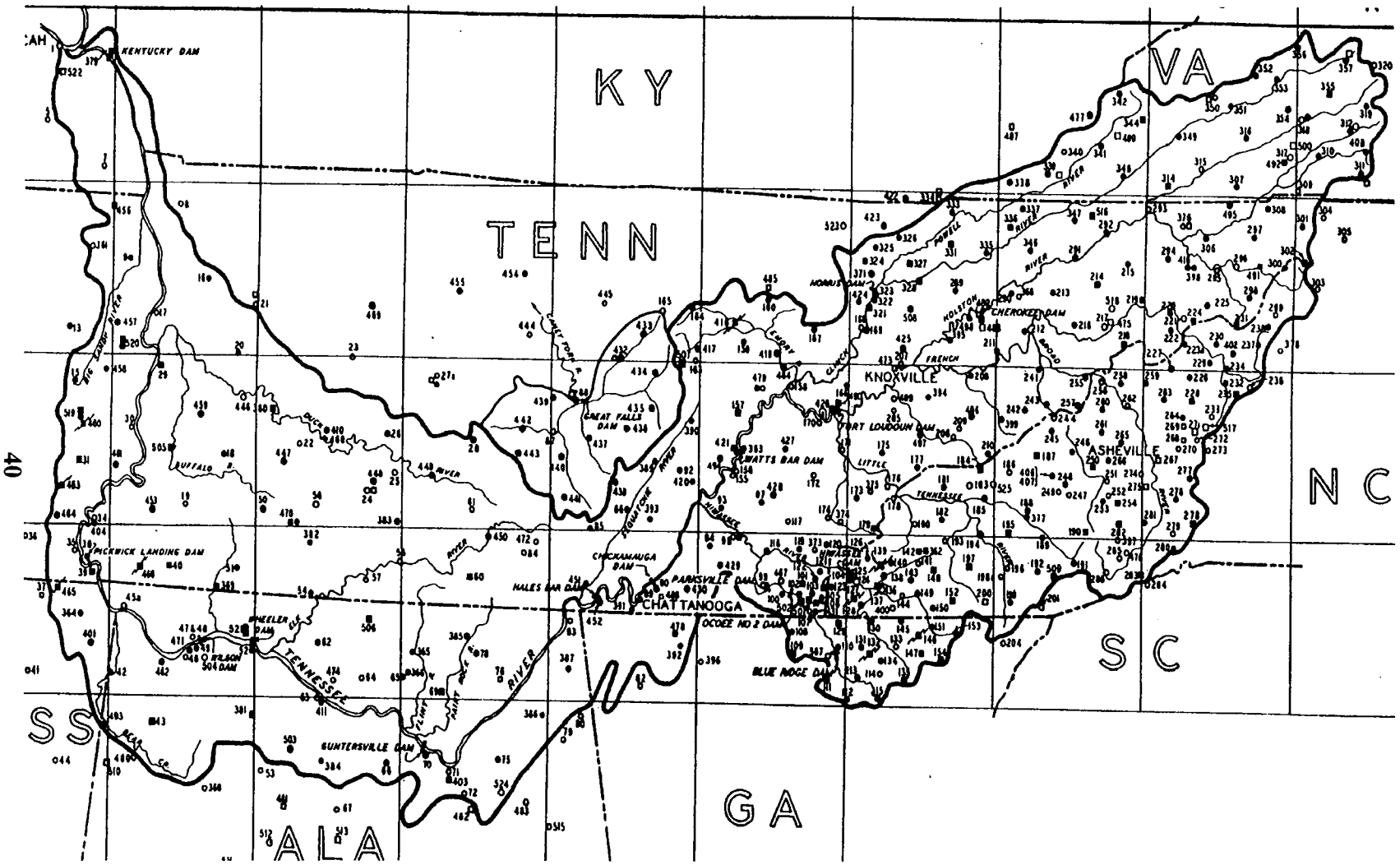


Figure 3.1. TVA Rain Gage Distribution Circa 1940.

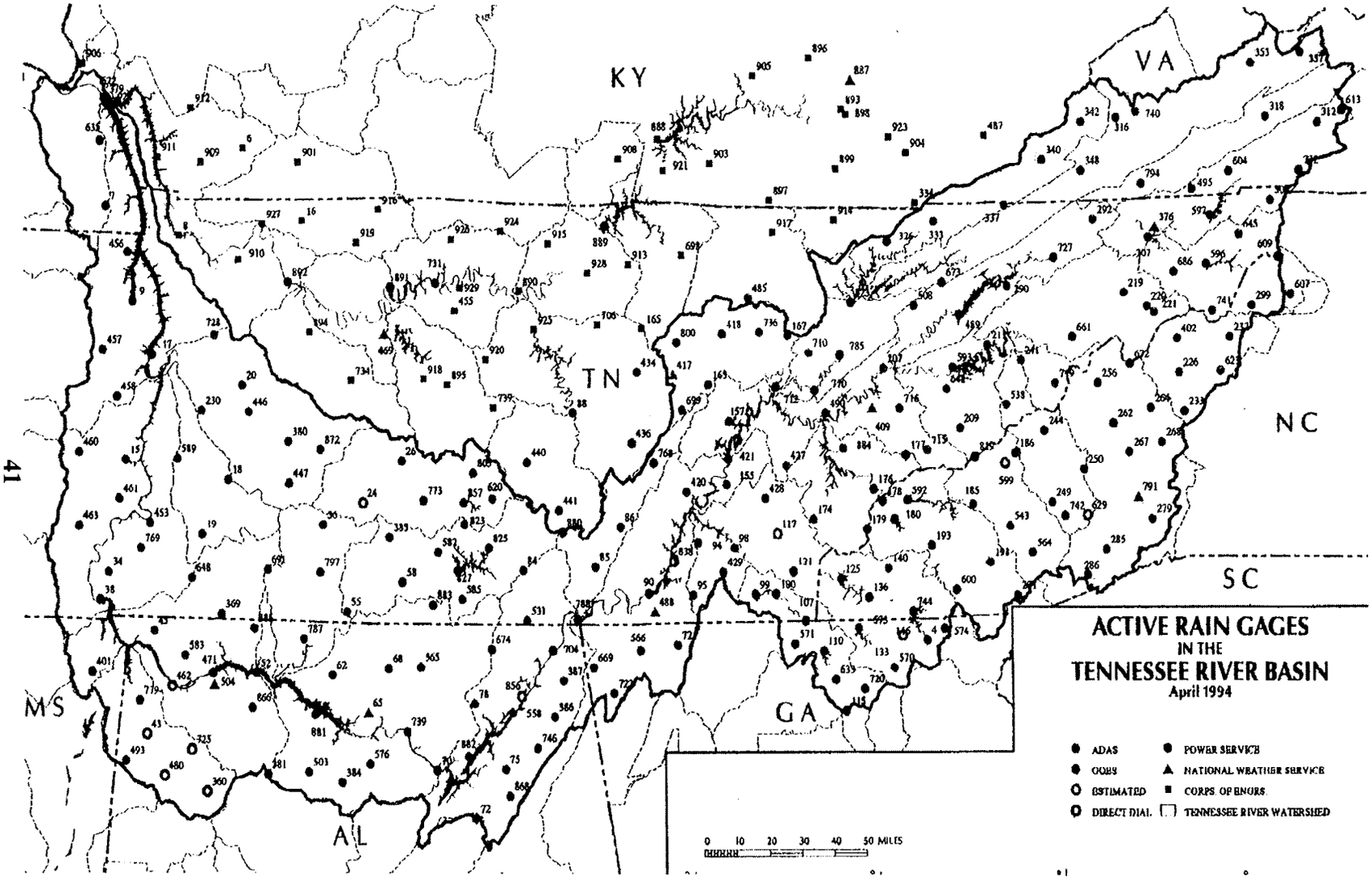


Figure 3.2. TVA Rain Gage Distribution Circa 1994.

fairly consistent distribution of rainfall. Within each of the two divisions, the distribution of gages is relatively uniform. The overall number of gages increases over time, peaking around the 1970s. After this point, some gages were retired, probably due to technological advances in communications (many early gages were reported by human observers) and budget restrictions. Additionally, many of the early gages were owned and operated by other agencies. TVA reviews also indicate no further need for discernment among close gages. Although the number of gages has changed that historical data set is based on, most of the gage locations have not changed significantly over the past 60 years.

The second step in the analysis of the historical data involved plotting the monthly historical data over time, first as a continuous stream of data from January 1890 through December 1996, and then as a graph of each month for all years of record. It was hoped that any long-term trends which existed would be revealed by plotting the data in this manner. After the data was plotted, an additional "smoothed plot was also constructed.

Smoothing is a technique which attempts to eliminate or reduce the effects of random variations in a data set and thus, highlight the systematic variations. Although several different smoothing techniques are available, a moving average approach was selected. A description of the methodology is presented in SYSTAT, 1992. It essentially involves fixing the number of periods for which the average is to be computed and determining

the average of values prior and subsequent to a particular value. The process is repeated for each value in the data set. For the beginning and end values where the number of periods before or after may be less than the period for the moving average, the actual value is used. The method can be applied in successive steps if desired, each resulting in a smoother curve appearance. The number of periods is reduced in each successive step. This reduces the number of unaveraged points at the beginning and end of the data set. Moreover, it further enhances the smoothing effect. An iterative approach was taken in the selection of the number of periods for the average and the number of times the curve was smoothed.

For the continuous data stream analysis, the data was smoothed initially with a 120-month moving average. Smoothes with 24, 6, and 2-month moving averages were then successively applied. Both of the areas above and below Chattanooga were examined in this manner. The Appendix contains full page graphs for this trend analysis as A.10 and A.23. Figures 3.3 and 3.4, the results of the continuous data stream analysis are summarized in single charts for each of the two major watershed divisions of the Tennessee Valley. Each graph indicates a relatively stable, horizontal trend. A slight upward trend is indicated in the mid to late 1970s. However, the severe drought of 1985 through 1988 is apparent as a large downward trend in each curve. Data for the last few years appears to be reversing that trend, with the curve turning upward.

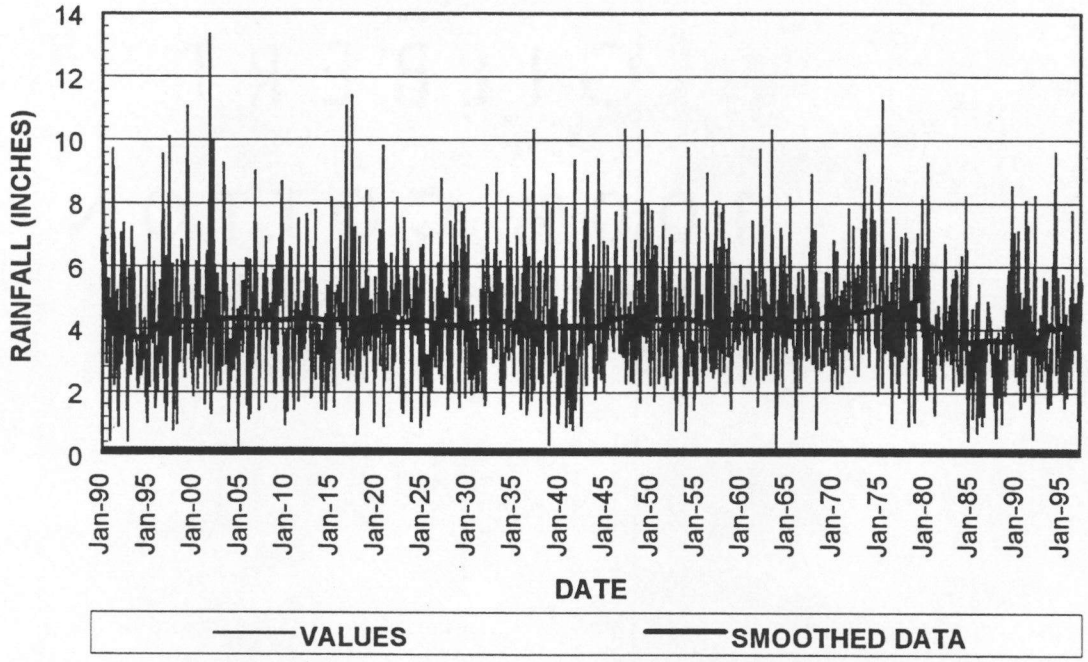


Figure 3.3. Continuous Monthly Precipitation (1890-1996). Area Above Chattanooga.

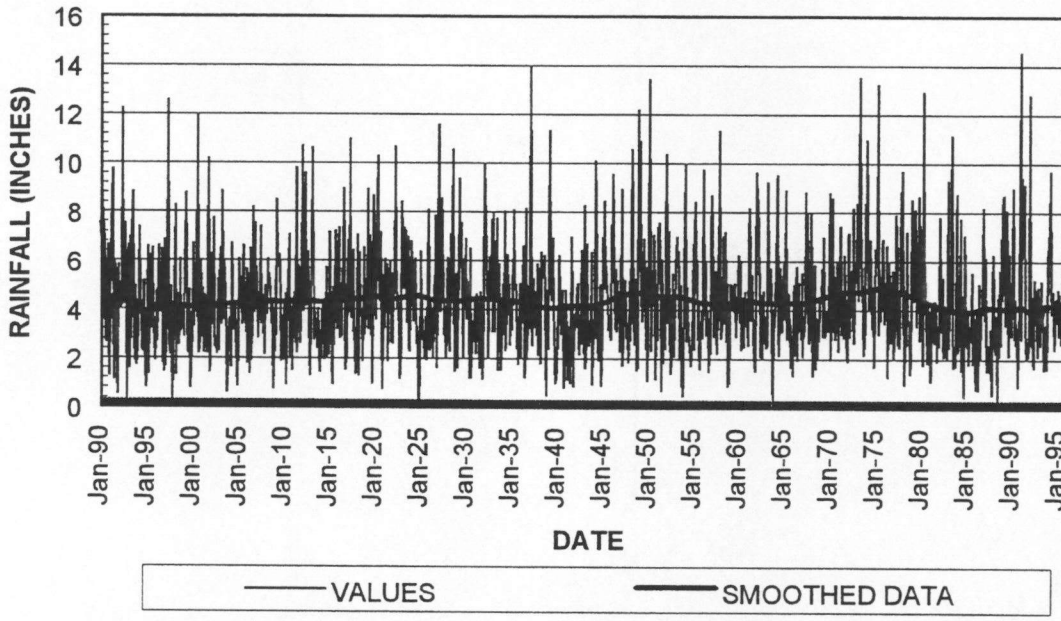


Figure 3.4. Continuous Monthly Precipitation (1890-1996). Area Below Chattanooga.

Trend analysis of average rainfall for each month is found in the Appendix as A.11 through A.22 for the area above Chattanooga and A.24 through A.35 for the area below Chattanooga. These trend curves were developed using an approach similar to that used for the continuous data stream analysis. The period for the moving averages was again selected iteratively. A 10-year period was selected for the initial smooth with successive smoothes using 4 and 2-year periods. The smoothed curves appear to indicate an approximately 20 to 30-year cyclical pattern. Some upward and downward trends are also indicated in some of the months. A situation similar to the continuous data is apparent in several months with a high precipitation period in the mid to late 1970s. The ensuing drought period is also apparent. Here again, the trend for these months appears to be turning upward in the recent years of the data set.

In summary, the historical data set is not a homogeneous data set in the strictest sense. Locations of rainfall gage stations have changed over time as well as the number of stations. Additionally, the method of computing the basin precipitation averages is not known for all years of record. Some trends are noted in the moving averages for a few of the individual months. However, the trends for the continuous period of record are essentially horizontal for all but the last 25 to 30 years. The average during this 25 to 30-year period seems consistent with the previous 75 to 80 years. Thus, no long-term climatic changes are indicated by the analysis. The non-homogeneities are considered to be minor for the purpose of this study due to the apparent lack of indications of long-

term average trend changes in the data (as shown in the smoothed trend line in A.10 and A.23 of the Appendix).

3.4 Method of Approach

Organization of Data

The Microsoft *Excel* computer spreadsheet application was used extensively in this analysis. All data was retrieved from the TVA data base in a simple text format and converted to the spreadsheet application. Data is available for each of the QPF forecast sub-basin areas. An *Excel* spreadsheet file was established for each sub-basin with sections for the 1 to 5-day period, the 6 to 10-day period, and the total 10-day period. A column in the file was specified for the observed rain for each forecast period, for the corresponding vendor forecast, and for each forecast based on the historical data. Data format was dictated by the format of the available data in the 1 to 2-day, 3 to 5-day, and 6 to 10-day forecast period values.

A statistical analysis of the historical data set for each month and each major watershed division was conducted in the form of a frequency analysis. For a discussion of the tools used in the analysis, the reader is referred to any text on statistical methods. However, some general information is provided within this discussion. The analysis period

excluded the last three years of available data (1994-1996) since these years would not have yet occurred at the time of the forecasts.

Descriptive processes include histograms, and statistical moments such as the mean, standard deviation, and skew for each month's average precipitation frequency distribution. The histogram provides a means to group the data within certain limits called value classes or bins. Grouping the data in this manner provides an indication of the frequency distribution characteristics of the data set. Prior to grouping, the data is ranked from largest to smallest. The number of bins is arbitrarily selected, but typically 10 to 12 bins are constructed at regular intervals between the maximum and minimum data values. The number of data points within each bin is called the frequency. The relative frequency is the fractional amount of data points within each bin in relation to the total number of data points. Examining the frequency of past events furnishes an idea of the frequency of future events, assuming that the conditions that affect the frequency distribution remain steady.

If the number of bins in the histogram is increased to infinity the frequency curve approaches a smooth distribution of the data. Many distributions of data are possible. A common distribution is the normal distribution. According to Yevjevich, four conditions are necessary for a data variable to have a normal probability distribution:

1. A very large number of causative factors affect the outcome of variable values;

2. Each factor taken separately has a relatively small influence on the outcome;
3. The effect of each factor is independent of the effects of all other factors;
4. The effects of the various is additive.

Typically, in comparison with the normal distribution, the distribution for annual rainfall data is generally a better fit than that for monthly rainfall data. The fit with distributions of daily data is generally not very good (Yevjevich, 1972).

The normal distribution curve can be expressed mathematically as:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

where: x is a data point

σ is the spread of the data distribution (standard deviation)

μ is the center of the data distribution (mean)

The normal distribution curve is symmetrically distributed about the mean. The skew, therefore is zero.

Thus, the purpose of the frequency analysis is to compare the monthly historical data to a standard distribution to better describe the data set. An example of the histogram developed in the frequency analysis is illustrated using the December data for the area above Chattanooga and is shown in Figure 3.5. For this analysis, the number of bins

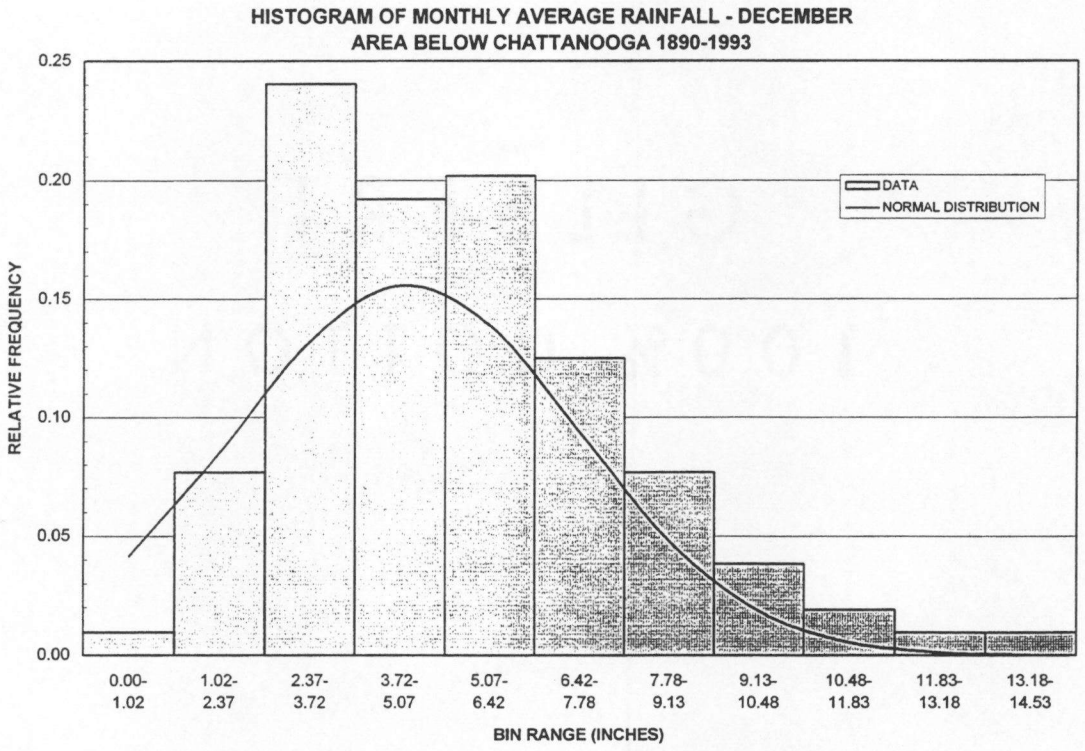


Figure 3.5. Example of Histogram Developed in Frequency Analysis.

and the range of values within each bin (bin range) was determined by using the default selection from the *Excel* application. The results of the analysis indicate the monthly historical data is essentially normally distributed. In examination of the histograms, a slight degree of skewness (assymmetry) seems to be evident in the distributions for some months. Descriptive statistical data for each of the major watersheds was computed and includes monthly maximum, minimum, range, median, mean, standard deviation, and variation (coefficient of variation, expressed as a percentage). Range is merely the

difference between the maximum and minimum. The mean and median are measures of central tendency. These are centrally located values about which the other values are clustered. The degree of dispersion of the data is indicated by the standard deviation and the coefficient of variation (Yevjevich, 1972).

Tables 3-1 and 3-2 summarize the descriptive statistical data. In inspecting the data, the median value for each month is less than the mean. This indicates a positive degree of skewness (the curve is shifted to the left). Also, the variation is largest (indicating a higher degree of relative variation) in September, October, and November. This is possibly due to the frequency of extra-tropical cyclone activity during this period (refer to Floods and Flood Control, TVA 1961). The number of data observations within plus or minus one standard deviation of the mean is indicated additionally. For the normal distribution, the percentage of data within plus or minus one standard deviation of the mean is about 68 percent (Kume, 1985). An examination of the descriptive statistics indicates the percentage of data for most of the months falls within this range. A normal distribution of the rainfall data is therefore used for this study. Additional analysis results are found in the Appendix as A.36 through A.59.

The *Excel* application also was used to compute percentile values for the historical data frequency distribution. A percentile is a statistical term used to describe any one of the

Table 3-1. Descriptive Statistics for Assumed Normally Distributed Historical Rainfall Data (1890-1993). Area Above Chattanooga.

N=104 Years	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MAXIMUM	10.32	9.69	11.40	7.49	8.19	8.67	11.07	13.33	7.69	8.37	10.30	9.98
MINIMUM	1.29	0.85	1.20	0.95	0.80	1.03	1.87	1.25	0.48	0.04	0.44	0.54
RANGE	9.03	8.84	10.20	6.54	7.39	7.64	9.20	12.08	7.21	8.33	9.86	9.44
MODE	3.89	2.87	5.80	5.24	6.53	3.55	4.56	3.83	2.61	2.48	4.62	3.77
MEDIAN	3.96	4.41	4.91	4.04	3.96	4.27	4.79	4.09	3.26	2.65	3.36	4.20
MEAN	4.49	4.56	5.25	4.08	4.17	4.27	5.04	4.32	3.36	2.97	3.47	4.55
STANDARD DEVIATION	1.93	1.95	2.15	1.46	1.53	1.43	1.67	1.66	1.60	1.64	1.69	2.04
VARIATION (%)	43.0	42.8	41.0	35.7	36.7	33.5	33.2	38.3	47.8	55.3	48.7	44.8
MEAN-1SD	2.56	2.61	3.10	2.62	2.64	2.84	3.37	2.66	1.75	1.33	1.78	2.51
MEAN+1SD	6.42	6.51	7.41	5.54	5.71	5.70	6.72	5.98	4.96	4.62	5.16	6.60
NO. OF POINTS W/IN ± 1 SD	71	74	75	73	72	78	78	80	70	72	75	72
%	68.3	71.2	72.1	70.2	69.2	75.0	75.0	76.9	67.3	69.2	72.1	69.2

Units in inches, except as noted.

Table 3-2. Descriptive Statistics for Assumed Normally Distributed Historical Rainfall Data (1890-1993). Area Below Chattanooga.

N=104Years	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MAXIMUM	13.94	11.31	13.49	12.19	11.13	11.87	8.94	10.18	8.83	8.65	12.15	14.53
MINIMUM	0.78	0.98	0.91	0.75	0.71	0.35	1.61	0.89	0.19	0.04	1.04	1.02
RANGE	13.16	10.33	12.58	11.44	10.42	11.52	7.33	9.29	8.64	8.61	11.11	13.51
MODE	6.31	3.68	4.57	3.61	3.86	3.28	4.33	2.99	3.69	2.80	2.15	4.46
MEDIAN	4.46	4.41	5.54	4.44	4.25	3.69	4.19	3.40	3.09	2.60	3.94	4.84
MEAN	5.03	4.85	5.79	4.68	4.37	3.85	4.37	3.65	3.31	2.92	4.10	5.19
STANDARD DEVIATION	2.51	2.30	2.58	2.11	1.95	1.76	1.62	1.63	1.72	1.79	2.12	2.56
VARIATION (%)	49.8	47.4	44.6	45.1	44.7	45.6	37.1	44.7	52.0	61.5	51.8	49.3
MEAN-1SD	2.52	2.55	3.21	2.57	2.42	2.09	2.75	2.02	1.59	1.12	1.98	2.63
MEAN+1SD	7.54	7.15	8.37	6.79	6.33	5.61	5.99	5.28	5.04	4.71	6.22	7.75
NO. OF POINTS W/IN ± 1 SD	76	73	68	77	73	79	68	74	75	74	76	77
%	73.1	70.2	65.4	74.0	70.2	76.0	65.4	71.2	72.1	71.2	73.1	74.0

Units in inches, except as noted.

values in a series that divides a distribution of data into 100 groups of equal frequency. The percentile corresponds to the percentage of the data which is less than the applicable data value. These values were used in the development of historical precipitation forecast values in the QPF analysis which follows in the next section. Percentile values are tabulated in the Appendix as A.8 and A.9.

Description of the QPF Forecast Analysis

A series of historical forecast values, each based upon a value derived from a historical data percentile, was developed and arranged in a format to match the observed-forecast data. The study included the 10, 30, 50, 70, and 90 percentiles of the historical data. These particular percentile values were arbitrarily chosen to give an indication of the relative position of the observed and vendor forecast values with respect to the historical record. Formatting the data involved taking the monthly percentile values and dividing them by the number of days in each month. This figure represents an average daily value. A value for each of the forecast periods, days 1 through 5, days 6 through 10, and days 1 through 10, was then computed for each of the 5 percentiles. This involved taking the daily value from each percentile and multiplying it by the number of days in each forecast period. A comparison to the corresponding observed and vendor forecast values for a particular forecast date was then made for each forecast period. The entire 27-month period was examined for each of the 5 QPF forecast sub-basins.

Two aspects of the forecast were examined: a cumulative volume of precipitation for the forecast period, and the residuals, the difference between the observed and what was forecast. The cumulative forecast volume involved summing each value for each forecast period for each QPF sub-basin. This is not the true volume of rainfall which was actually recorded, but the value does give a relative indication of the volumetric amounts for the observed precipitation values versus the forecast precipitation values (1 vendor value and 5 historical values based on the percentiles).

The residual value, which may be positive or negative, is merely the forecast value (vendor or historical) for a particular forecast period subtracted from the corresponding observed value. The residual for the historical forecast was taken from the percentile which was the closest match to the observed from the cumulative volume analysis. These residuals were plotted over time to examine them for trends. An approach similar to the one used earlier in the analysis of the historical data is also utilized here. The data is smoothed using a series of successively applied moving averages. Selection of the periods for the averaging and the number of smoothing applications was again iteratively determined. Ultimately, a 60-day moving average was chosen for the initial smooth with smoothes of 10, 4, and 2-day periods successively applied.

CHAPTER 4

SUMMARY OF QPF ANALYSIS RESULTS

4.1 Results of Cumulative Volume Analysis

Comparison of the observed and vendor cumulative volume curves reveals consistent trends in the short-term forecast (1 to 5-day forecast period) and the long-term forecasts (6 to 10 day forecast period). The trends in the cumulative volume curves indicate that:

- The vendor forecasts about 90 percent of the observed volume for the short-term period for the Valley as a whole;
- The vendor under-forecasts the QPF, especially in the long-term forecast period;
- The vendor forecasts for the short-term period corresponded to slightly higher than the 30^{th} percentile of the historical data;
- The vendor forecasts for the long-term period corresponded to less than the 10^{th} percentile of the historical data.

Graphical representations of the analysis are included in the Appendix as A.60 through A.74. An example of a 1 to 5-day, short-term forecast period comparison for the Central QPF Area is shown in Figure 4.1.

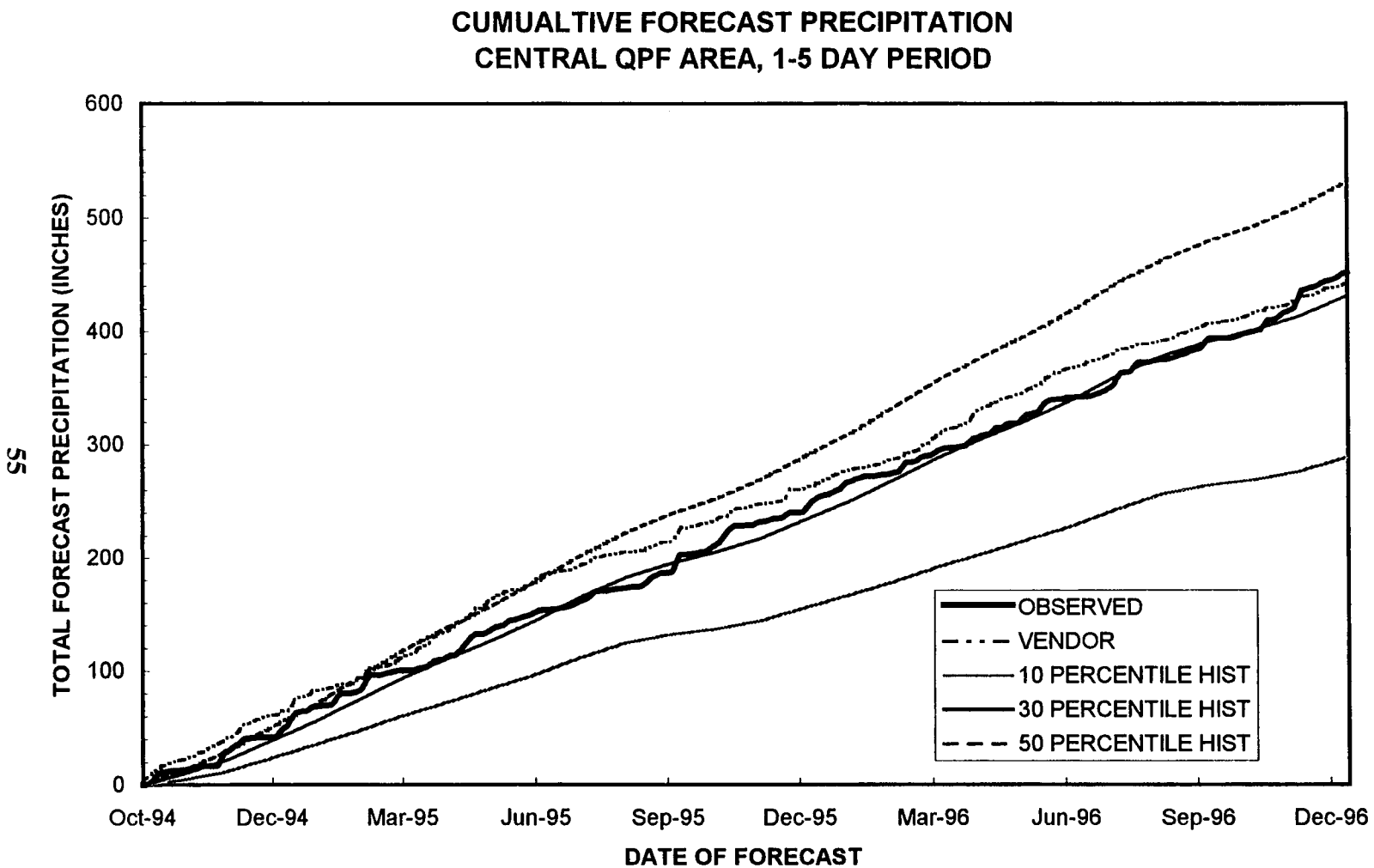


Figure 4.1 Example of Cumulative Volume Comparison Graph.

The cumulative volumes for the area above Chattanooga indicate that the vendor averages about 94 percent of the observed volume for the forecast period. This percentage corresponds to a historical percentile of about 35. Values for the individual QPF sub-basins ranged from a low of 93 percent (East and Northeast) to a high of 98 percent (Central). A notable feature of the volumes for the area below Chattanooga was that only 86 percent of the volume was forecast by the vendor. A figure of 91 percent was determined for the Northwest QPF. In particular, for the Southwest QPF area, the vendor projected only 83 percent of the observed volume.

Results of the cumulative volume analysis for the long-term forecast period indicated a marked tendency by the vendor to under-forecast rainfall for this period. This was the case for each of the 5 QPF sub-basins. Only about 50 percent of the observed volume was predicted by the vendor. This figure represents less than the 10^{th} percentile of the historical record. The same characteristics are seen here as with the short-term forecast, namely the highest percentage (57) overall in the Central QPF (for the area above Chattanooga), and the lowest percentage (50) overall in the Southwest QPF (for the area below Chattanooga).

For the total 10-day forecast period, the vendor averages about 72 percent of the observed volume for the forecast period which is approximately the 20^{th} percentile of the historical data. Higher percentages were again observed in the Central QPF and lower

percentages in the Southwest. Results of the cumulative volume analysis are summarized in Table 4-1.

4.2 Results of Residual Trend Analysis

In the results of the analysis of residuals, similar trends are noted as with the cumulative volume analysis but with a few exceptions. A positive value for the residual indicates an under-forecast and a negative value indicates an over-forecast. The trend for the short-term forecast is generally along the line of zero residual for the smoothed curve in each of the 5 QPF areas. Trends for the long-term forecast exhibit the vendor's tendency to under-forecast precipitation for this period. Table 4-2 is a summary of the results of the residual trend analysis.

Examination of residual maxima and minima indicate a 4 to 6-inch range of variation (about 2 ½ to 3 standard deviations) for the vendor in the short term forecast compared to a 3 to 5-inch range (about 2 to 2 ½ standard deviations) for the historical forecasts. Average residual is computed as the square root of the sum of the squares of the residuals (positive and negative) divided by the total number of observations. These residual values support earlier indications from the cumulative volume analysis. Larger residual values are experienced in the East and Northeast QPF sub-basins (where lower percentages of the cumulative volumes were noted) for the area above Chattanooga.

Table 4-1. Cumulative Forecast Volume Summary.

QPF AREA	Drainage Area (Sq. Mi.)[1]	% OF OBSERVED VOLUME Historical Percentile					
		VENDOR	10	30	50	70	90
1-5 DAY PERIOD							
CENTRAL	6,081	98	64	95	118	145	192
EAST	8,753	93	57	86	106	130	172
NORTHEAST	6,340	93	61	91	112	138	183
NORTHWEST	7,380	91	60	92	119	150	208
SOUTHWEST	11,646	83	49	74	96	121	168
ABOVE CHATTANOOGA	21,174	94	60	90	111	137	181
BELOW CHATTANOOGA	19,026	86	53	81	105	132	184
BASIN	40,200	90	57	86	108	135	182
6-10 DAY PERIOD							
CENTRAL	6,081	57	64	96	118	146	192
EAST	8,753	53	57	86	106	130	172
NORTHEAST	6,340	52	61	91	112	138	182
NORTHWEST	7,380	55	61	92	120	151	209
SOUTHWEST	11,646	50	49	74	96	121	168
ABOVE CHATTANOOGA	21,174	54	60	90	111	137	181
BELOW CHATTANOOGA	19,026	52	54	81	105	133	184
BASIN	40,200	53	57	86	108	135	182
1-10 DAY PERIOD							
CENTRAL	6,081	77	64	96	118	145	192
EAST	8,753	73	57	86	106	130	172
NORTHEAST	6,340	73	61	91	112	138	182
NORTHWEST	7,380	73	61	92	120	150	208
SOUTHWEST	11,646	67	49	74	96	121	168
ABOVE CHATTANOOGA	21,174	74	60	90	111	137	181
BELOW CHATTANOOGA	19,026	69	54	81	105	132	184
BASIN	40,200	72	57	86	108	135	182

1. Drainage area above Chickamauga Dam is used for area above Chattanooga. Figure includes 384 sq. mi. in Central QPF Area that is actually below Chattanooga. Total basin drainage area is area above Kentucky Dam.

Table 4-2. Summary of Residual Trend Analysis.

QPF AREA	VENDOR FORECAST PERIOD			BEST HISTORICAL FORECAST PERIOD		
	SHORT TERM	LONG TERM	FULL TERM	SHORT TERM	LONG TERM	FULL TERM
CENTRAL	NONE	UNDER	**UNDER**	NONE	NONE	UNDER
EAST	UNDER	UNDER	UNDER	NONE	NONE	NONE
NORTHEAST	**NONE-UNDER**	**UNDER**	**UNDER**	NONE-UNDER	UNDER	NONE-UNDER
NORTHEWEST	**NONE-UNDER**	UNDER	UNDER	NONE-UNDER	NONE-UNDER	NONE-UNDER
SOUTHWEST	**UNDER**	UNDER	**UNDER**	UNDER	NONE-UNDER	NONE-UNDER

Key:
Under = General trend is to under-forecast
None = No general trend.
None-Under = Varying trend.
A bold underline signifies a greater trend where entries are the same for corresponding periods.

Additionally, residual values for the Southwest QPF sub-basin experience the largest values of any of the 5 sub-basins (also in concurrence with the results of the cumulative volume analysis). Not suprisingly, the residual increases the farther the forecast is into the future. Similar characteristics are noted for the long-term and full forecast periods as with the short-term forecast period. Relative to the residuals, the best historical forecast (from the cumulative volume analysis) has less or equal values as the vendor forecast. A summary of the residual analysis is shown in Table 4-3.

Table 4-3. Summary of Forecast Residuals.

	MAX	MIN	RANGE	AVE	MAX	MIN	RANGE	AVE	MAX	MIN	RANGE	AVE
1-5 DAY PERIOD												
	VENDOR				**10 PERCENTILE HISTORICAL**				**30 PERCENTILE HISTORICAL**			
CENTRAL	3.1	-2.9	6.0	0.57	3.0	-0.5	3.5	0.65	2.9	-0.7	3.6	0.62
EAST	3.4	-4.4	7.8	0.67	4.0	-0.5	4.5	0.73	3.9	-0.7	4.6	0.69
NORTHEAST	3.0	-4.0	7.0	0.65	3.1	-0.5	3.6	0.65	3.0	-0.7	3.7	0.62
NORTHWEST	2.1	-1.9	4.0	0.55	2.7	-0.4	3.1	0.65	2.4	-0.7	3.1	0.62
SOUTHWEST	3.4	-3.2	6.6	0.73	4.7	-0.4	5.1	0.89	4.5	-0.7	5.2	0.84
	50 PERCENTILE HISTORICAL				**70 PERCENTILE HISTORICAL**				**90 PERCENTILE HISTORICAL**			
CENTRAL	2.8	-0.8	3.6	0.63	2.7	-1.0	3.7	0.67	2.3	-1.3	3.6	0.80
EAST	3.8	-0.8	4.6	0.69	3.7	-1.0	4.7	0.71	3.3	-1.3	4.6	0.82
NORTHEAST	2.9	-0.8	3.7	0.62	2.6	-1.0	3.6	0.66	2.4	-1.3	3.7	0.78
NORTHWEST	2.2	-0.9	3.1	0.63	2.0	-1.1	3.1	0.68	1.7	-1.5	3.2	0.88
SOUTHWEST	4.4	-0.9	5.3	0.82	4.2	-1.1	5.3	0.84	3.9	-1.5	5.4	0.95
6-10 DAY PERIOD												
	VENDOR				**10 PERCENTILE HISTORICAL**				**30 PERCENTILE HISTORICAL**			
CENTRAL	2.9	-1.1	4.0	0.68	3.0	-0.5	3.5	0.64	2.9	-0.7	3.6	0.62
EAST	3.9	-1.1	5.0	0.76	4.0	-0.5	4.5	0.73	3.9	-0.7	4.6	0.69
NORTHEAST	3.3	-1.0	4.3	0.69	3.1	-0.5	3.6	0.66	3.0	-0.7	3.7	0.62
NORTHWEST	2.9	-1.4	4.3	0.69	2.9	-0.4	3.3	0.65	2.6	-0.7	3.3	0.62
SOUTHWEST	4.5	-1.3	5.8	0.91	4.7	-0.4	5.1	0.89	4.5	-0.7	5.2	0.84
	50 PERCENTILE HISTORICAL				**70 PERCENTILE HISTORICAL**				**90 PERCENTILE HISTORICAL**			
CENTRAL	2.8	-0.8	3.6	0.63	2.7	-1.0	3.7	0.67	2.3	-1.3	3.6	0.80
EAST	3.8	-0.8	4.6	0.69	3.7	-1.0	4.7	0.71	3.3	-1.3	4.6	0.82
NORTHEAST	2.9	-0.8	3.7	0.62	2.6	-1.0	3.6	0.66	2.4	-1.3	3.7	0.78
NORTHWEST	2.4	-0.9	3.3	0.65	2.2	-1.1	3.3	0.69	1.9	-1.5	3.4	0.88
SOUTHWEST	4.4	-0.9	5.3	0.82	4.2	-1.1	5.3	0.84	3.9	-1.5	5.4	0.95
1-10 DAY PERIOD												
	VENDOR				**10 PERCENTILE HISTORICAL**				**30 PERCENTILE HISTORICAL**			
CENTRAL	3.0	-2.8	5.8	0.92	3.4	-0.9	4.3	0.95	3.1	-1.3	4.4	0.88
EAST	4.6	-4.6	9.2	1.06	4.4	-1.0	5.4	1.08	4.1	-1.4	5.5	0.97
NORTHEAST	3.8	-3.4	7.2	1.01	3.9	-0.9	4.8	0.97	3.6	-1.3	4.9	0.88
NORTHWEST	3.0	-2.0	5.0	0.91	3.1	-0.9	4.0	0.96	2.7	-1.4	4.1	0.88
SOUTHWEST	4.3	-2.3	6.6	1.23	4.5	-0.9	5.4	1.35	4.2	-1.4	5.6	1.20
	50 PERCENTILE HISTORICAL				**70 PERCENTILE HISTORICAL**				**90 PERCENTILE HISTORICAL**			
CENTRAL	2.8	-1.6	4.4	0.90	2.5	-1.9	4.4	1.01	2.0	-2.5	4.5	1.34
EAST	3.9	-1.6	5.5	0.96	3.5	-1.9	5.4	1.03	2.9	-2.6	5.5	1.30
NORTHEAST	3.4	-1.6	5.0	1.01	3.0	-1.9	4.9	0.97	2.4	-2.6	5.0	1.30
NORTHWEST	2.5	-1.8	4.3	0.91	2.2	-2.1	4.3	1.06	1.7	-3.0	4.7	1.52
SOUTHWEST	4.0	-1.8	5.8	1.15	3.7	-2.1	5.8	1.20	3.0	-3.0	6.0	1.50

Values in inches.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Because of extensive use of the computer forecast models and the current level of technology with these models, vendor forecast results were anticipated to be better for the short-term forecast than for the long-term. Due to the complexity of the atmosphere and weather systems, model forecast performance decreases dramatically beyond the first 36 to 48 hours. In the cumulative volume analysis, the slightly lower values for the East and Northeast as compared to the Central and Northwest, are attributed to the possible orographic effects of the eastern mountains which are difficult to model. Inclusion of the precipitation data from the Cumberland River Basin for the vendor forecast in the Central QPF could also affect the comparison to the historical percentile.

Considering the results of the cumulative volume and residual analyses, the vendor forecasts for the long-term forecasting period demonstrate a large tendency for under-forecasting expected precipitation in each of the 5 QPF sub-basins. A forecast with the 30 percentile historical values for the Central, Northeast, and Northwest QPF areas and the 50 percentile for the East and Southwest QPF areas gives superior results in terms of forecast volume of expected precipitation as compared to the vendor forecast. The

vendor forecasts for the long term period are not even within one standard deviation of the mean historical value (16^{th} percentile). Also, the marked difference in the Southwest QPF area indicates the possibility of unusual or special circumstances in regard to the QPF forecast for this area. Several possible causes for this deviation are offered in the following discussion.

The vendor uses TVA rain gage data in calibration of their forecast models. The difference in rain gage density for this region relative to the other regions could explain this variation for the summer months due to the localized convective nature of summer storm events. Another possible cause could be that the intensity of storms is higher in this region and thus more difficult to forecast. Examination of Weather Bureau Reports (Hershfield, 1961) indicates rainfall intensities in this area are generally higher for all durations and frequencies than in the other areas of the Valley (except the eastern mountains).

As evidenced from the variation as presented in Tables 3-1 and 3-2, the relative variability of the monthly rainfall data is greater for the area below Chattanooga than the area above Chattanooga. Furthermore, during the year 1995, two extra-tropical storm systems moved through this region. The remnants of *Erin* (July 31 through August 6) and *Opal* (September 27 through October 6) each could have affected vendor forecast projections.

5.2 Recommendations

Based on the results and conclusions reached earlier, recommended actions are proposed in light of this study. The first recommendation is to perform case studies of reservoir inflow forecasts based on use of the historical values. Use the historical values in the QPF forecasts or adjust the vendor forecast upward (or downward, if need be) by some factor. Which historical forecast to use or the degree of adjustment to the vendor forecast would depend upon current weather conditions and persistence of recent past weather patterns. Either the vendor or TVA could incorporate the data into the forecasts. Develop reservoir inflow forecasts and operating plans based on both the adjusted QPF and the unadjusted vendor QPF. Perform parallel reservoir inflow forecast runs to compare the results.

As the second recommended action, conduct additional studies for certain periods of the year to determine if any seasonal or other trends exist based upon that particular time of the year. Some possible seasonal trends were noted in the examination of the monthly historical data. Examine weather patterns during these periods to determine the type of storm system (frontal, convective, or extra-tropical) which was associated with the rainfall.

Other recommended actions include repeating this study as more precipitation data becomes available. At the time of writing, collection and maintenance of this data is

ongoing by TVA. Additionally, further study of the Southwest QPF area is needed to determine the cause of the variation of the vendor forecast for this area as compared to the other QPF forecast areas.

Finally, the vendor should be consulted with the results of this study. In light of the cumulative volume and residual analyses, some adjustments to the vendor's precipitation forecast models are necessary for the short-term forecast. The vendor should also be shown the results for the Southwest QPF area for both the short and long-term forecasts.

Through implementation of the above actions, it is hoped that the result will be a more effective precipitation forecast. This will in turn provide a better reservoir inflow forecast and thus allow the reservoir system to be operated in an efficient and cost-effective manner. A manner which encompasses all of TVA's multipurpose objectives and maximizes the benefits received from each objective.

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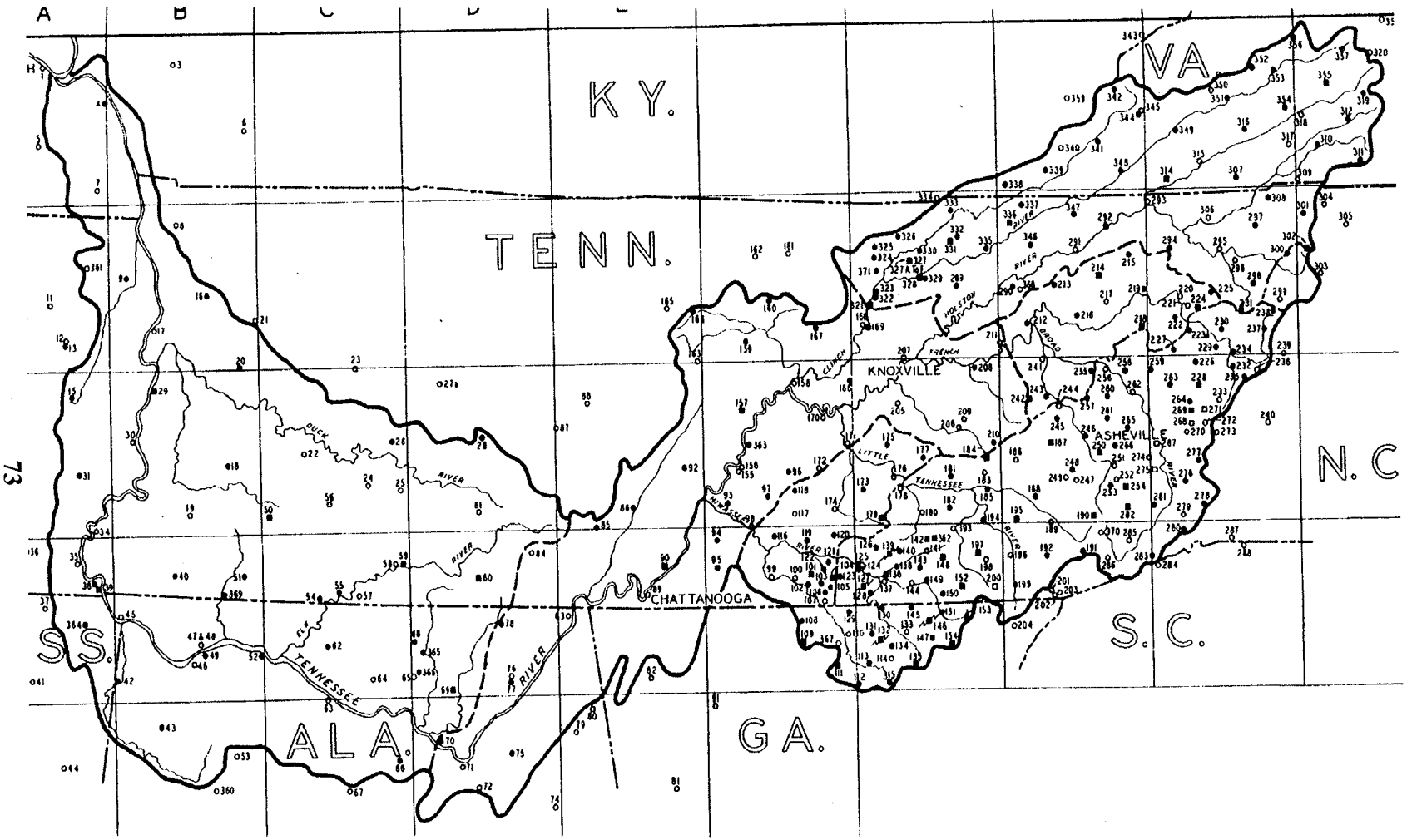
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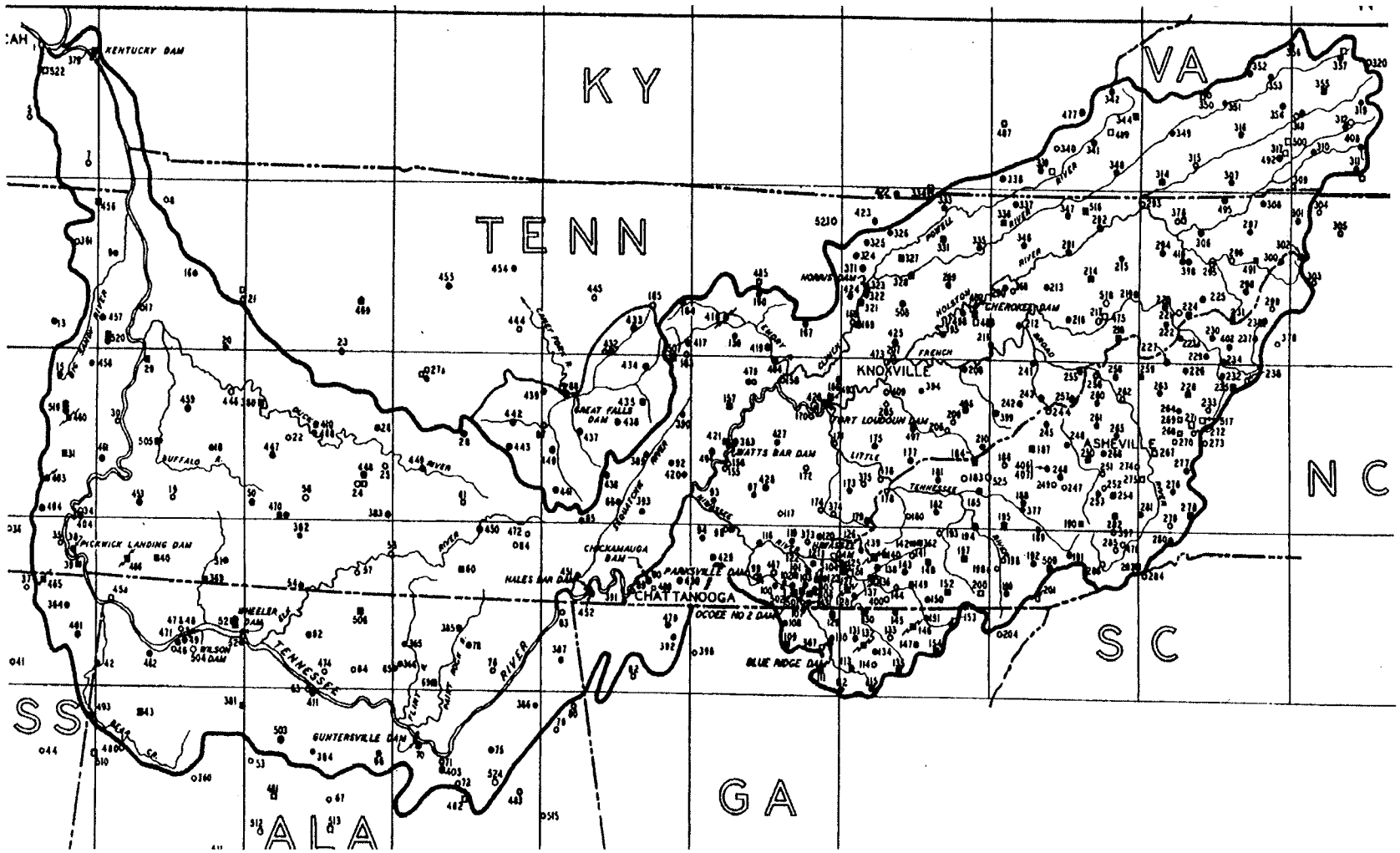
APPENDIX

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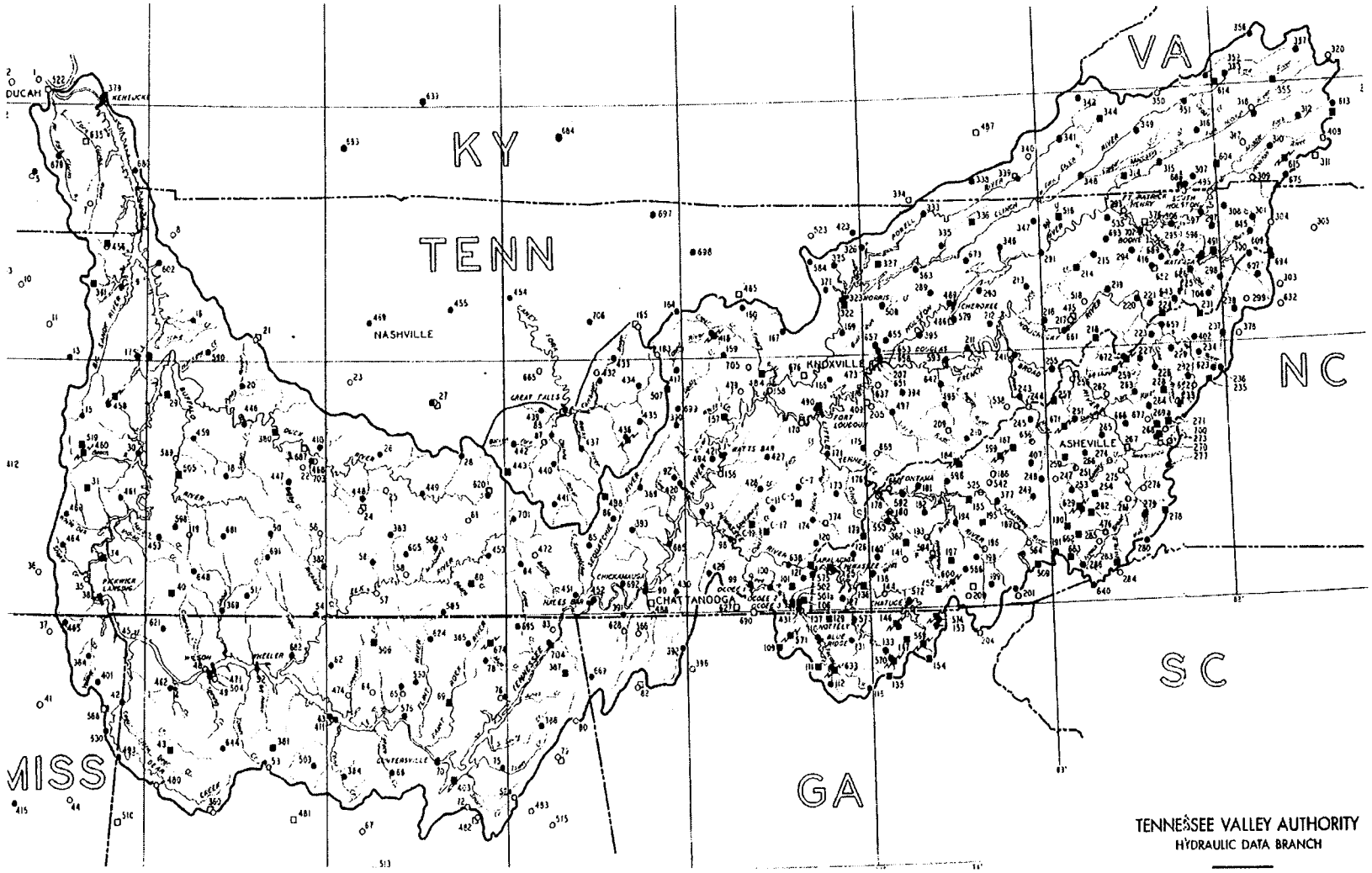
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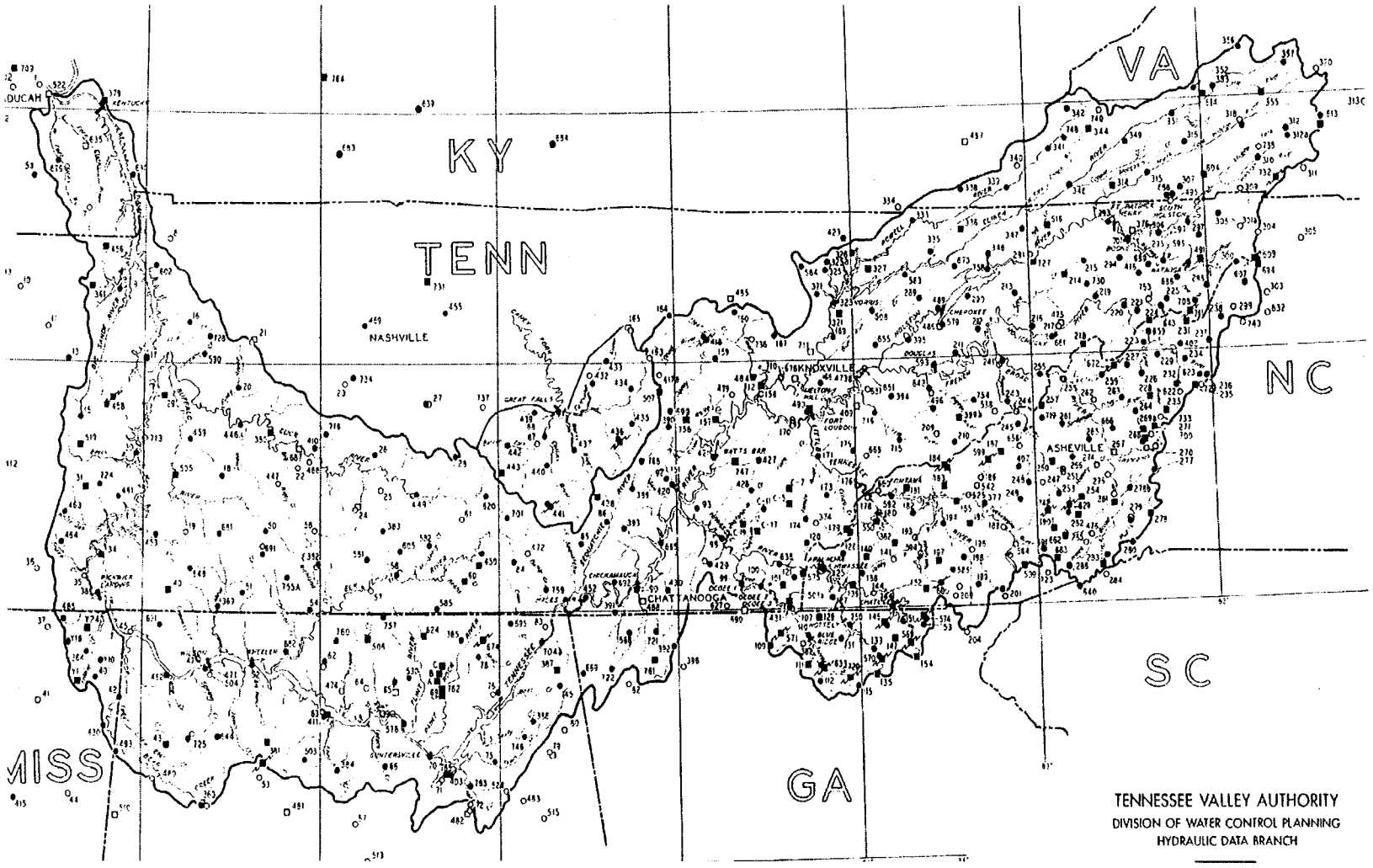
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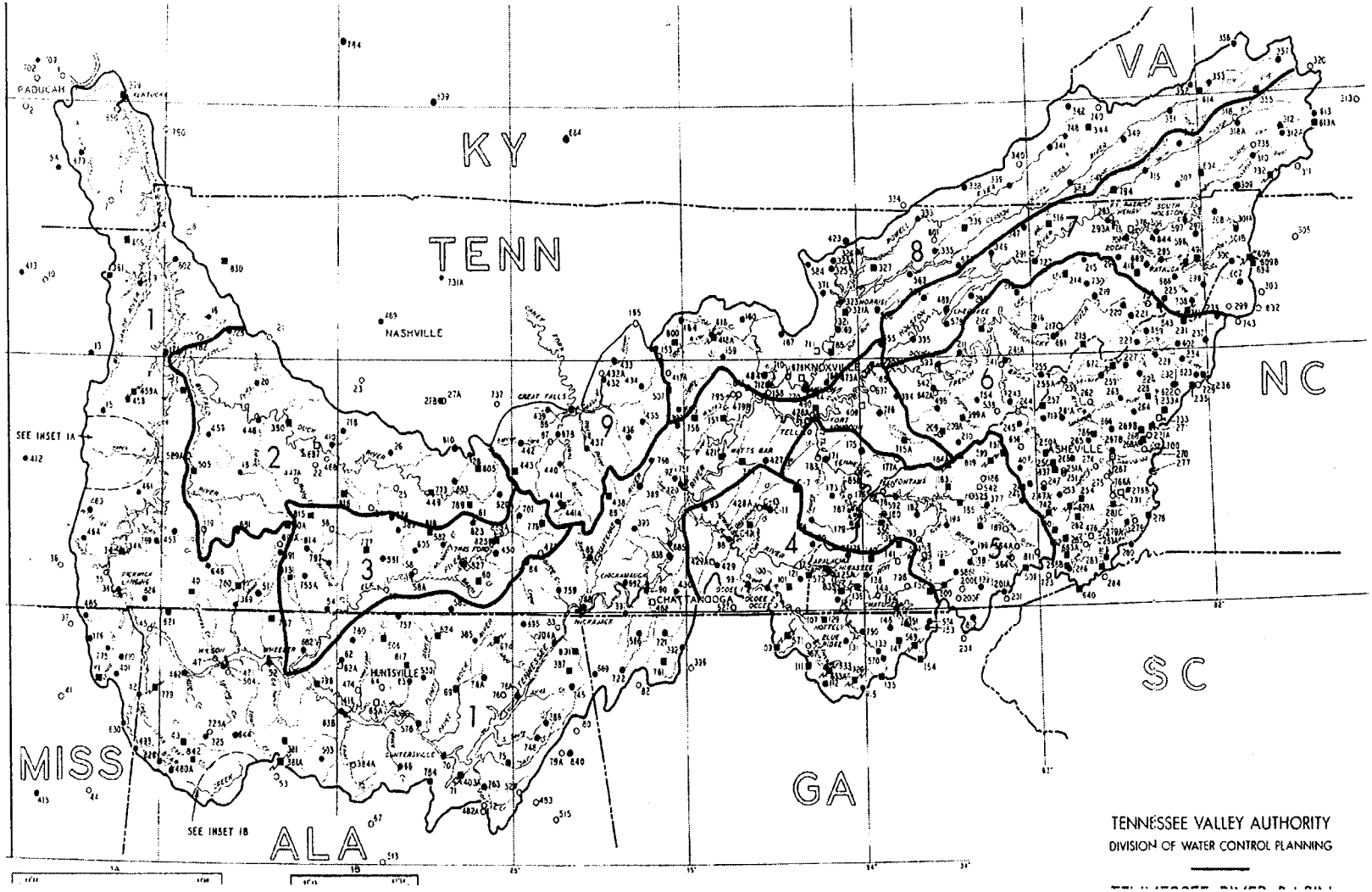
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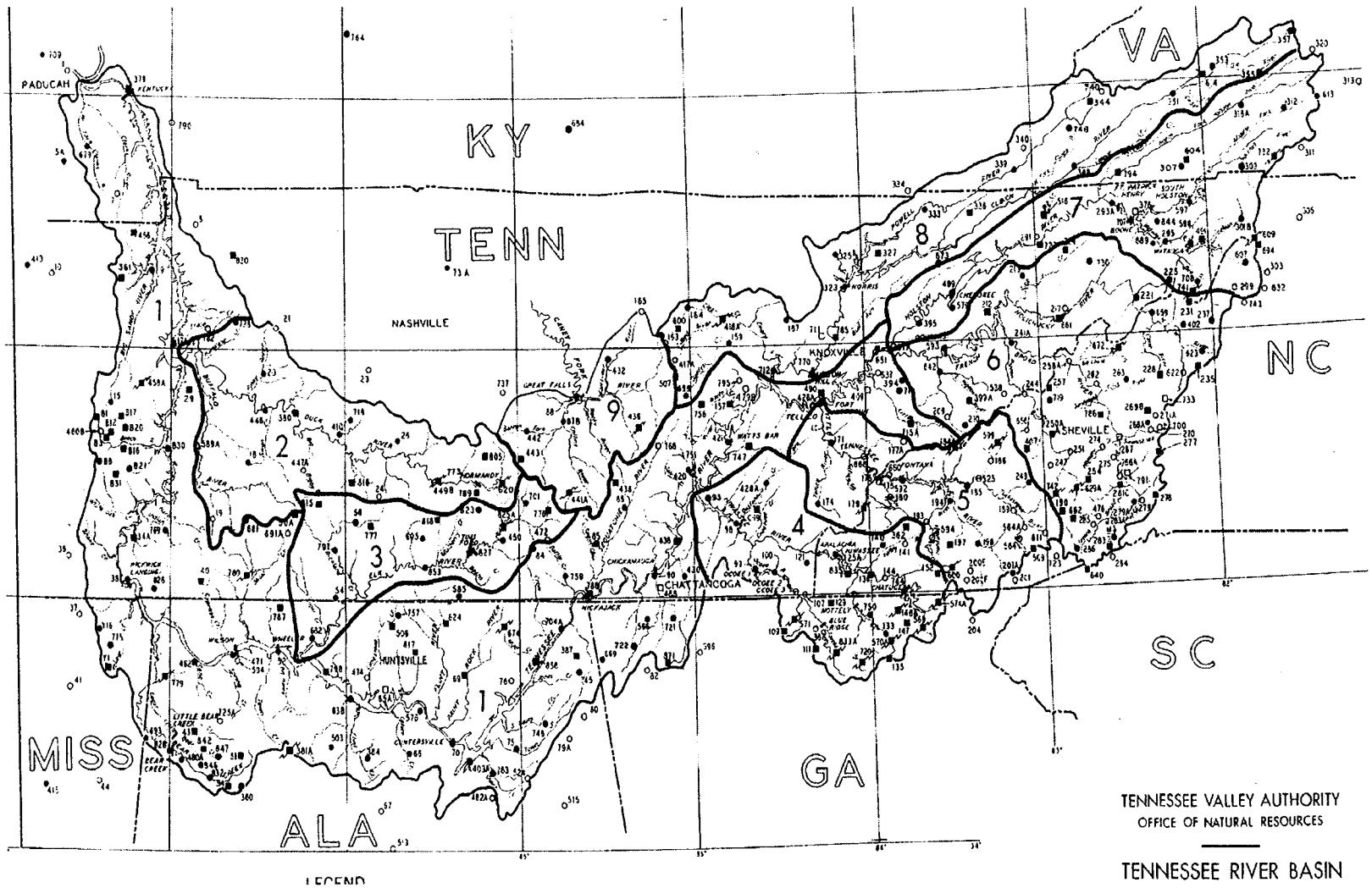
A.3. TVA Rain Gage Distribution - 1950.



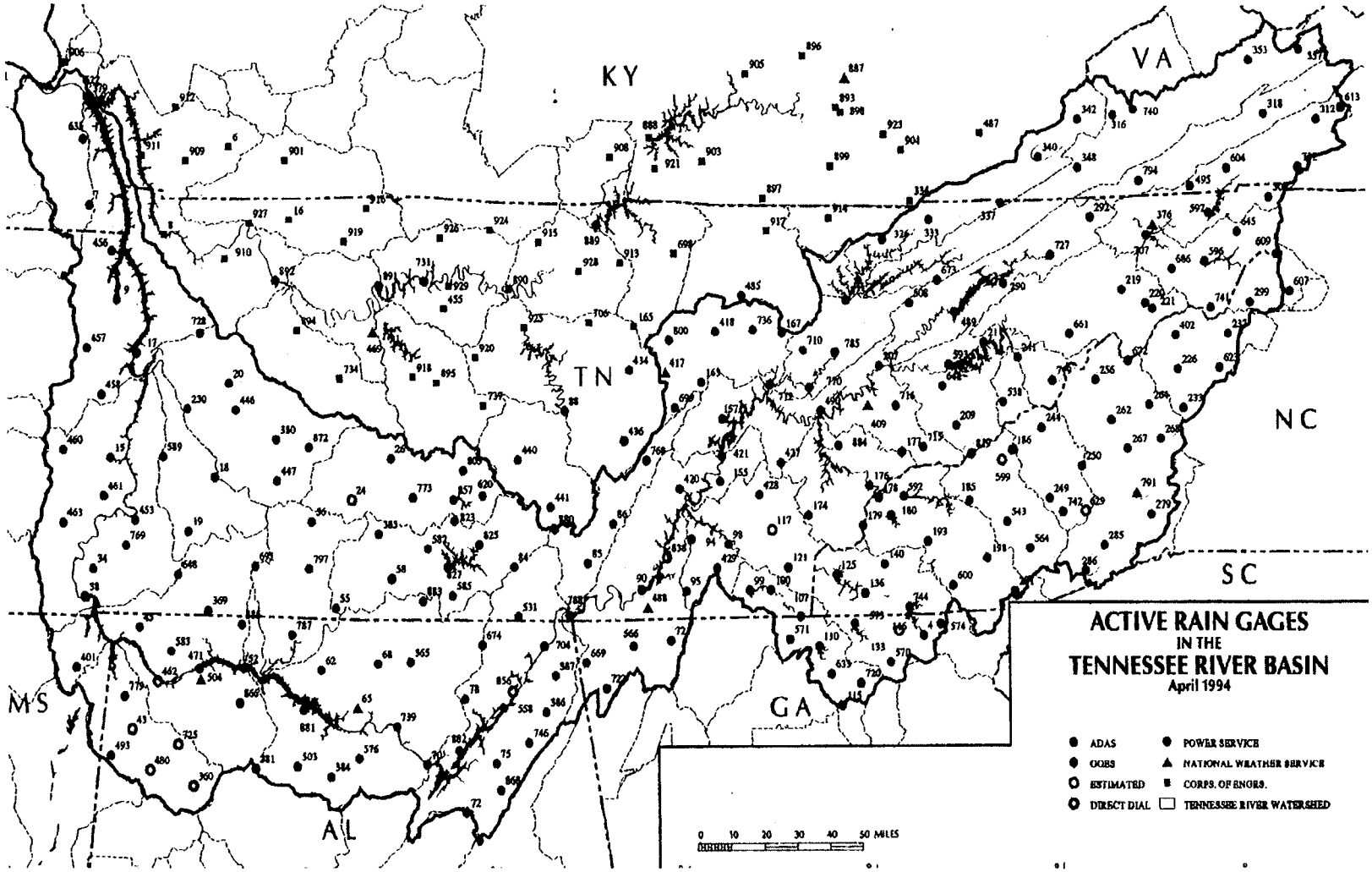
A.4. TVA Rain Gage Distribution - 1960.



A.5. TVA Rain Gage Distribution - 1970.



A.6. TVA Rain Gage Distribution - 1980.



A.7. TVA Rain Gage Distribution - 1994.

A-8. Percentiles for Monthly Historical Precipitation Data (1890-1993). Area Above Chattanooga.

PERCENTILES

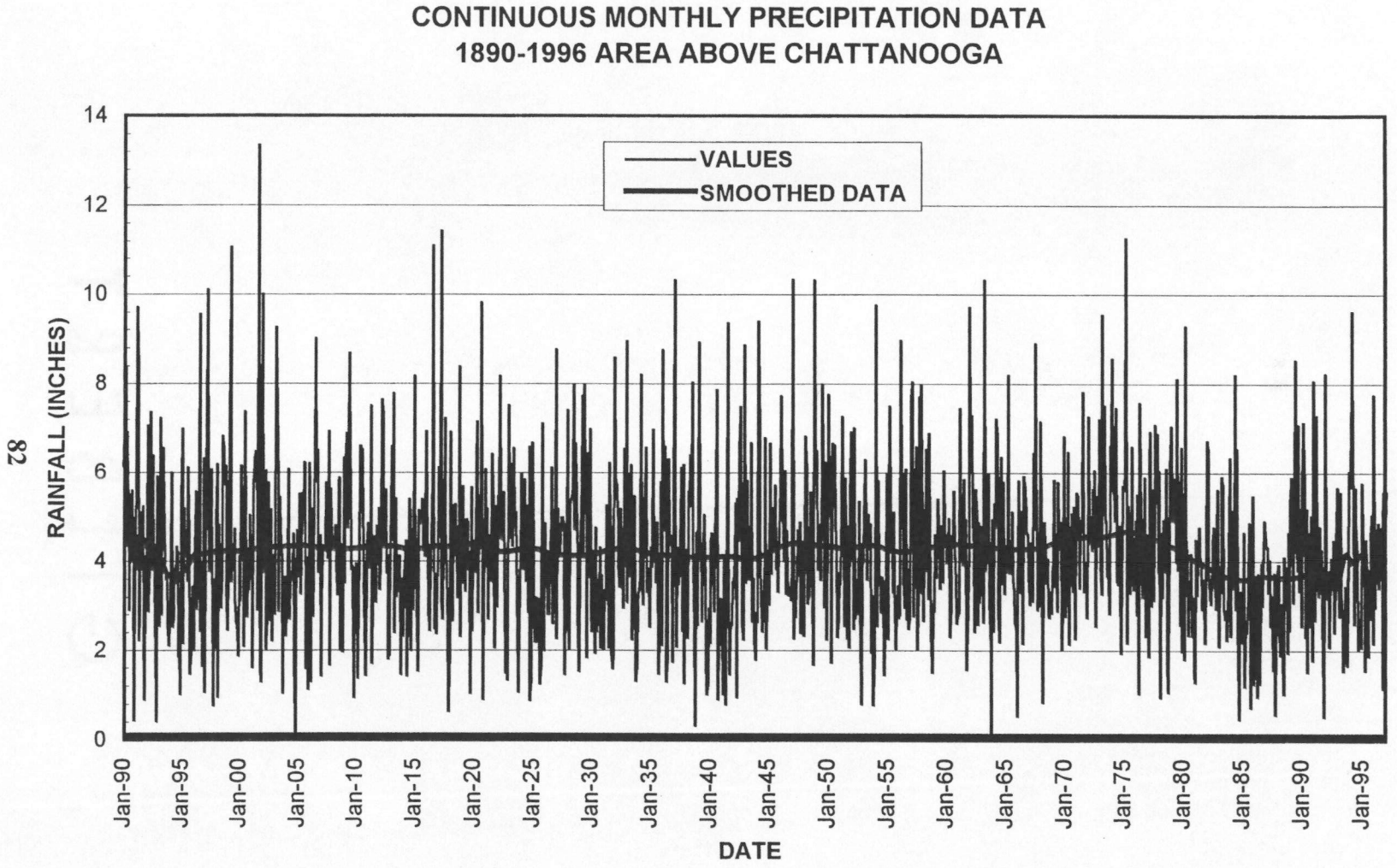
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	1.29	0.85	1.20	0.95	0.80	1.03	1.89	1.25	0.48	0.04	0.44	0.54
5	2.10	1.64	2.23	1.95	2.10	2.07	2.70	2.28	1.10	0.61	1.23	1.75
10	2.36	2.22	2.78	2.30	2.53	2.42	2.97	2.68	1.46	0.94	1.44	2.32
15	2.59	2.64	3.29	2.69	2.71	2.91	3.51	2.90	1.57	1.48	1.78	2.54
20	2.79	2.84	3.51	2.88	2.86	3.16	3.70	3.13	1.95	1.68	2.02	2.77
25	3.01	3.41	3.72	3.11	3.01	3.30	3.93	3.29	2.24	2.00	2.26	3.02
30	3.34	3.59	4.01	3.32	3.28	3.53	4.27	3.49	2.44	2.07	2.38	3.39
35	3.54	3.77	4.34	3.43	3.48	3.57	4.48	3.64	2.61	2.15	2.57	3.60
40	3.78	3.87	4.52	3.64	3.59	3.90	4.58	3.80	2.89	2.41	2.85	3.73
45	3.89	4.21	4.63	3.80	3.74	4.08	4.68	3.84	3.03	2.50	3.18	3.88
50	3.96	4.43	4.93	4.05	3.94	4.27	4.83	4.08	3.28	2.63	3.34	4.23
55	4.35	4.52	5.21	4.21	4.14	4.54	4.95	4.19	3.47	2.95	3.62	4.45
60	4.67	4.70	5.46	4.30	4.33	4.71	5.09	4.54	3.60	3.08	3.82	4.68
65	4.97	5.11	5.54	4.45	4.73	4.83	5.37	4.75	3.72	3.25	3.94	5.07
70	5.28	5.44	5.98	4.79	4.91	4.98	5.54	4.85	3.86	3.36	4.30	5.60
75	5.57	5.76	6.29	4.93	5.18	5.18	5.97	4.99	4.10	3.83	4.59	5.95
80	5.98	5.96	6.97	5.24	5.44	5.41	6.14	5.39	4.28	4.32	4.63	6.27
85	6.53	6.45	7.45	5.63	5.72	5.58	6.52	5.64	5.01	4.65	4.98	6.74
90	7.01	7.18	8.08	6.05	6.44	5.76	6.85	6.09	5.74	5.41	5.55	7.33
95	7.75	8.32	9.48	6.83	6.64	6.28	8.08	6.57	6.57	6.11	6.51	8.52
100	10.32	9.69	11.40	7.49	8.19	8.67	11.07	13.33	7.69	8.37	10.30	9.98

Values in inches.

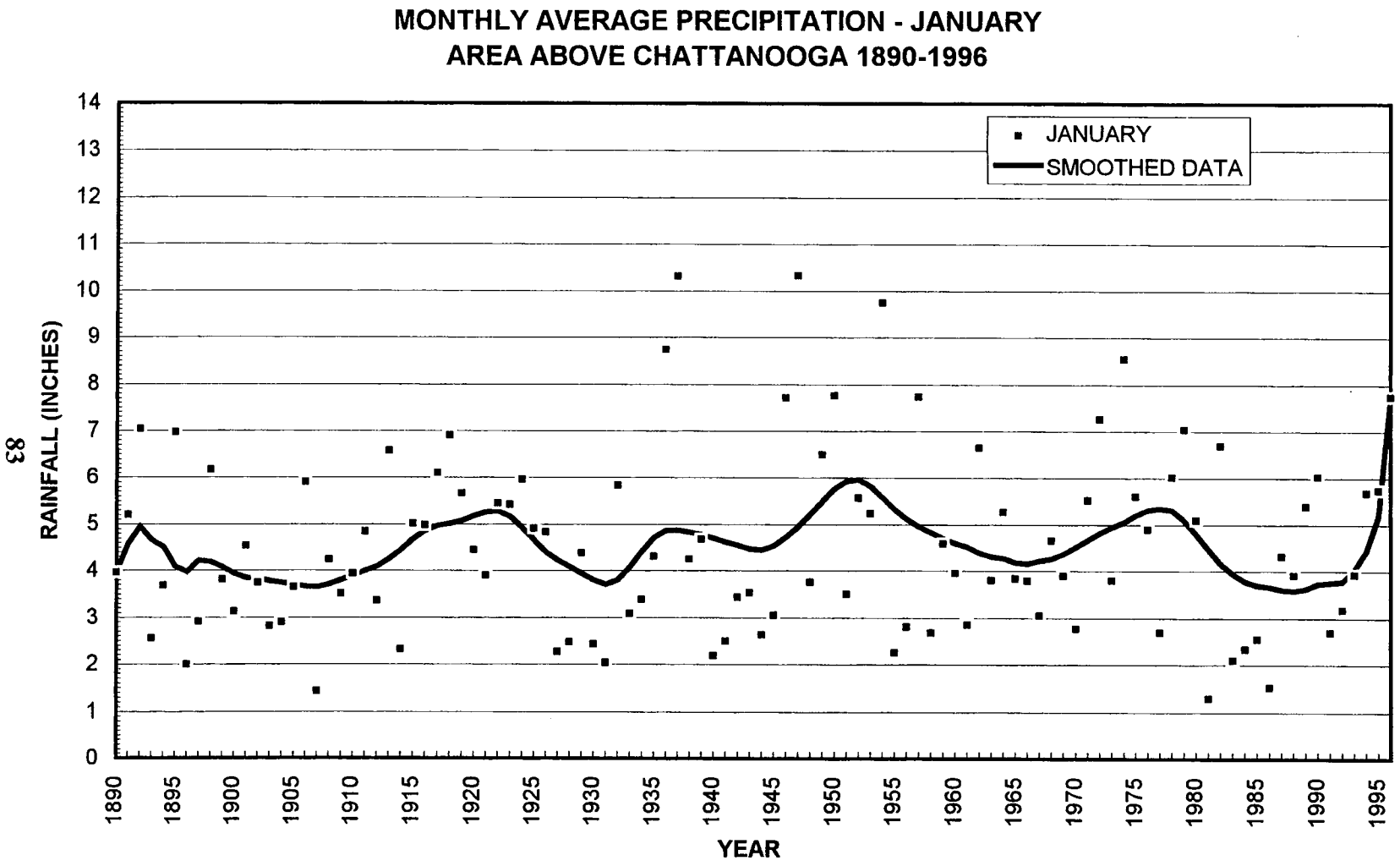
A-9. Percentiles for Monthly Historical Precipitation Data (1890-1993). Area Below Chattanooga.

PERCENTILES	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0.78	0.98	0.91	0.75	0.71	0.35	1.61	0.89	0.19	0.04	1.04	1.02
5	2.07	1.43	2.55	1.87	1.69	1.58	2.19	1.84	0.89	0.55	1.33	1.68
10	2.44	2.26	2.79	2.40	2.05	2.01	2.48	1.94	1.26	0.87	1.74	2.64
15	2.66	2.59	3.00	2.76	2.42	2.25	2.64	2.03	1.62	1.29	2.09	2.83
20	2.91	2.98	3.77	3.03	2.57	2.54	2.93	2.14	1.77	1.59	2.29	3.10
25	3.23	3.52	4.06	3.24	2.99	2.65	3.23	2.26	2.04	1.84	2.54	3.34
30	3.39	3.66	4.29	3.46	3.16	2.87	3.40	2.71	2.37	1.99	2.82	3.59
35	3.83	3.82	4.57	3.60	3.36	3.14	3.56	2.81	2.54	2.09	2.98	3.85
40	4.11	3.96	4.88	3.74	3.73	3.22	3.78	2.99	2.76	2.23	3.40	4.08
45	4.31	4.20	5.11	4.18	3.89	3.38	3.97	3.17	2.99	2.35	3.53	4.40
50	4.46	4.41	5.54	4.44	4.25	3.69	4.19	3.40	3.09	2.60	3.94	4.84
55	4.92	4.53	5.70	4.62	4.43	3.91	4.33	3.54	3.34	2.74	4.01	5.24
60	5.14	4.64	6.15	4.93	4.81	4.09	4.55	3.79	3.52	2.82	4.31	5.45
65	5.40	5.26	6.34	5.29	5.00	4.21	4.77	3.98	3.69	3.12	4.61	6.03
70	5.76	5.68	6.64	5.52	5.30	4.49	4.98	4.21	3.90	3.44	4.96	6.26
75	6.30	6.19	7.18	5.77	5.60	4.62	5.24	4.62	4.34	3.81	5.12	6.51
80	6.66	6.93	7.93	5.91	5.85	4.93	5.72	4.95	4.73	4.01	5.50	6.83
85	7.34	7.31	8.48	6.52	6.14	5.44	6.16	5.21	4.95	4.49	5.93	7.55
90	8.43	8.47	8.89	7.21	6.94	5.84	6.47	5.62	5.47	5.60	6.85	8.49
95	9.91	8.94	10.50	8.56	7.68	6.52	7.46	6.72	6.31	6.42	7.70	9.91
100	13.94	11.31	13.49	12.19	11.13	11.87	8.94	10.18	8.83	8.65	12.15	14.53

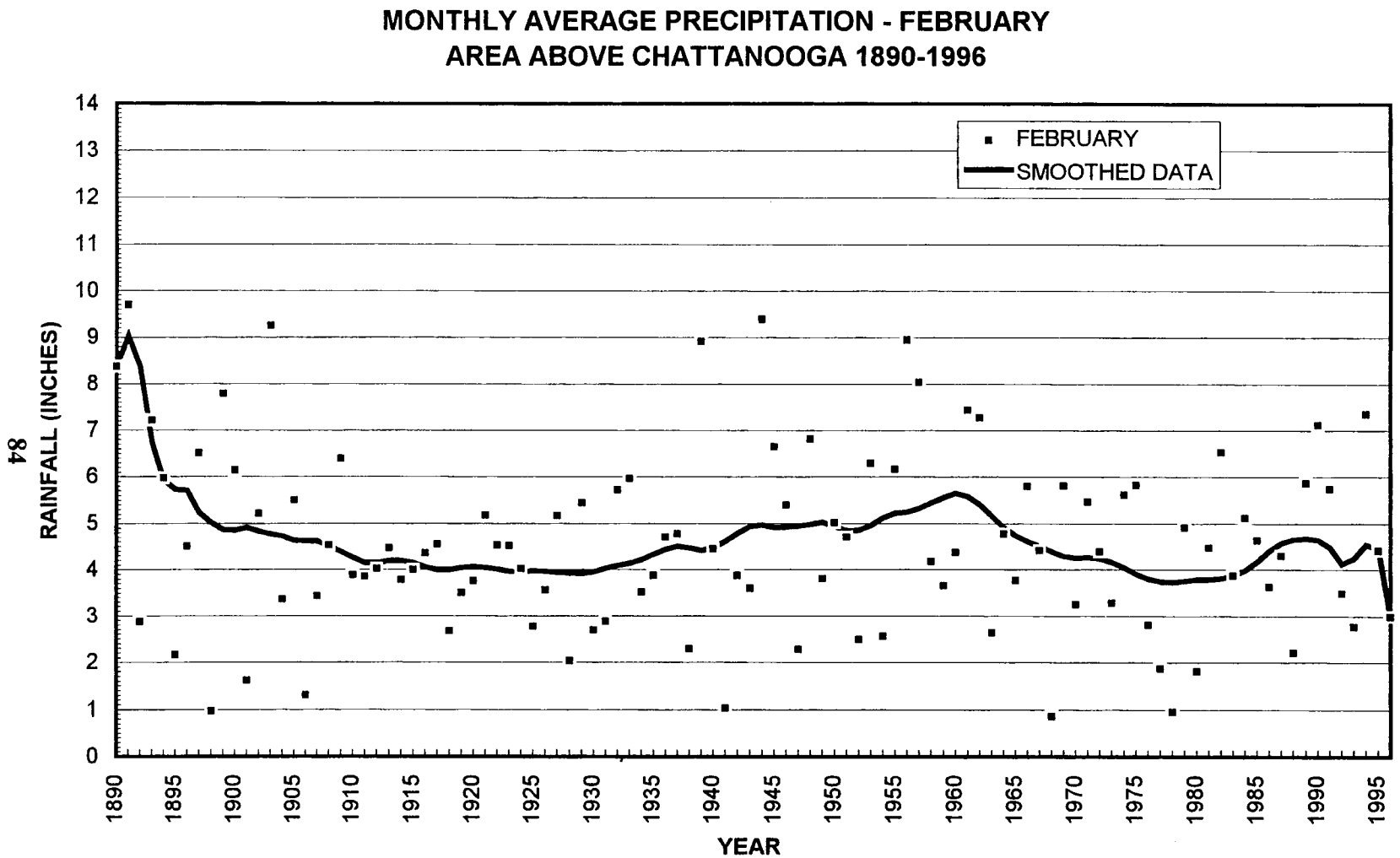
Values in inches.



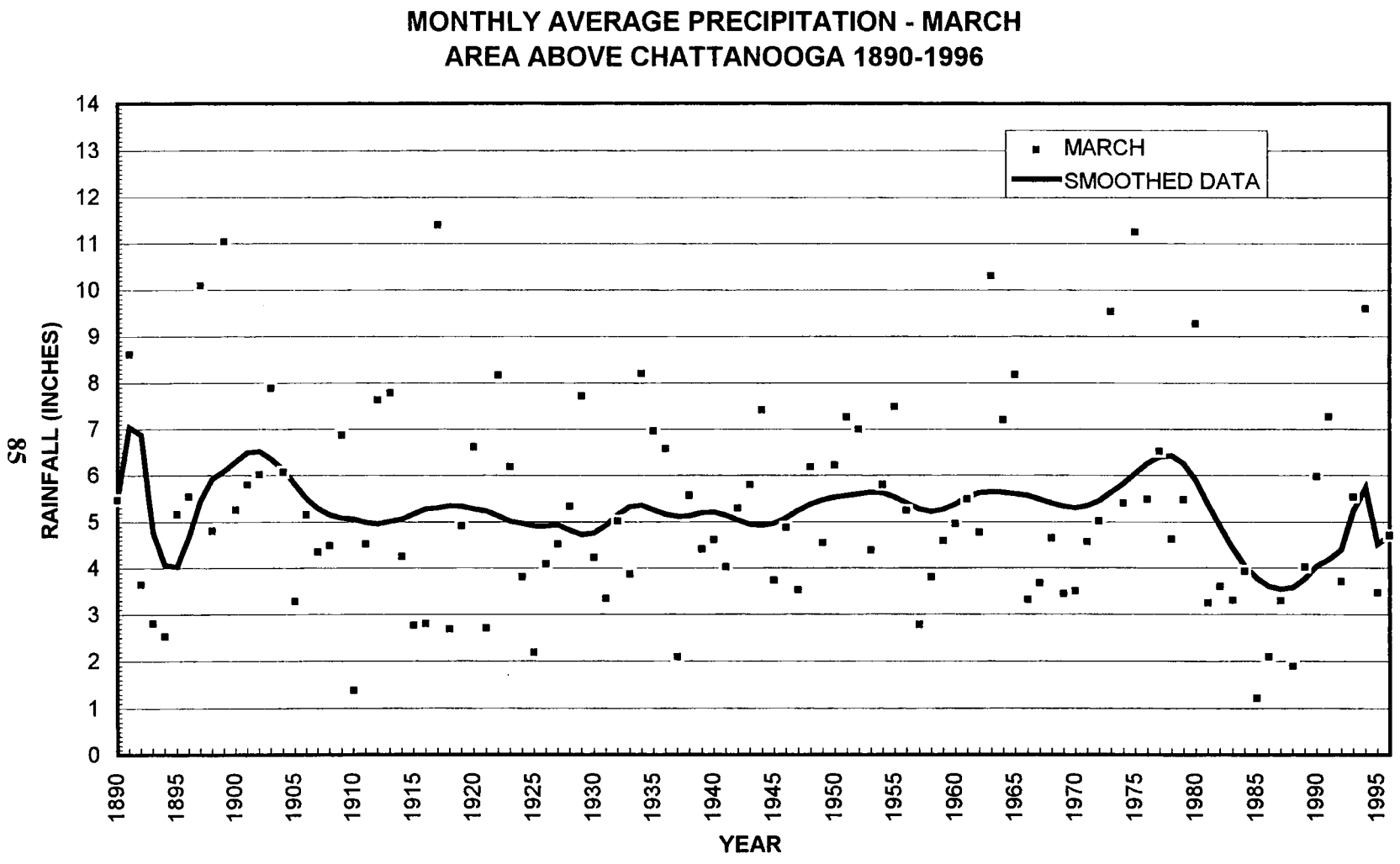
A.10. Historical Data Trend Analysis (Period of Record). Area Above Chattanooga.



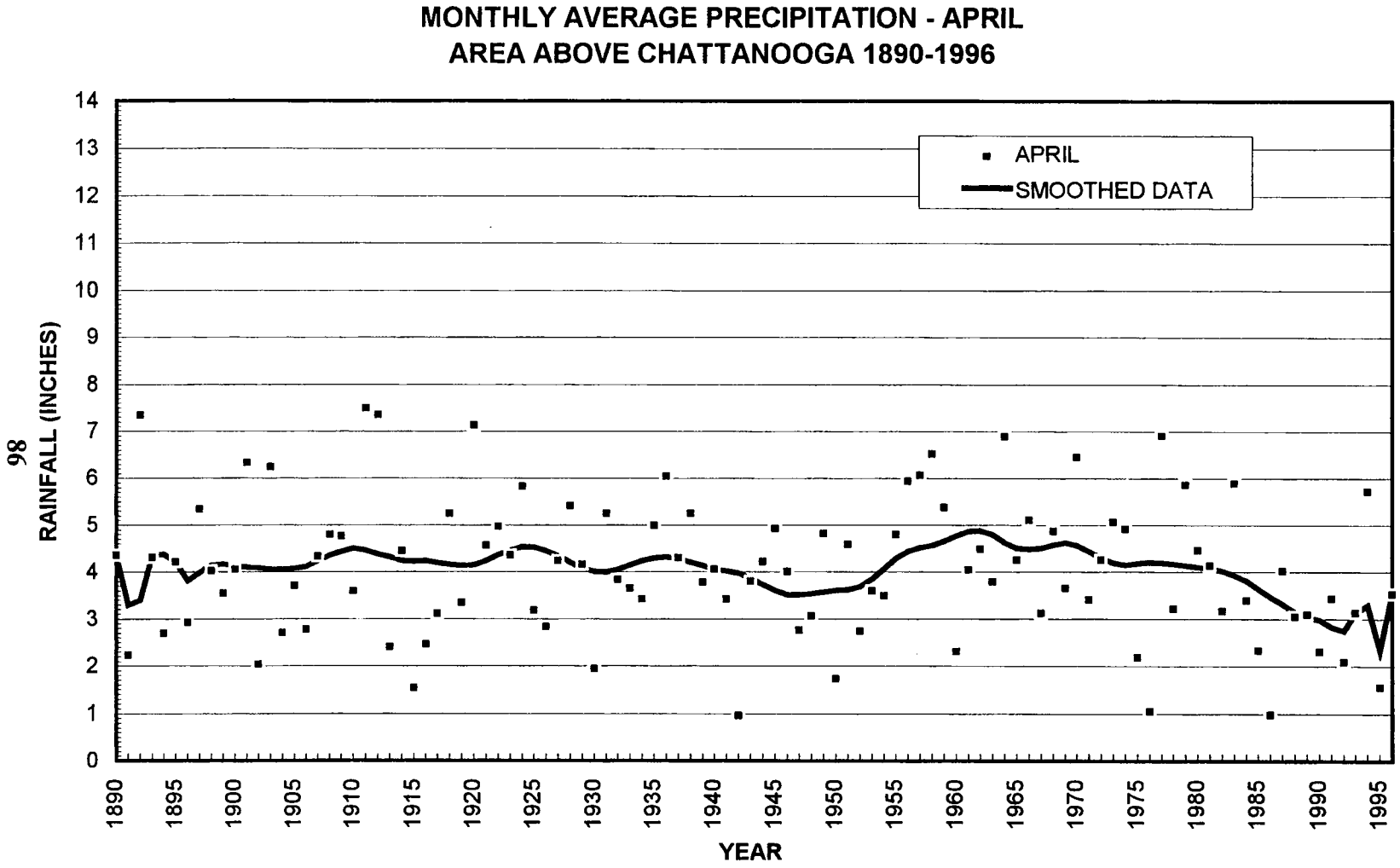
A.11. Monthly Historical Data Trend Analysis (January). Area Above Chattanooga.



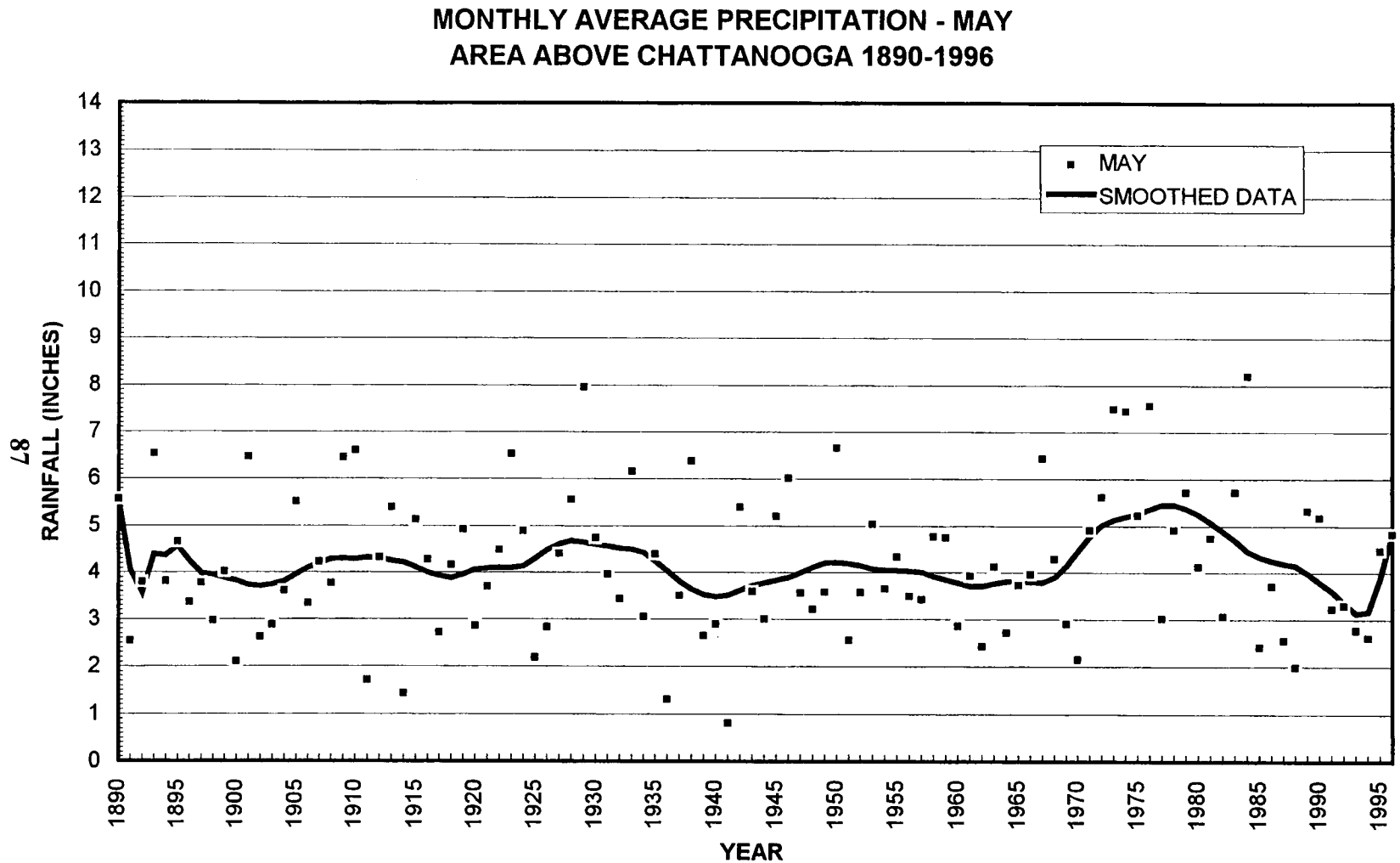
A.12. Monthly Historical Data Trend Analysis (February). Area Above Chattanooga.



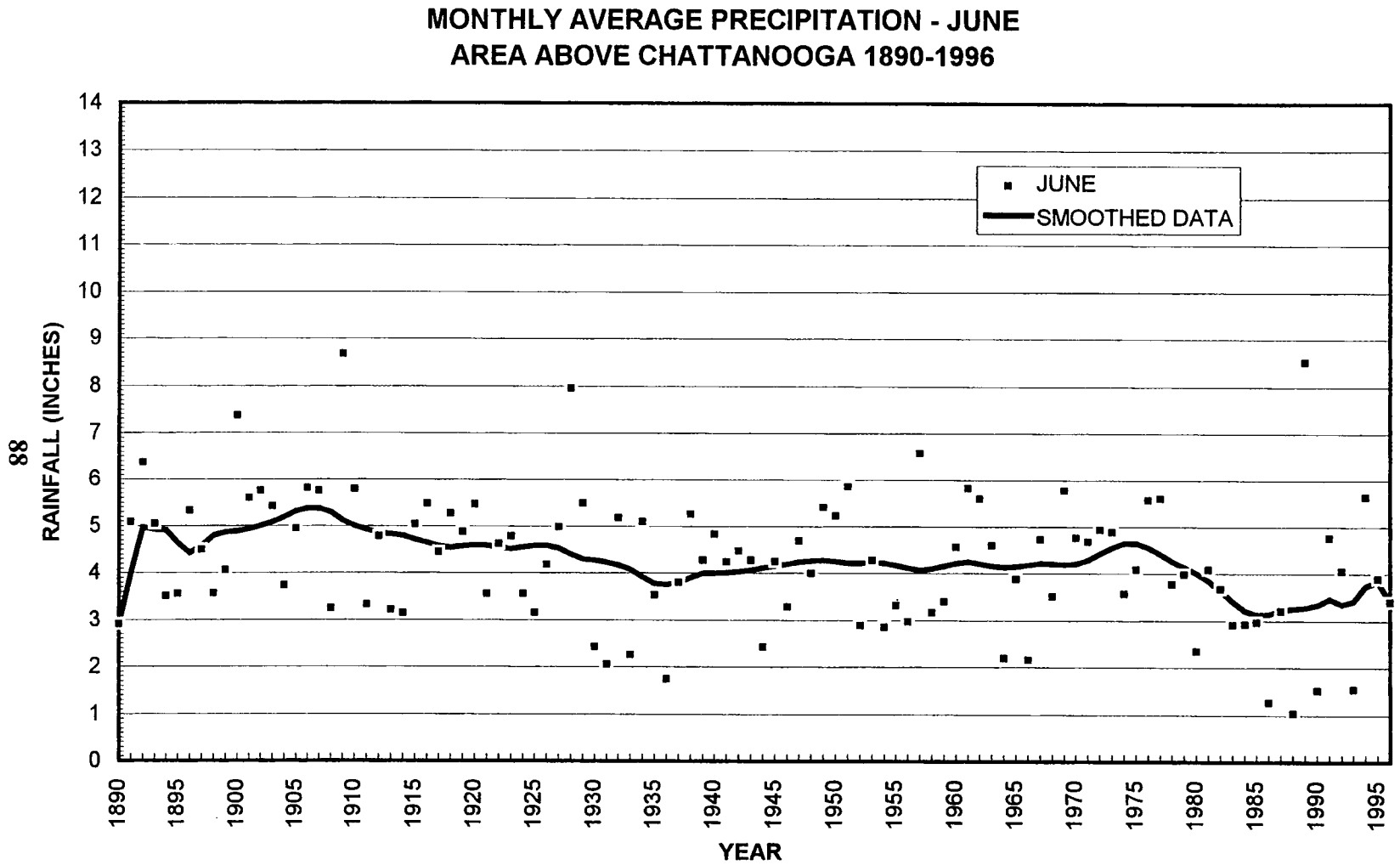
A.13. Monthly Historical Data Trend Analysis (March). Area Above Chattanooga.



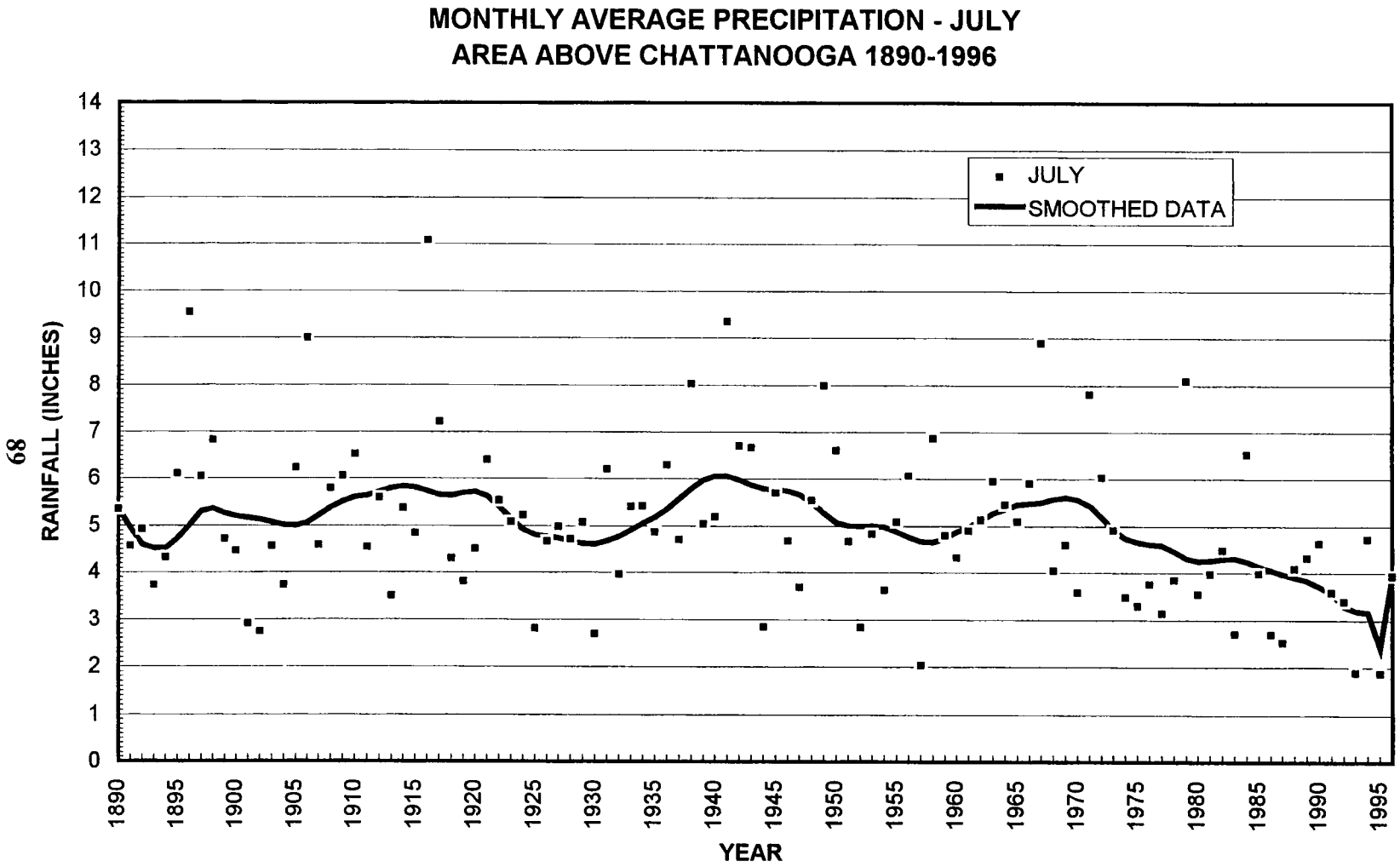
A.14. Monthly Historical Data Trend Analysis (April). Area Above Chattanooga.



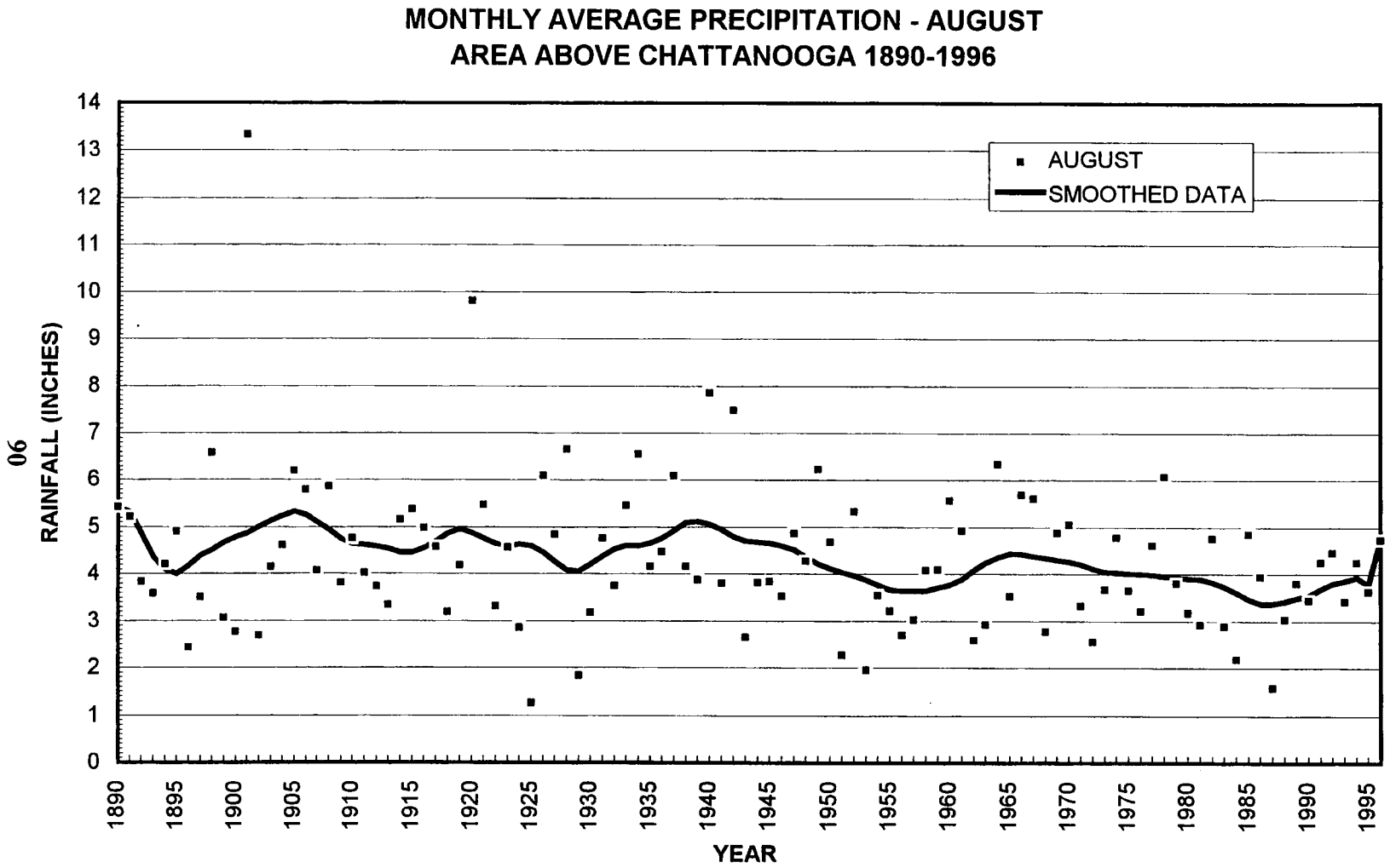
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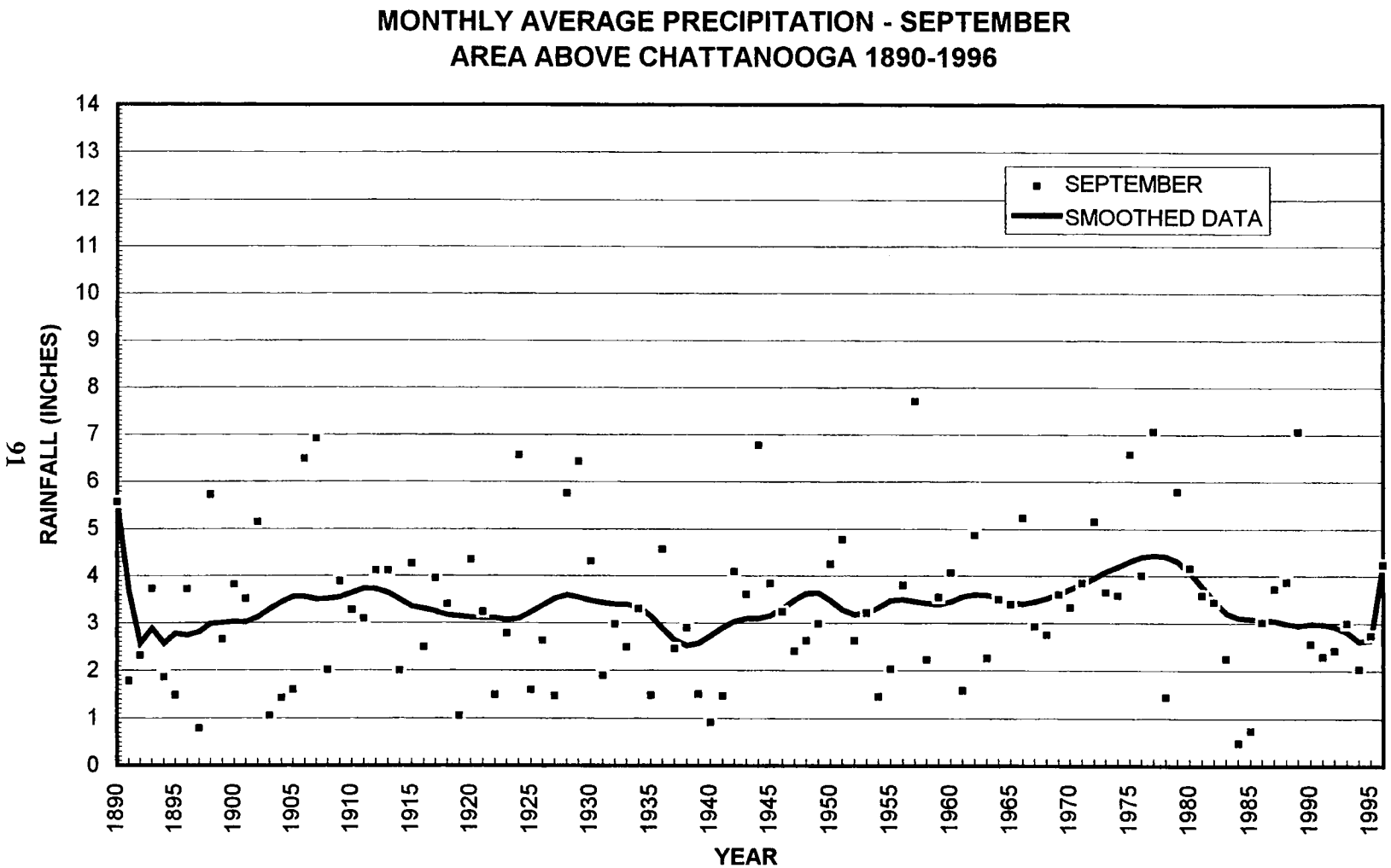
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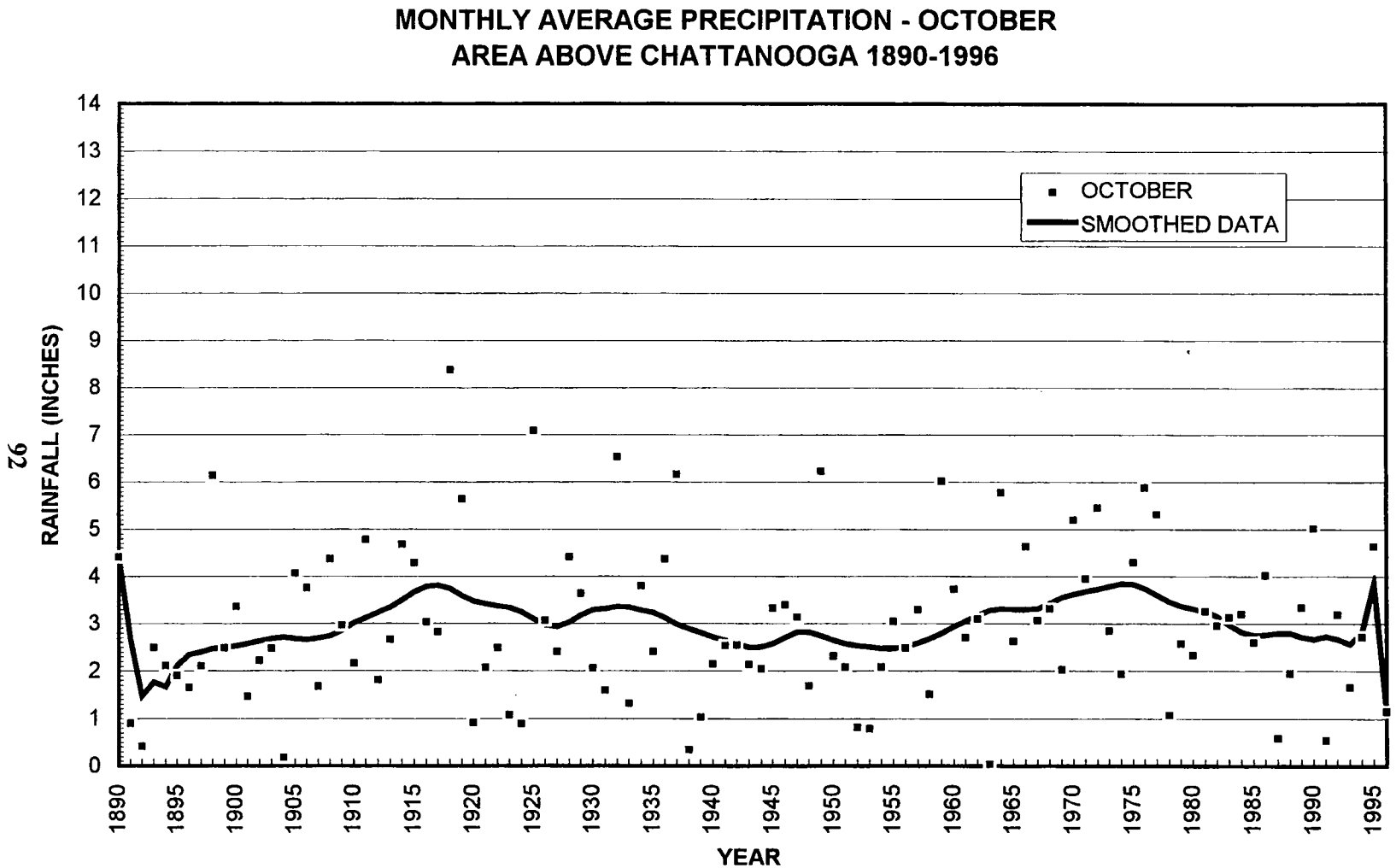
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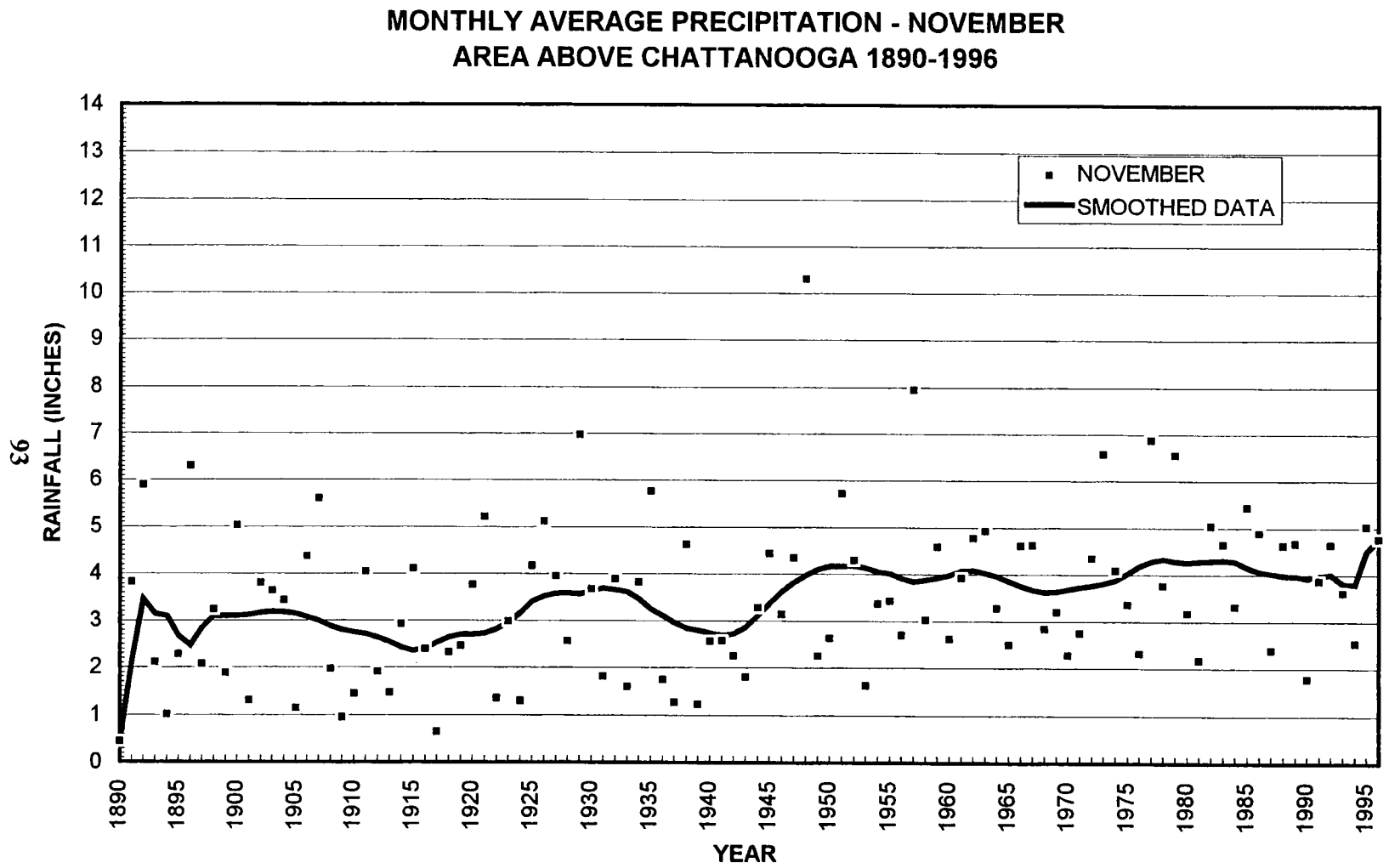
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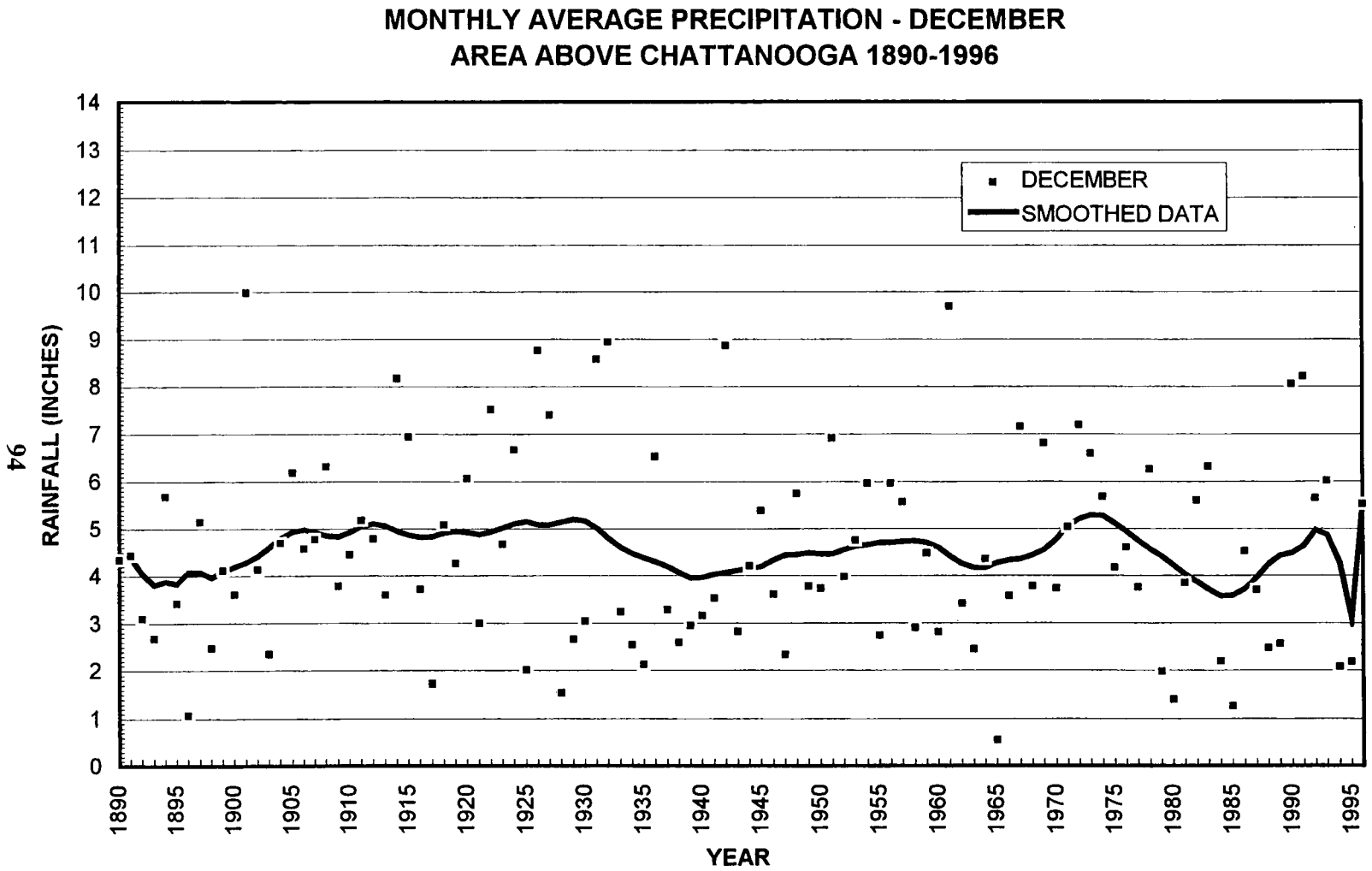
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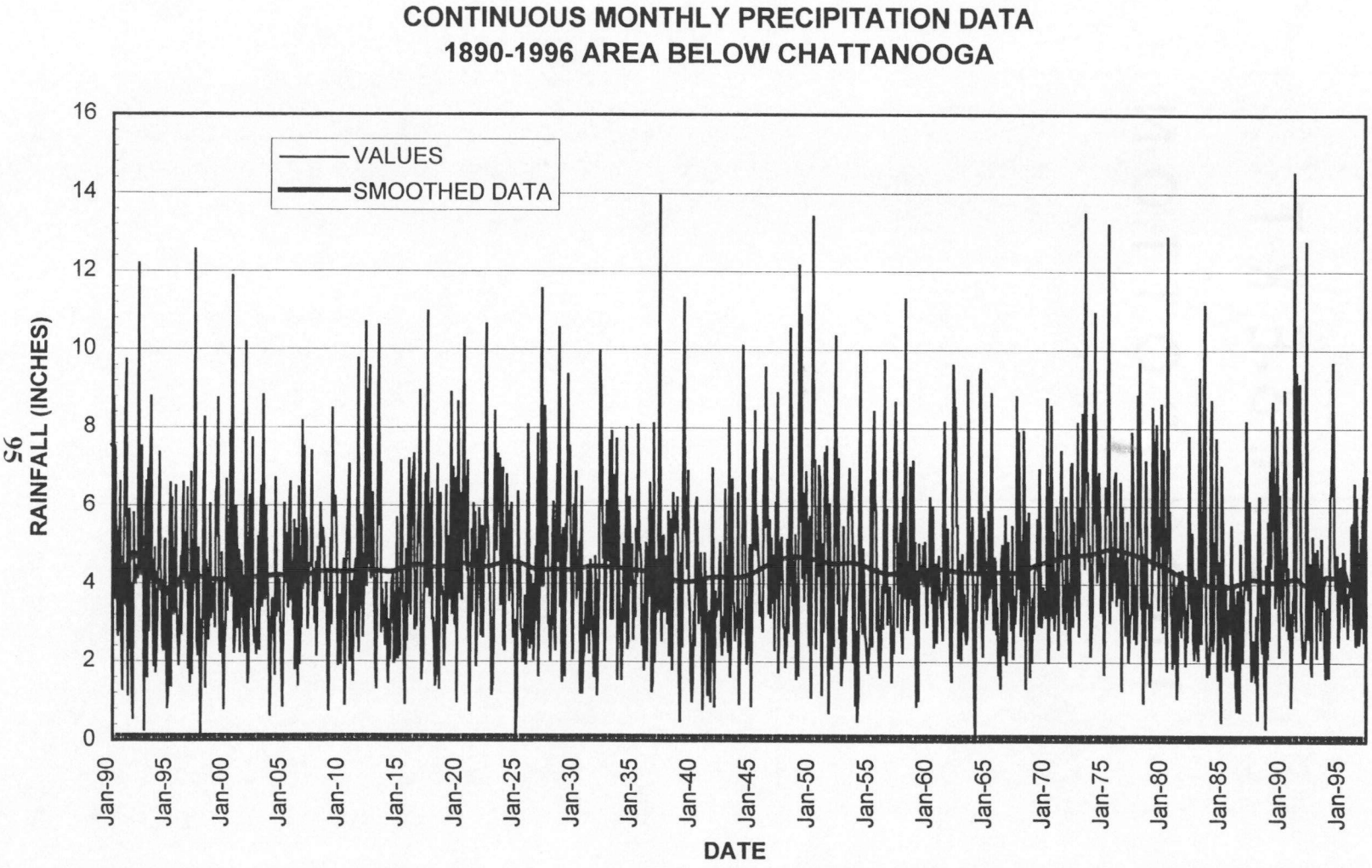
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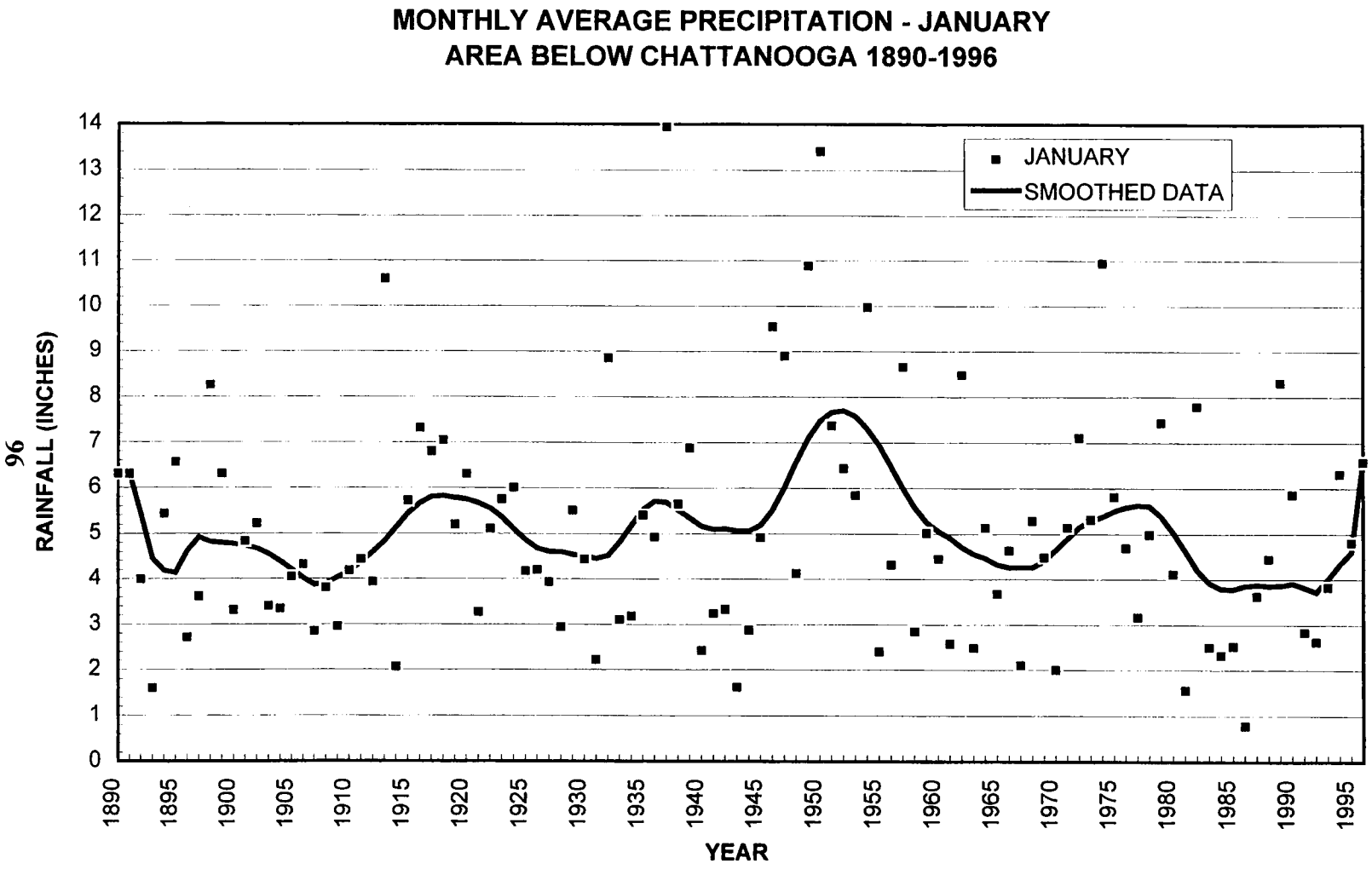
A.21. Monthly Historical Data Trend Analysis (November). Area Above Chattanooga.



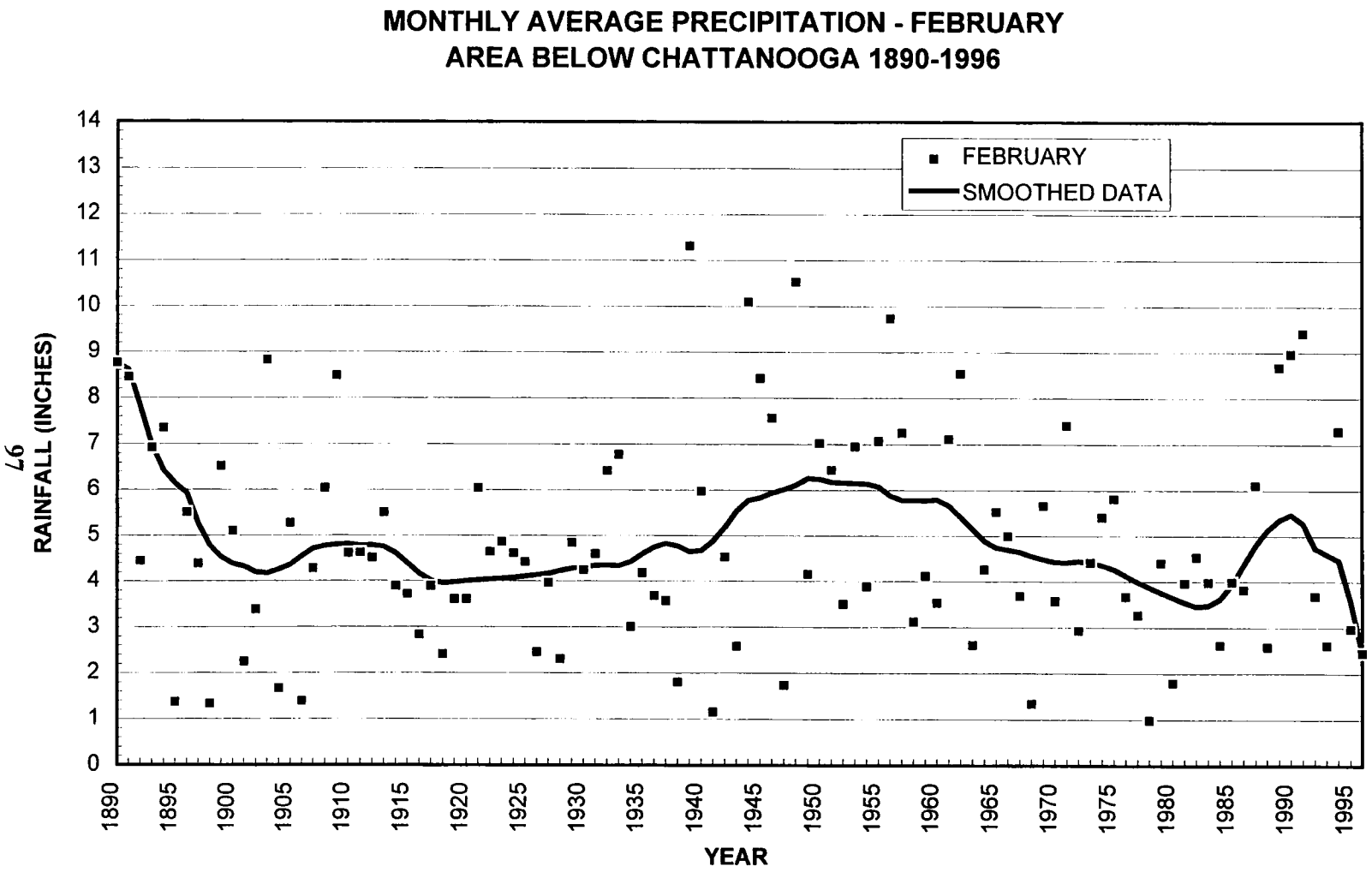
A.22. Monthly Historical Data Trend Analysis (December). Area Above Chattanooga.



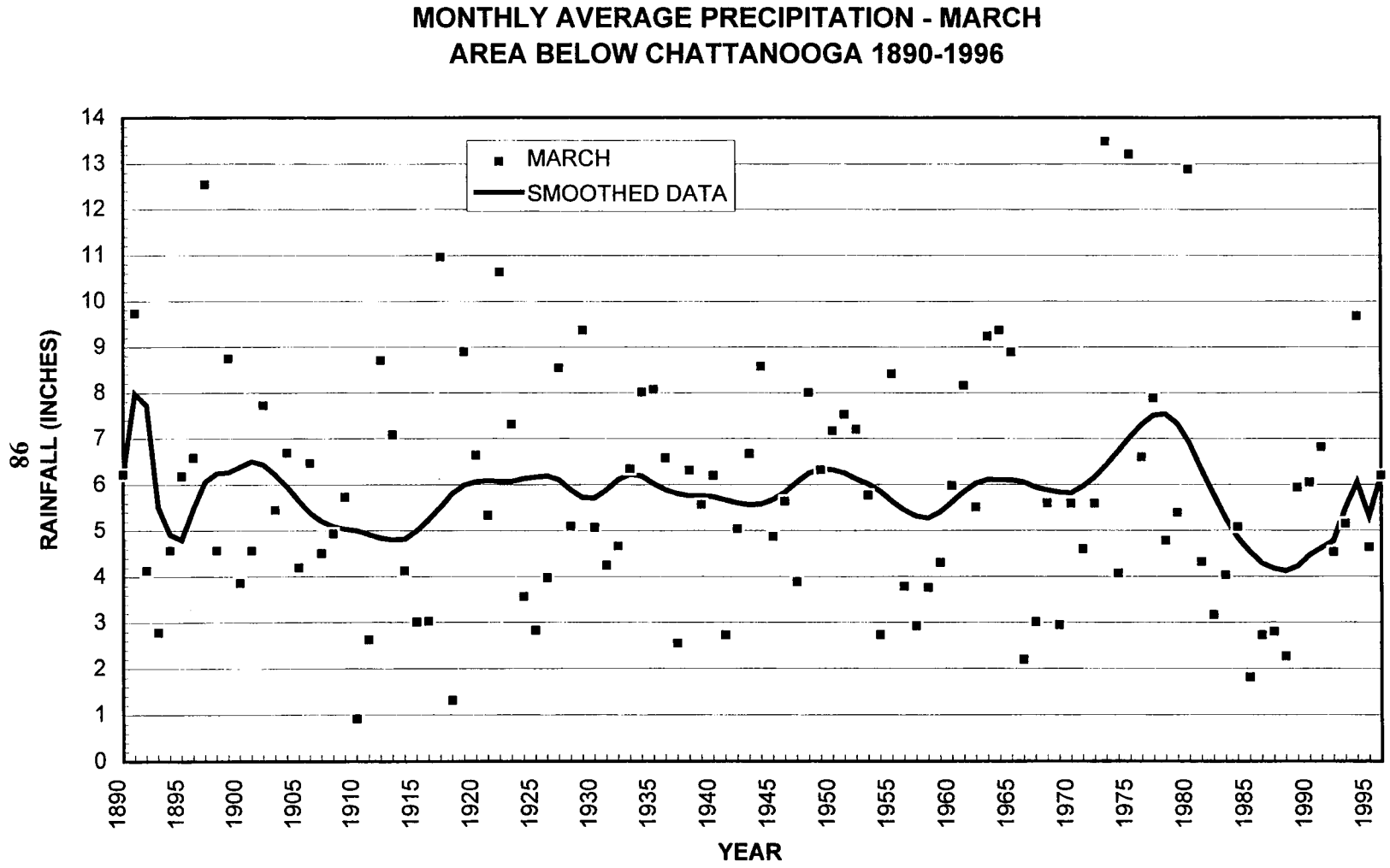
A.23. Historical Data Trend Analysis (Period of Record). Area Below Chattanooga.



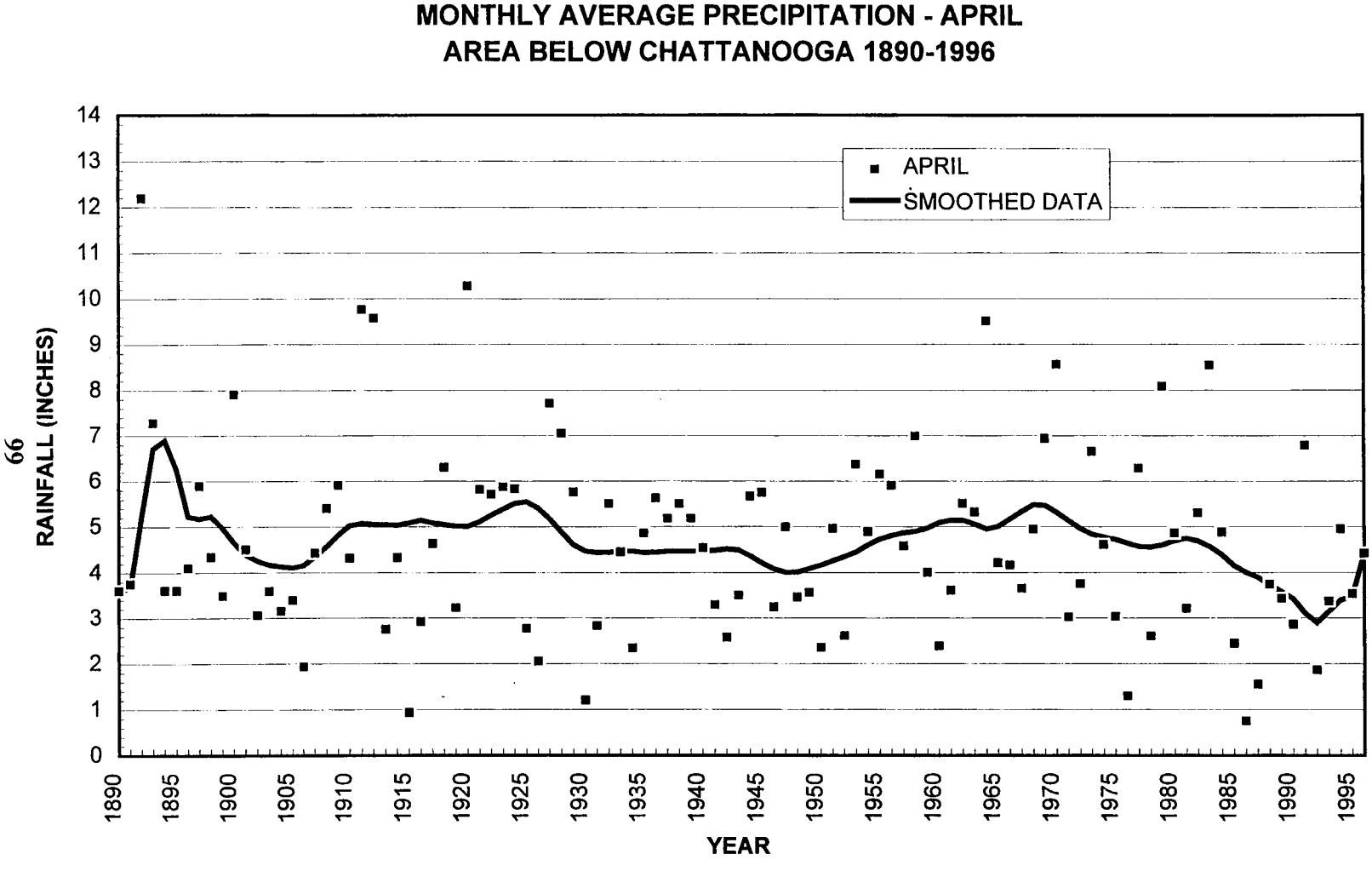
A.24. Monthly Historical Data Trend Analysis (January). Area Below Chattanooga.



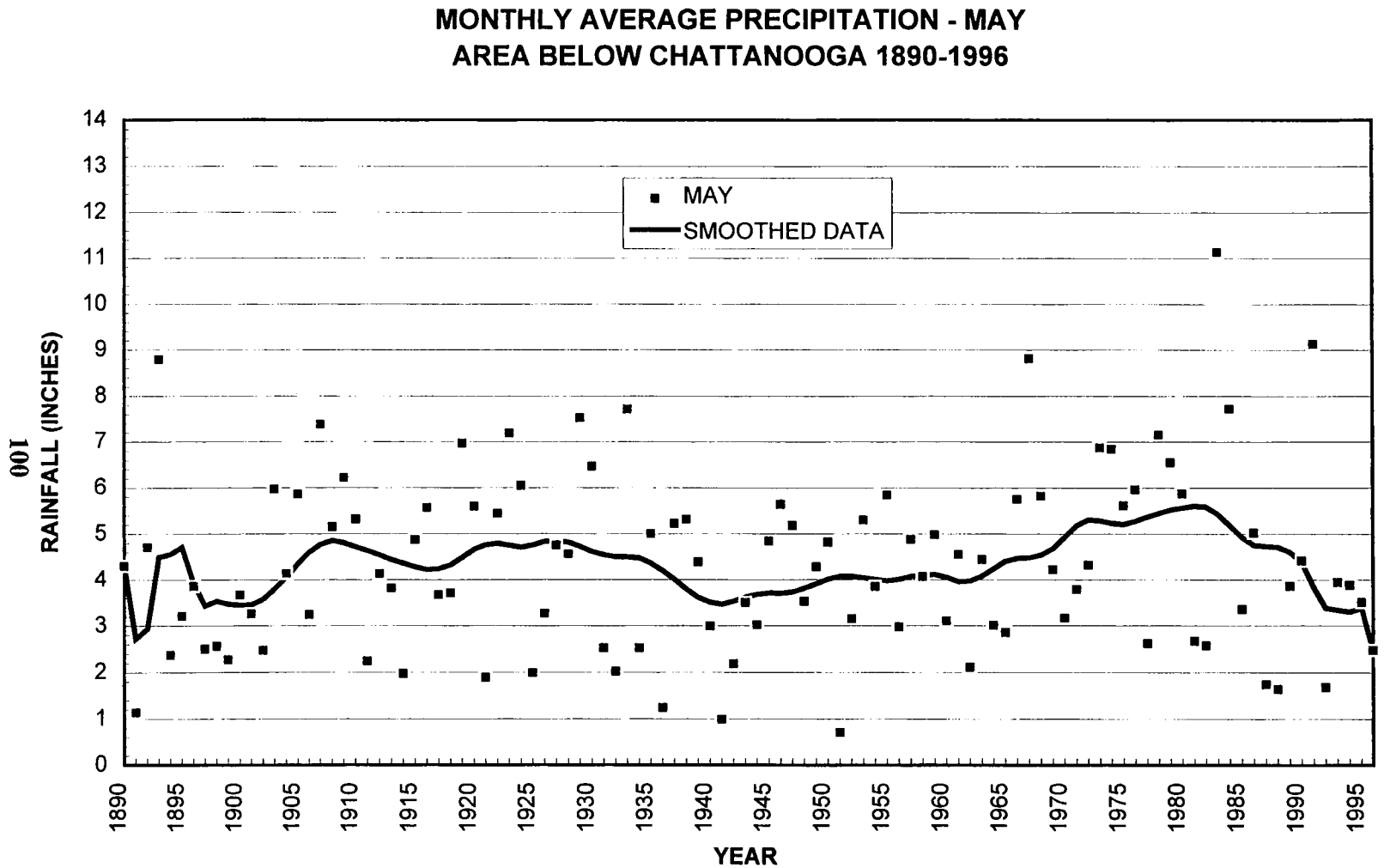
A.25. Monthly Historical Data Trend Analysis (February). Area Below Chattanooga.



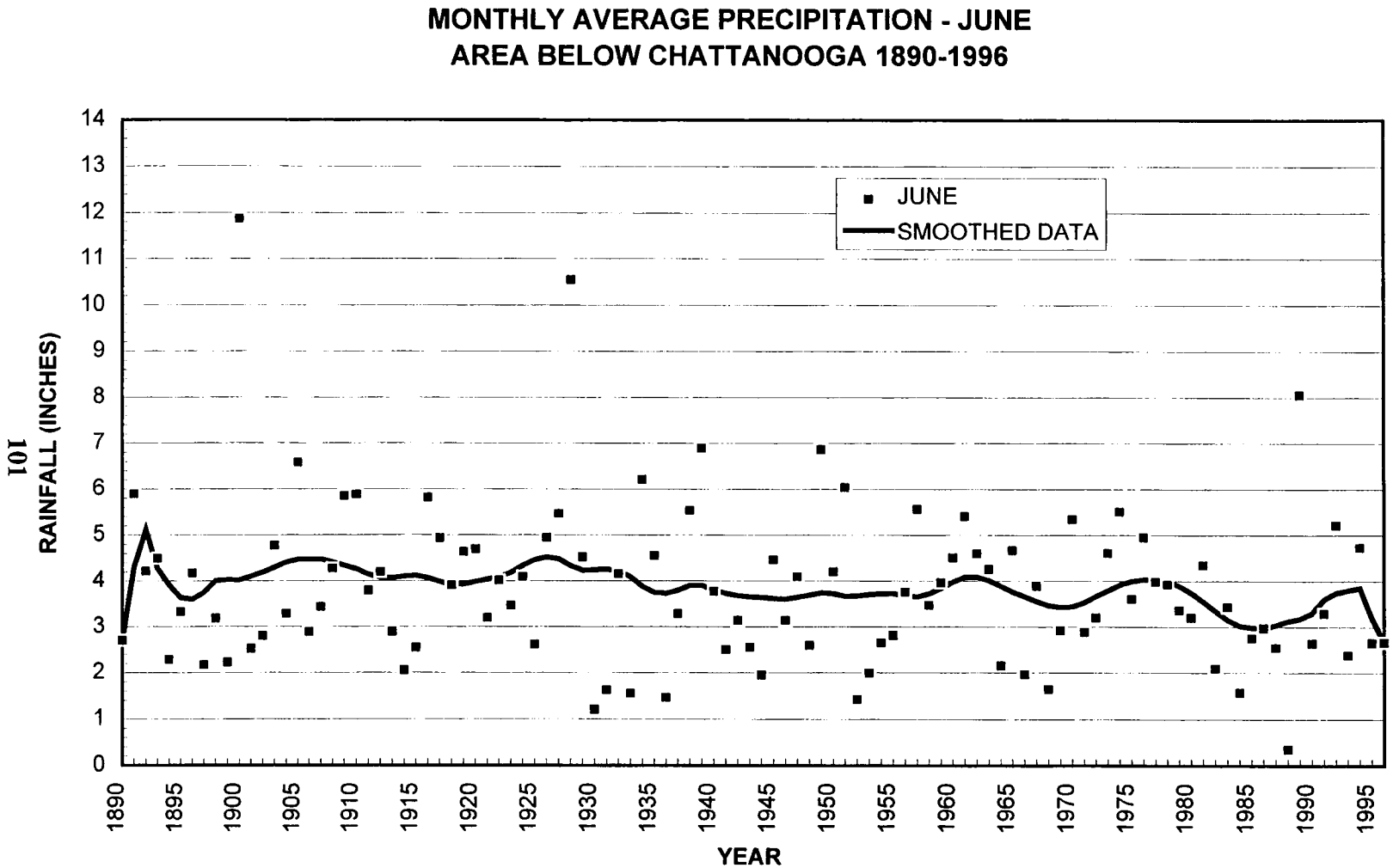
A.26. Monthly Historical Data Trend Analysis (March). Area Below Chattanooga.



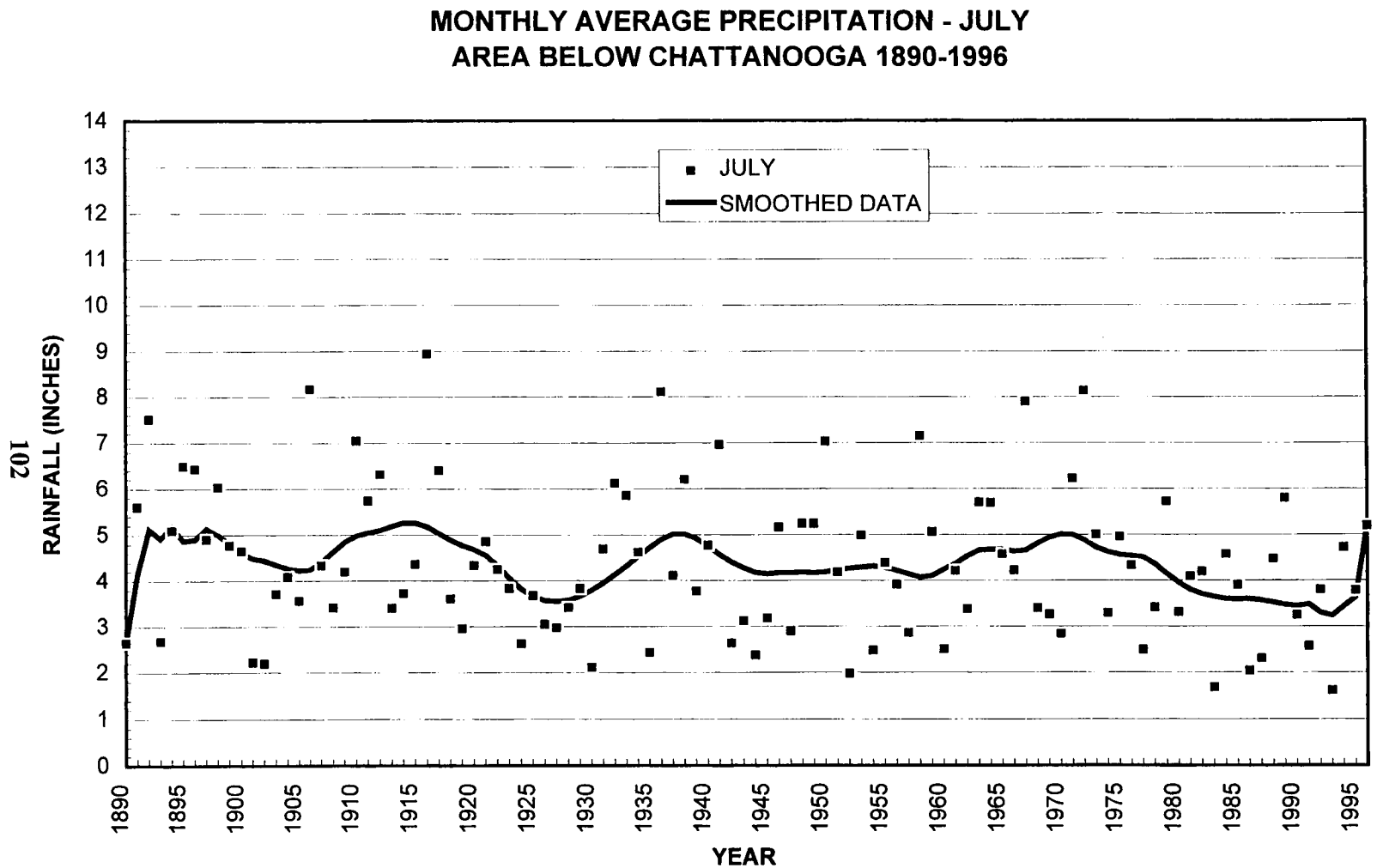
A.27. Monthly Historical Data Trend Analysis (April). Area Below Chattanooga.



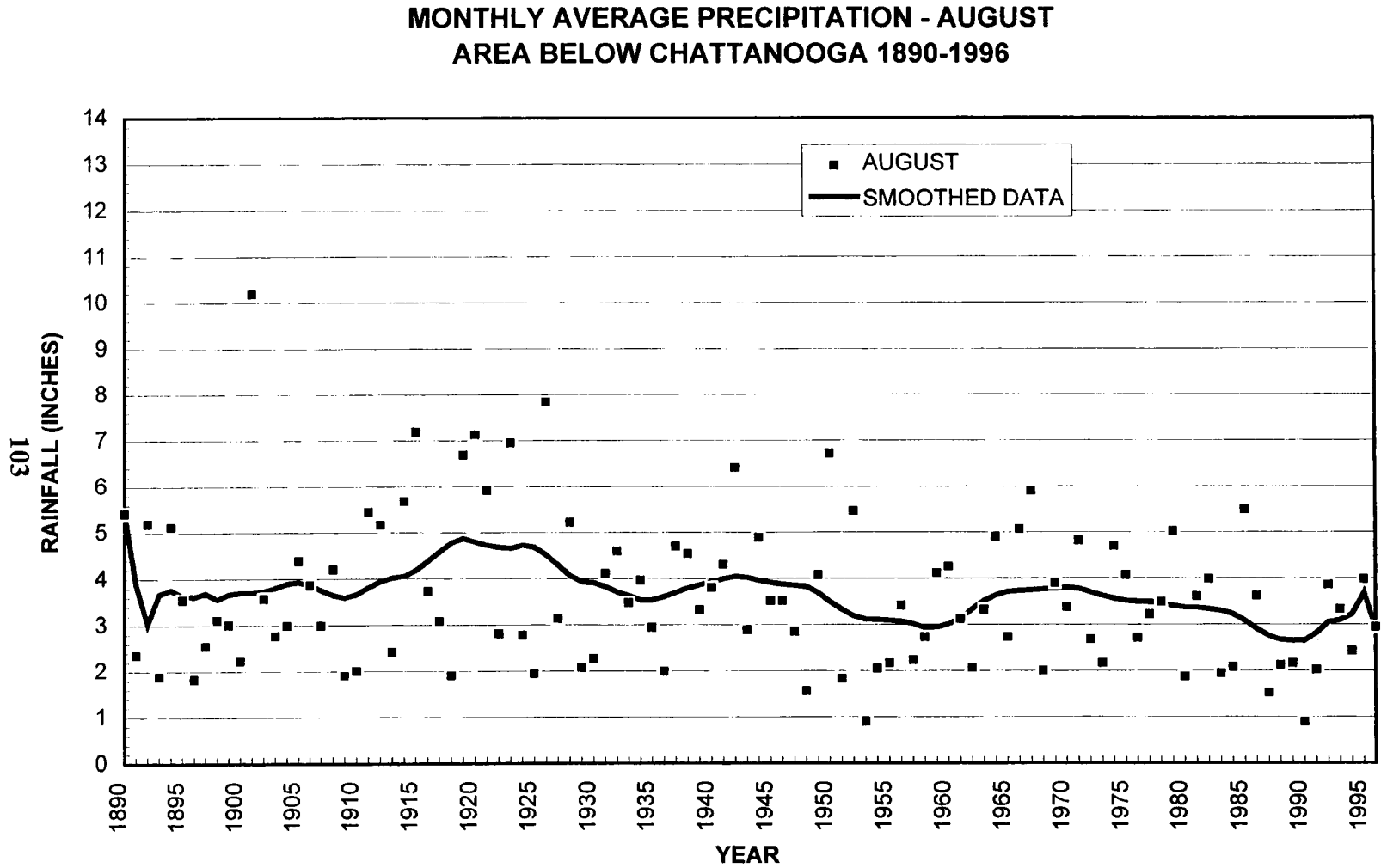
A.28. Monthly Historical Data Trend Analysis (May). Area Below Chattanooga.



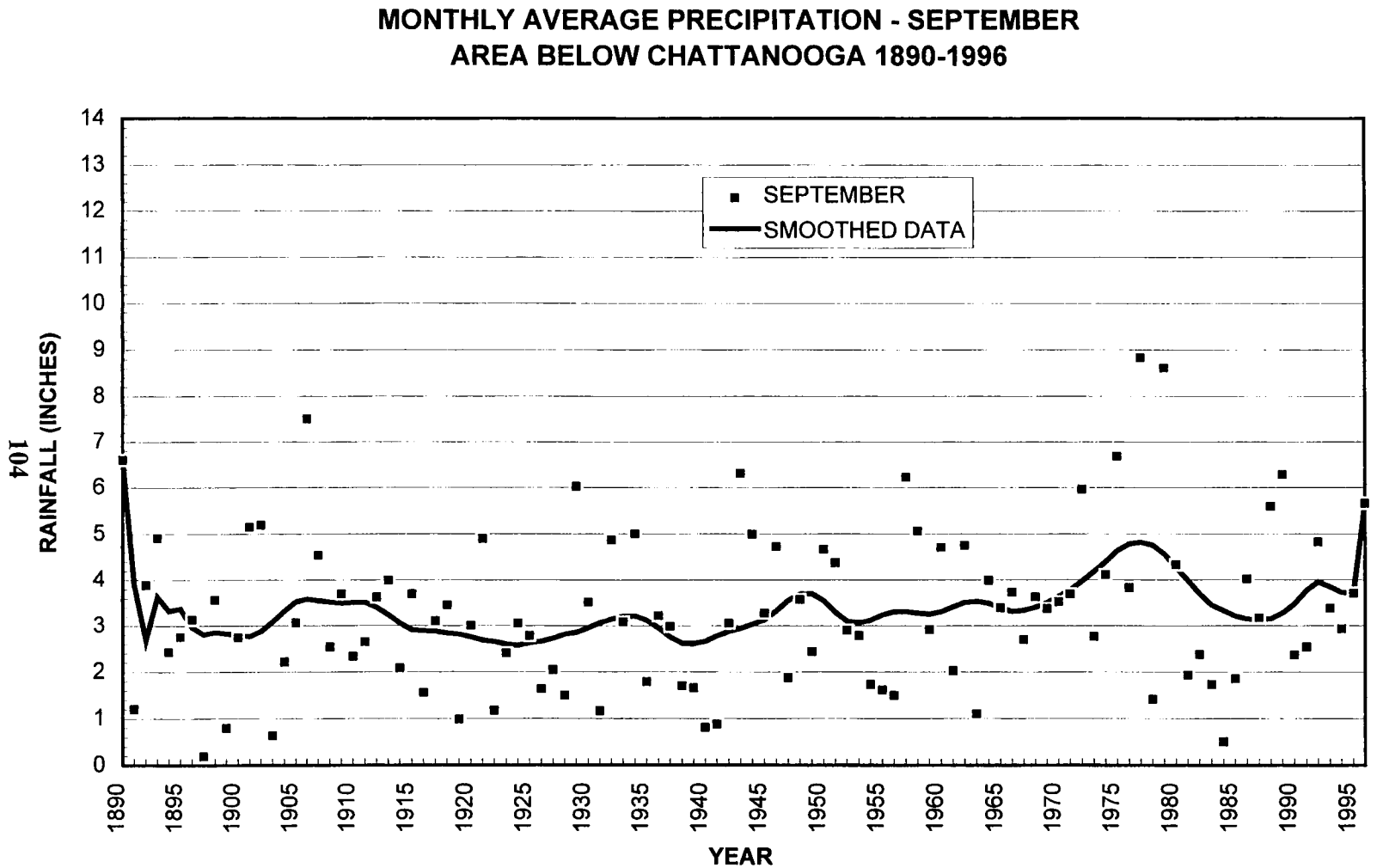
A.29. Monthly Historical Data Trend Analysis (June). Area Below Chattanooga.



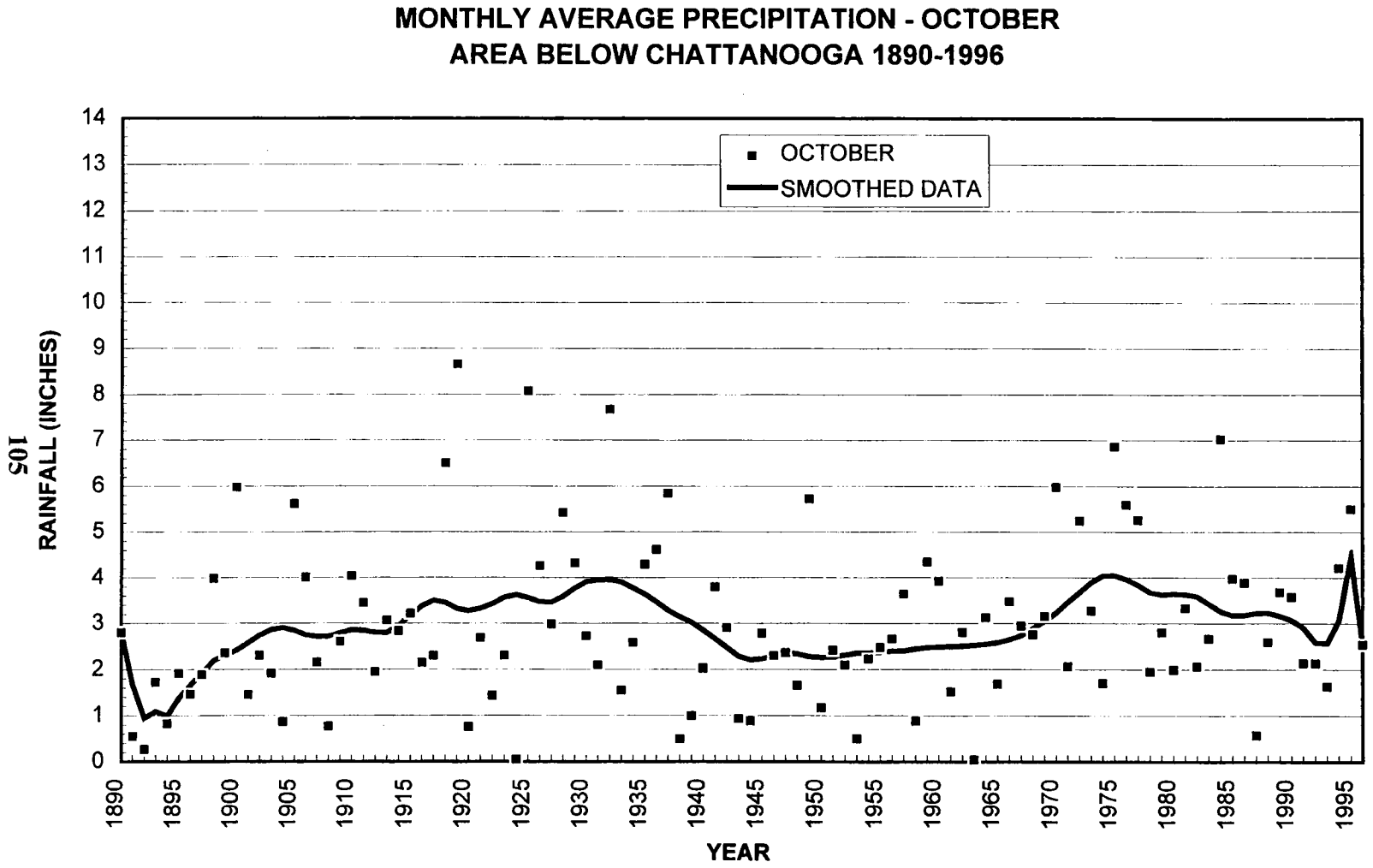
A.30. Monthly Historical Data Trend Analysis (July). Area Below Chattanooga.



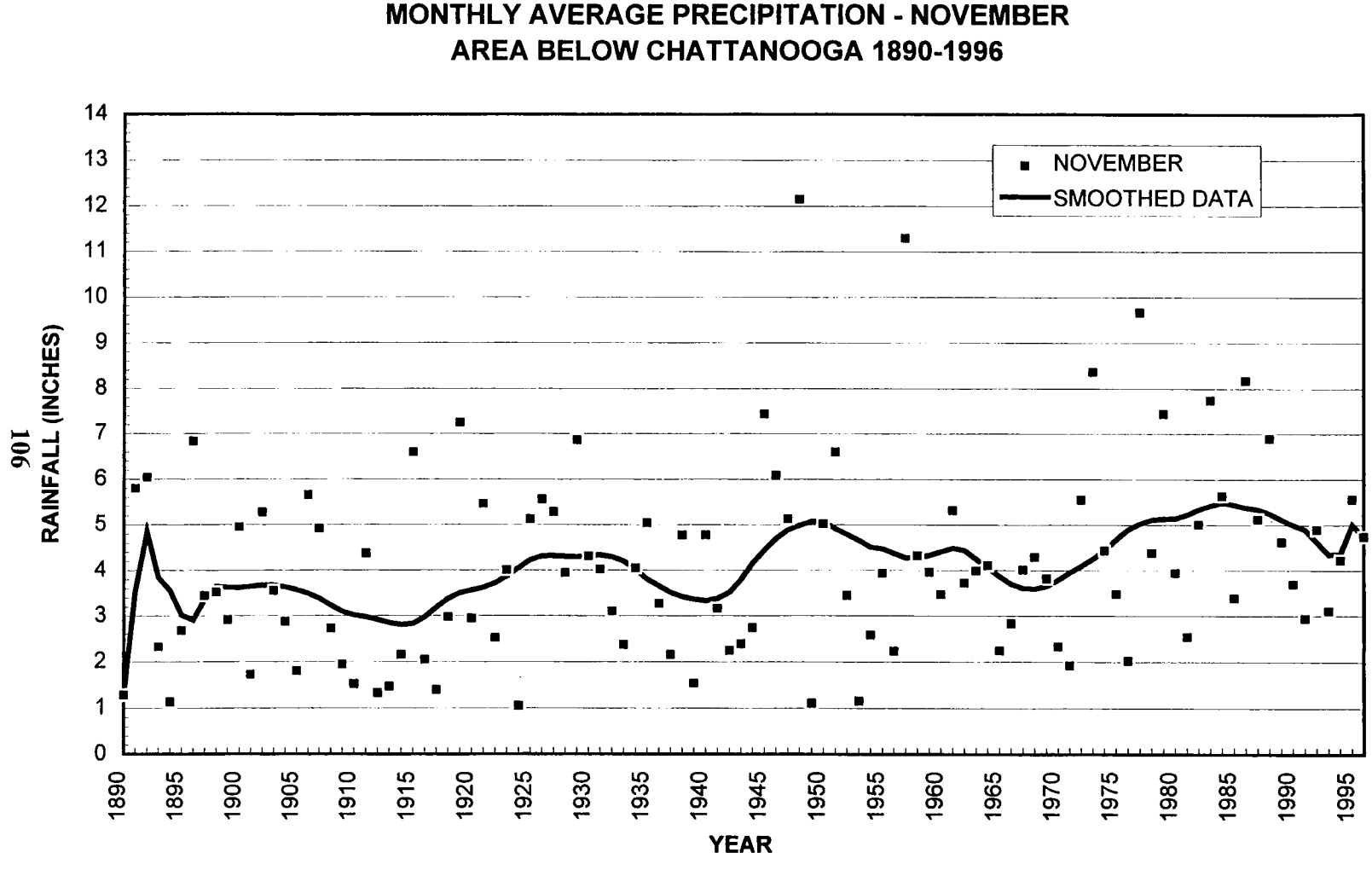
A.31. Monthly Historical Data Trend Analysis (August). Area Below Chattanooga.



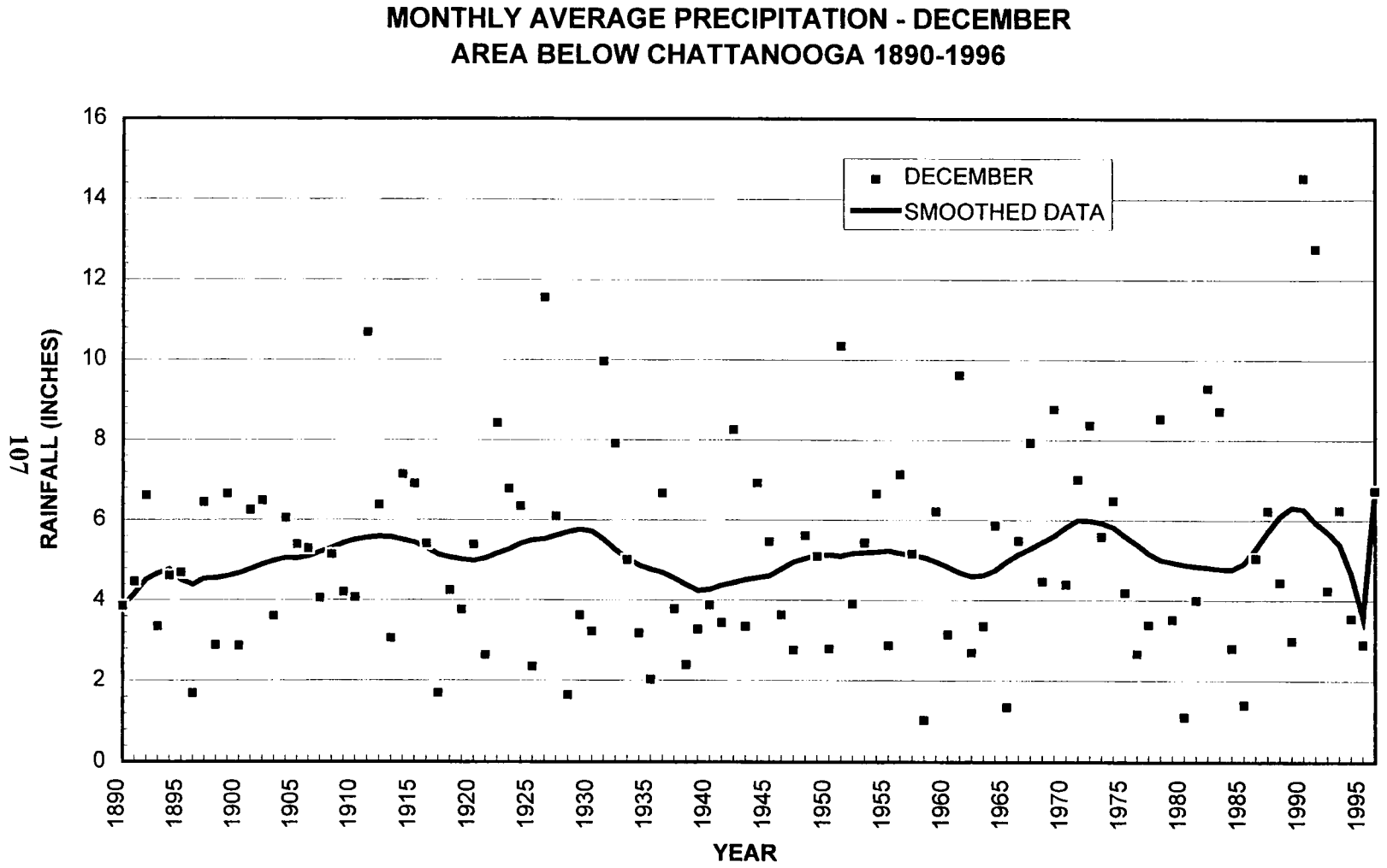
A.32. Monthly Historical Data Trend Analysis (September). Area Below Chattanooga.



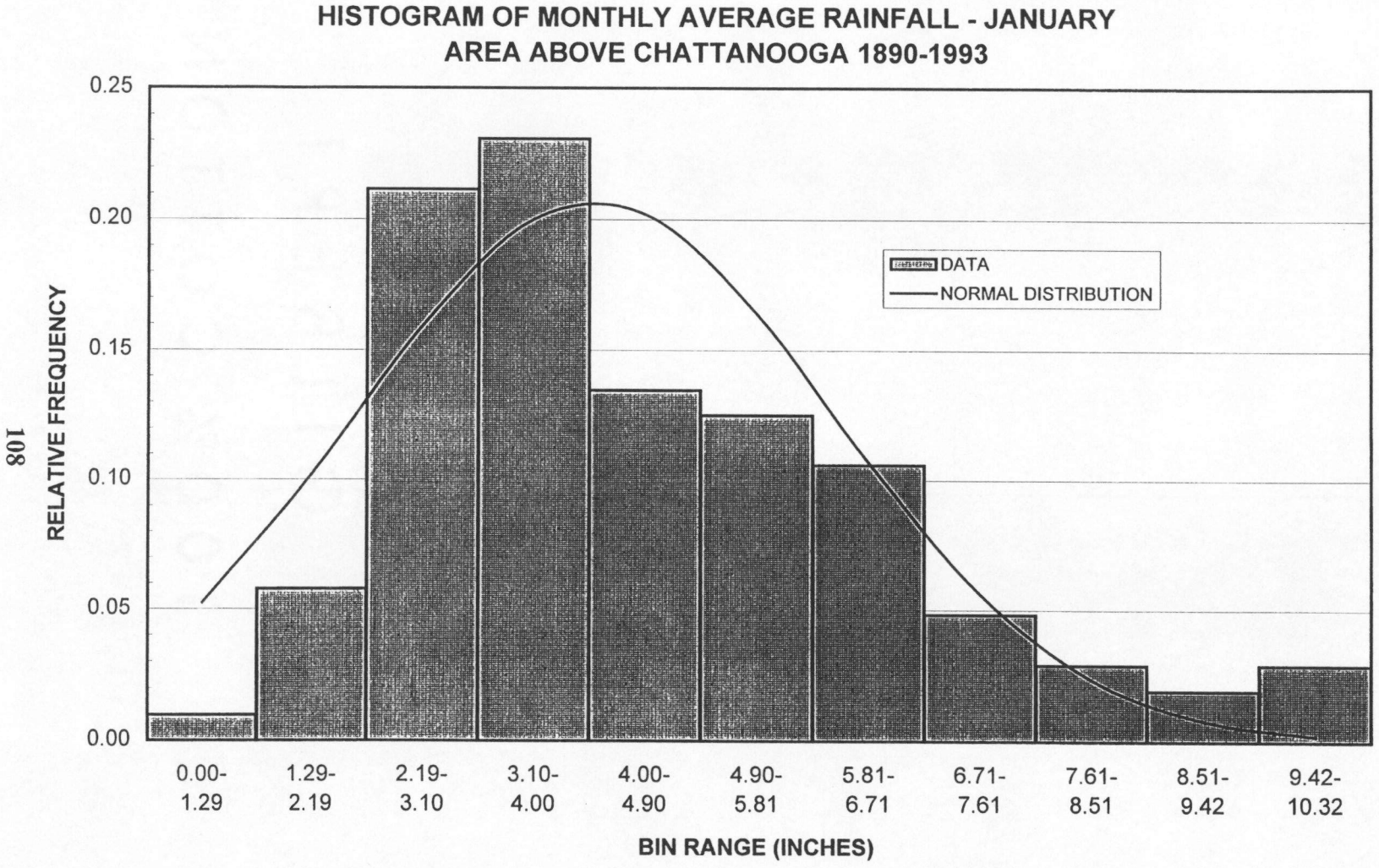
A.33. Monthly Historical Data Trend Analysis (October). Area Below Chattanooga.



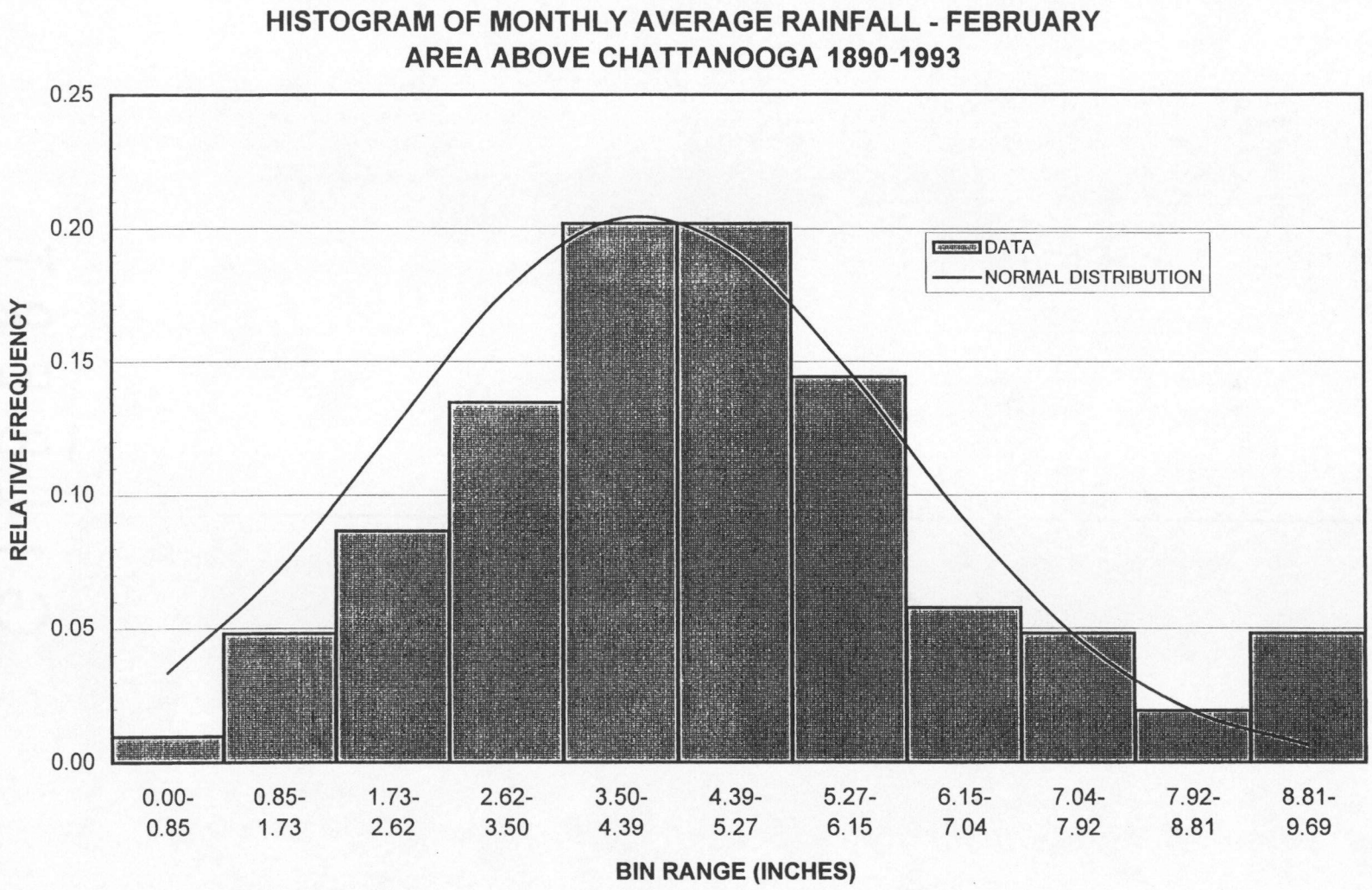
A.34. Monthly Historical Data Trend Analysis (November). Area Below Chattanooga.



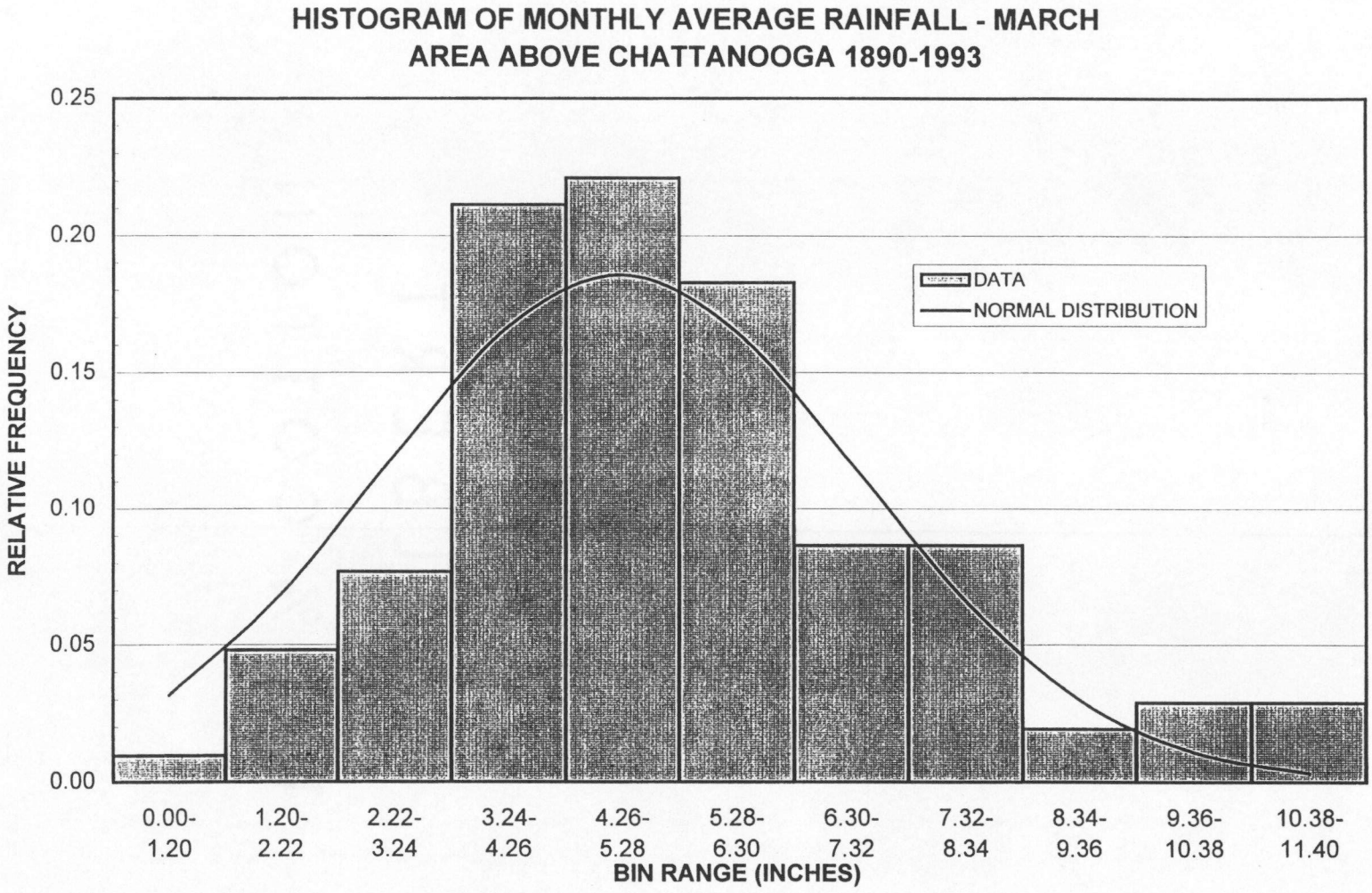
A.35. Monthly Historical Data Trend Analysis (December). Area Below Chattanooga.



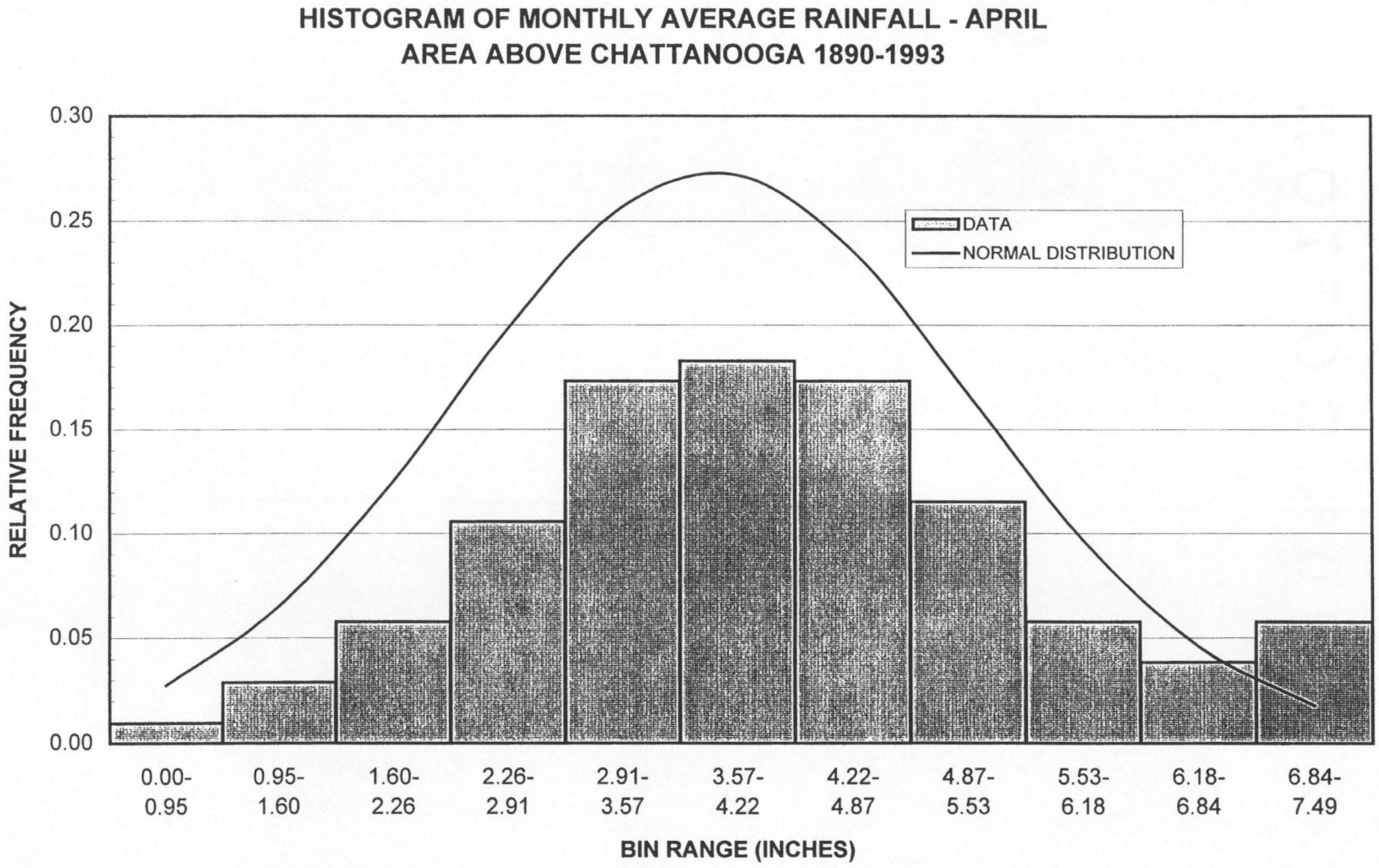
A.36. Frequency Analysis (January). Area Above Chattanooga.



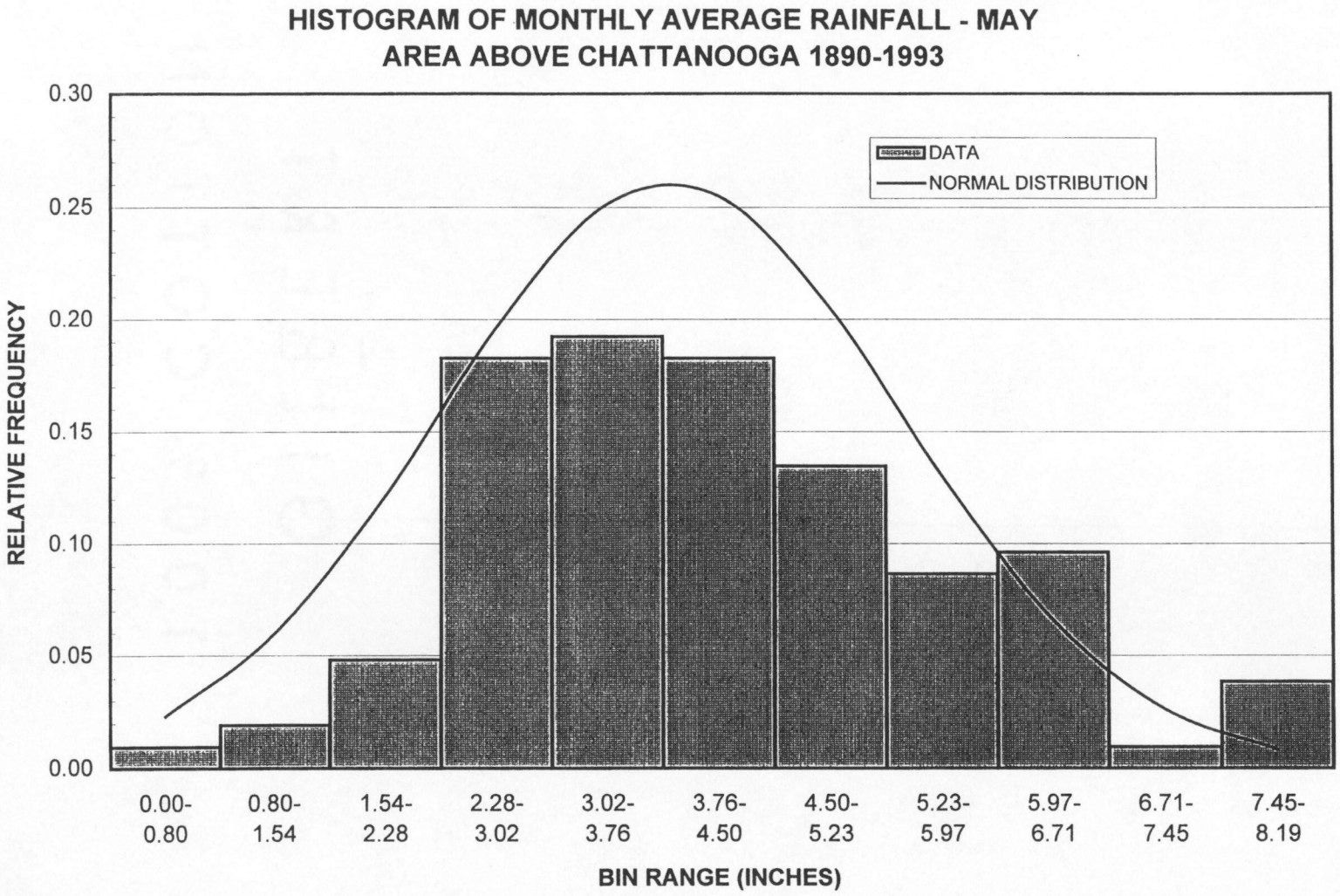
A.37. Frequency Analysis (February). Area Above Chattanooga.



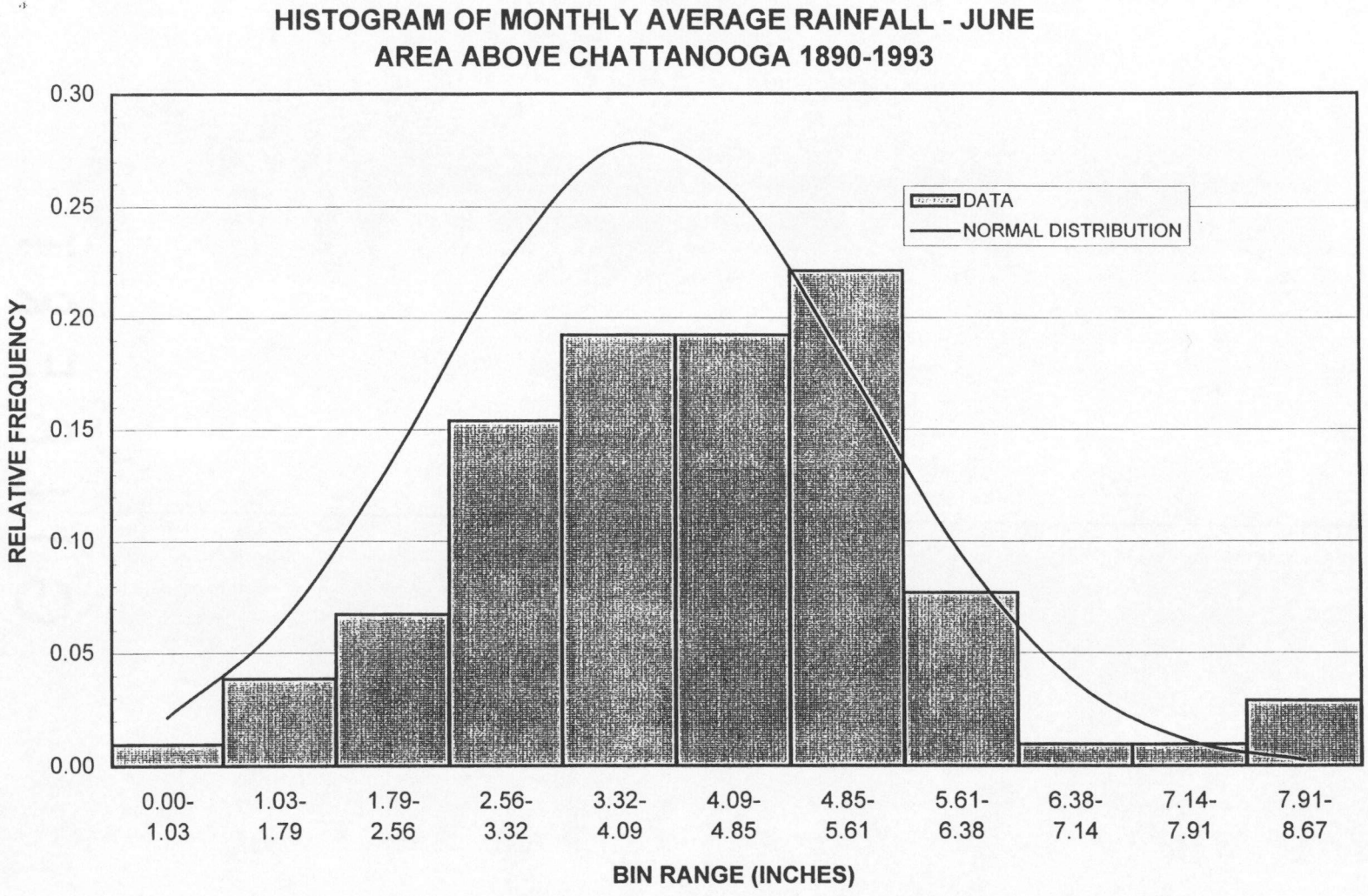
A.38. Frequency Analysis (March). Area Above Chattanooga.



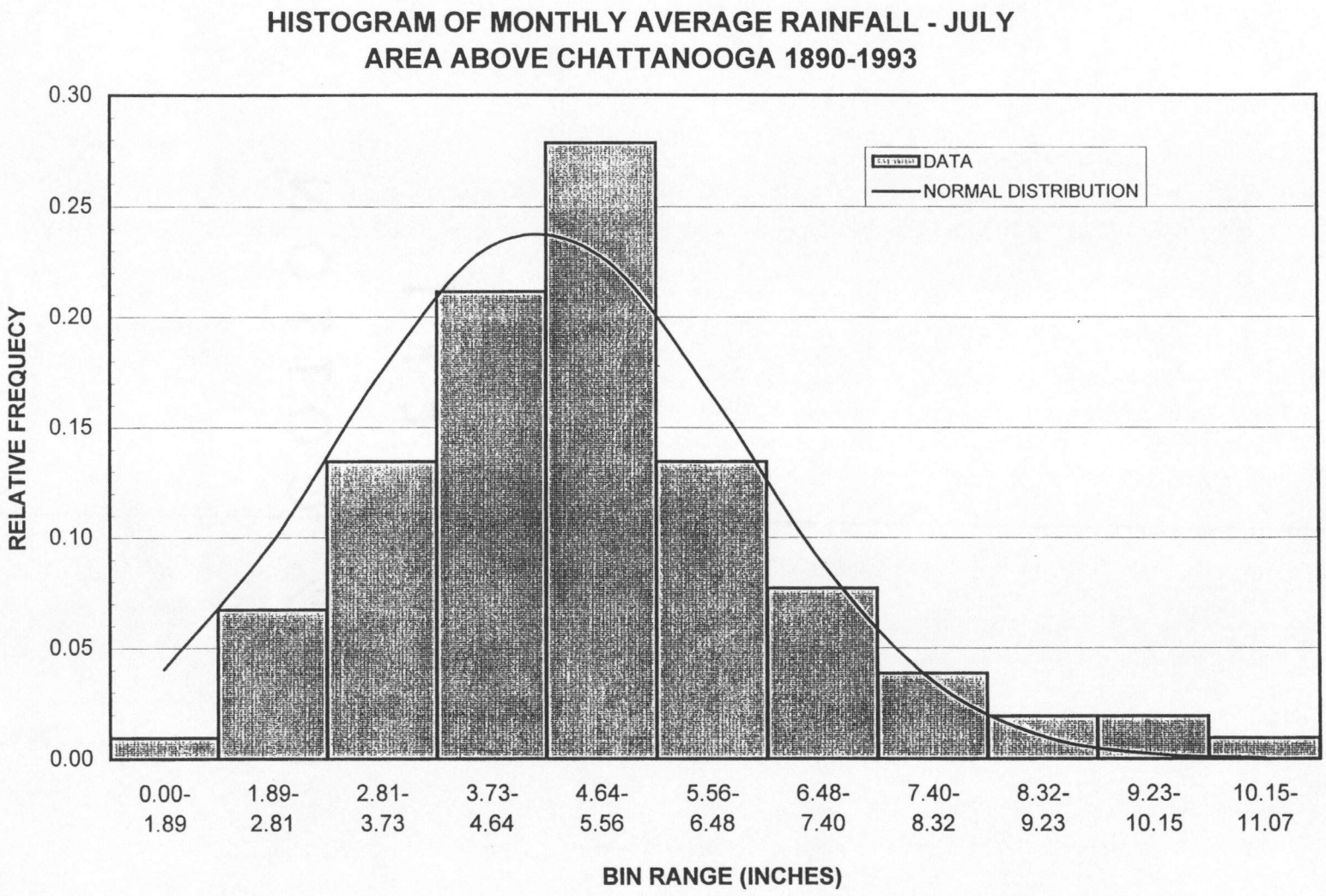
A.39. Frequency Analysis (April). Area Above Chattanooga.



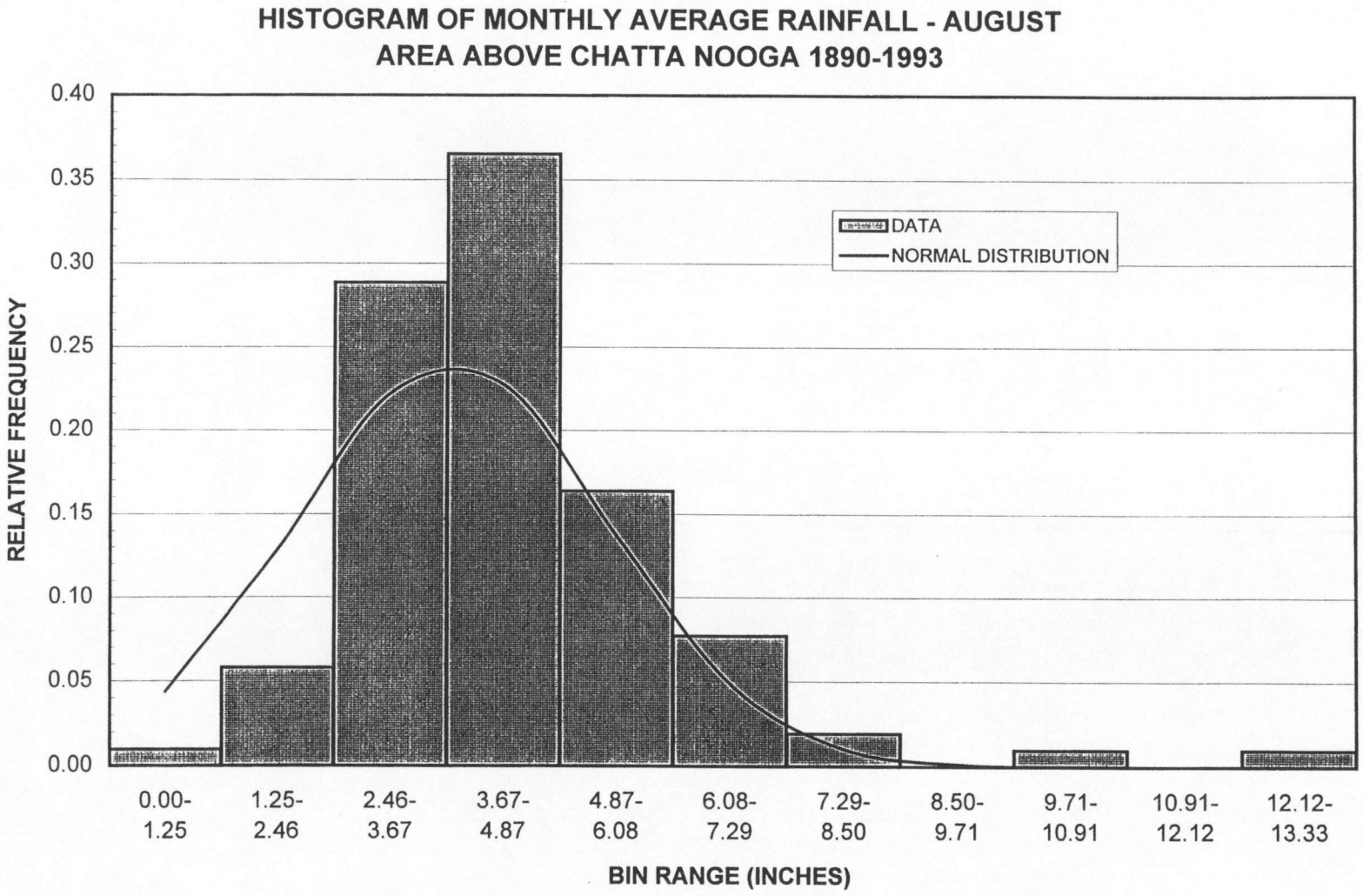
A.40. Frequency Analysis (May). Area Above Chattanooga.



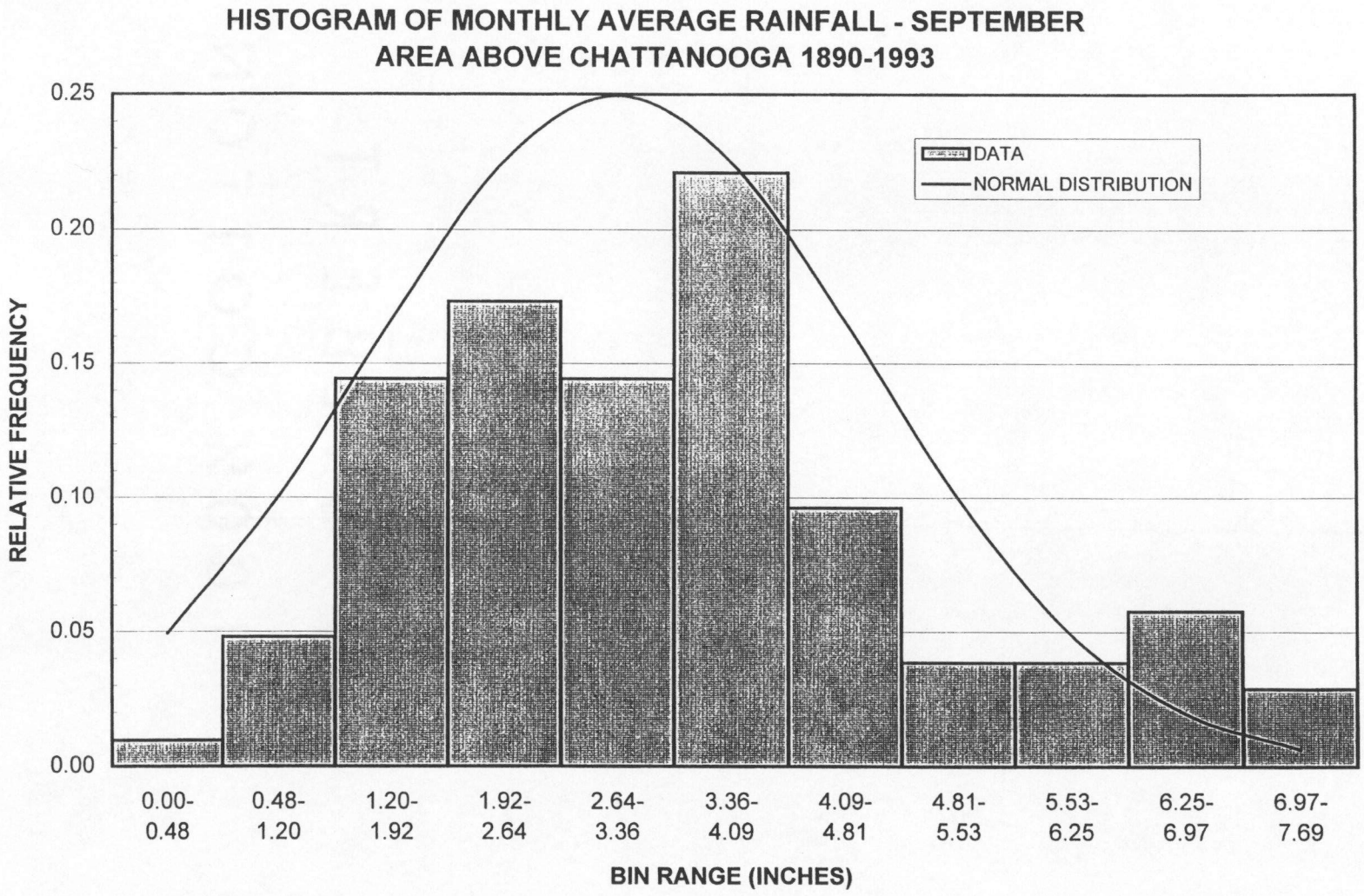
A.41. Frequency Analysis (June). Area Above Chattanooga.



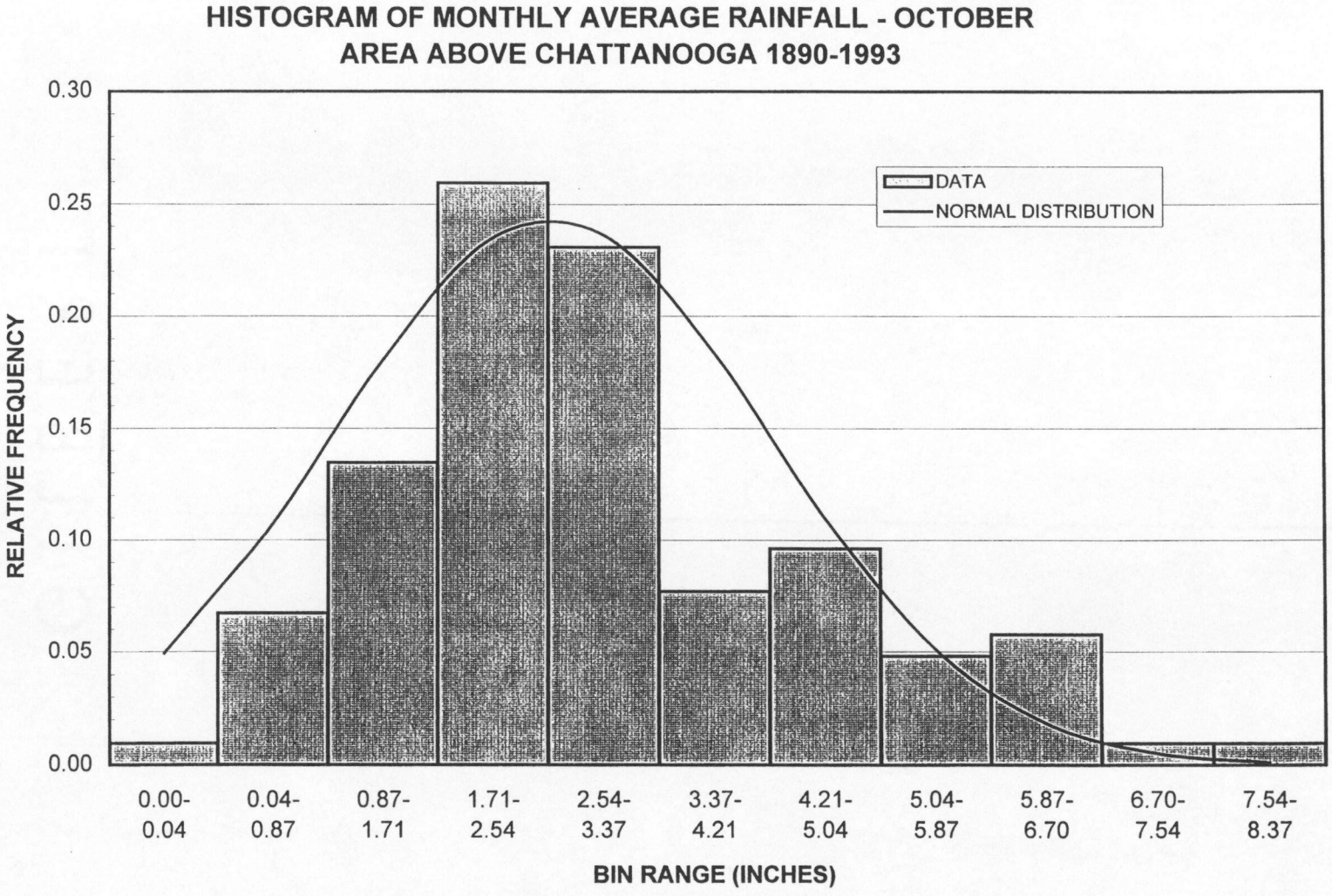
A.42. Frequency Analysis (July). Area Above Chattanooga.



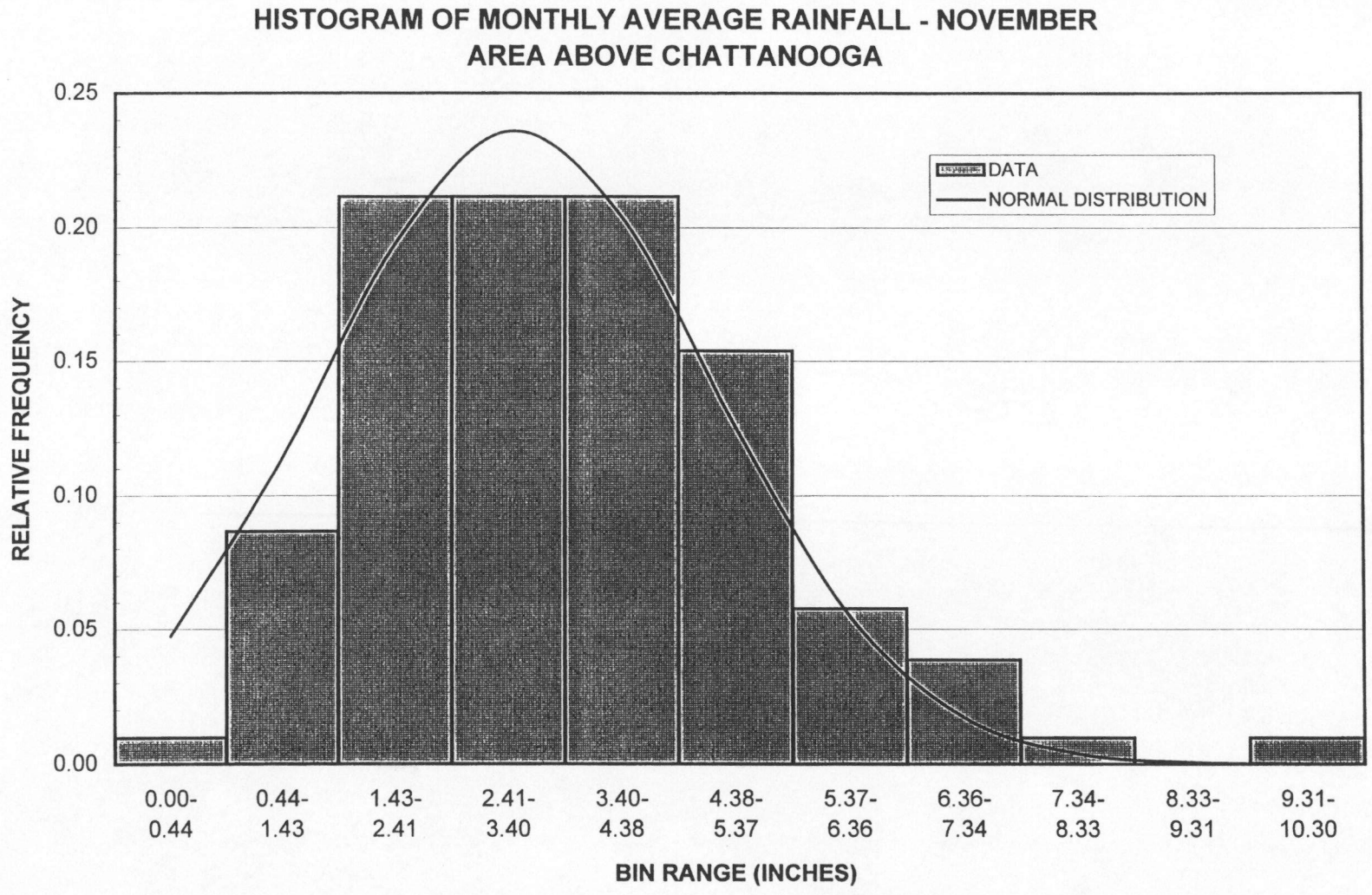
A.43. Frequency Analysis (August). Area Above Chattanooga.



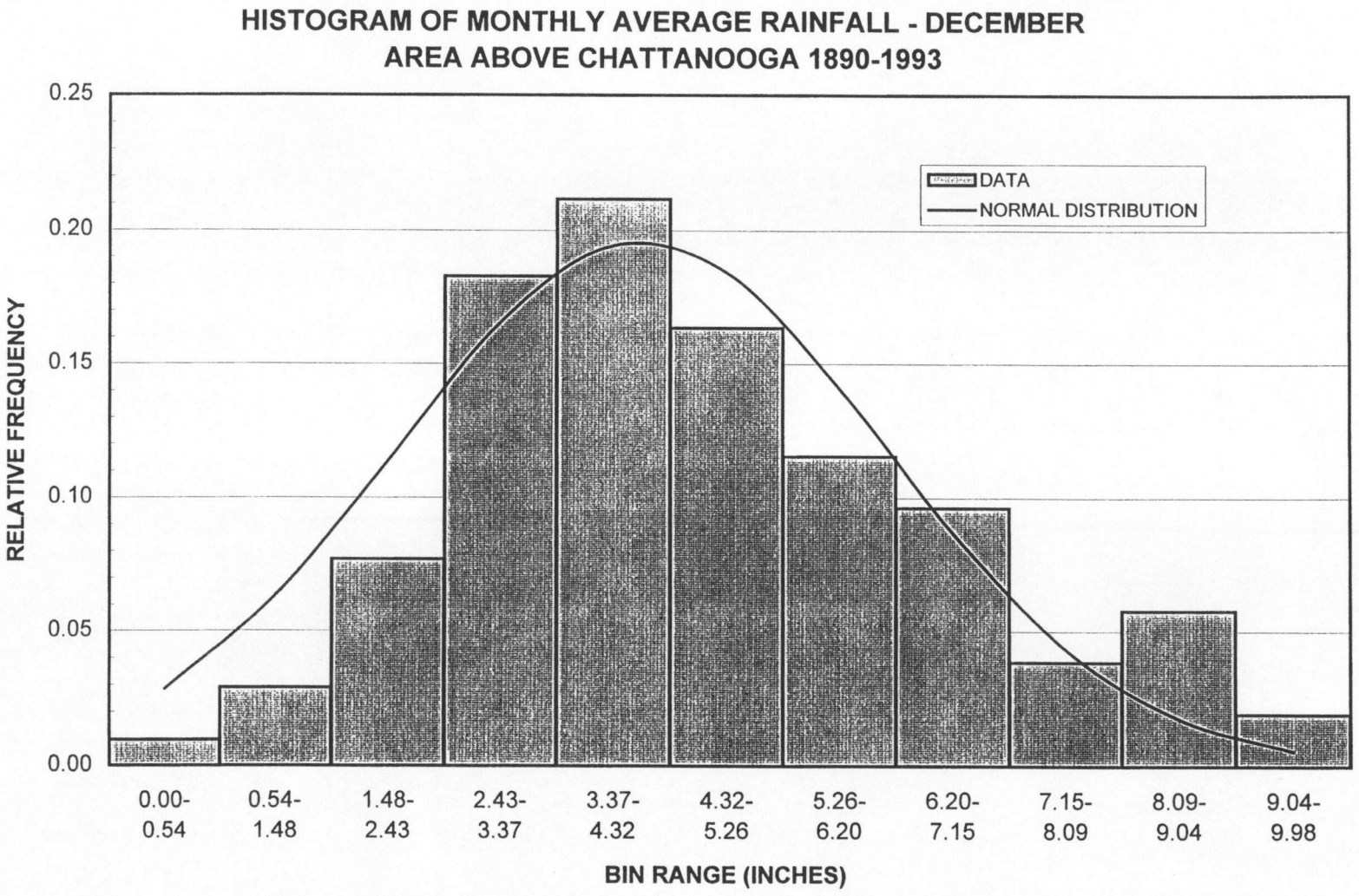
A.44. Frequency Analysis (September). Area Above Chattanooga.



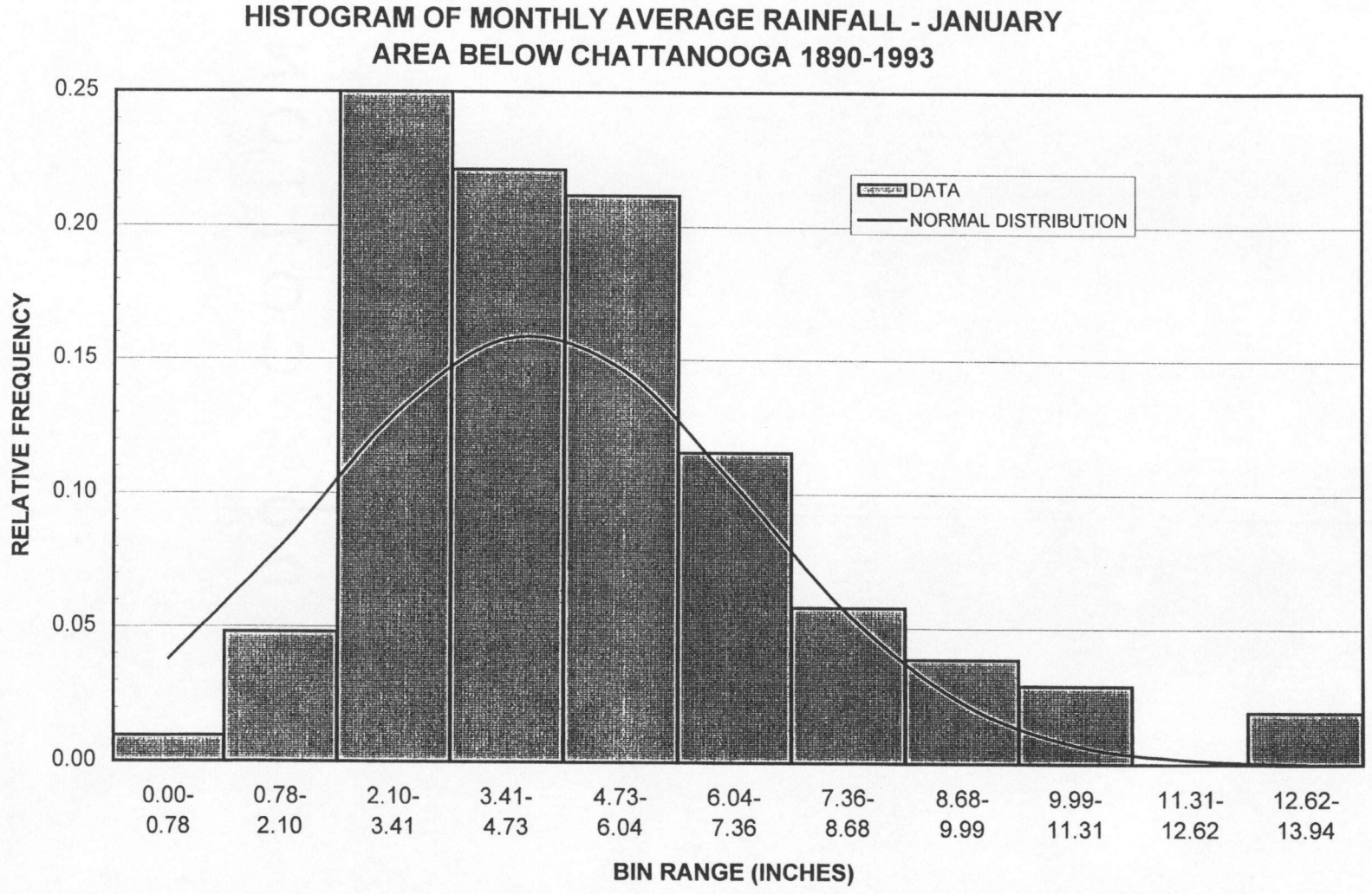
A.45. Frequency Analysis (October). Area Above Chattanooga.



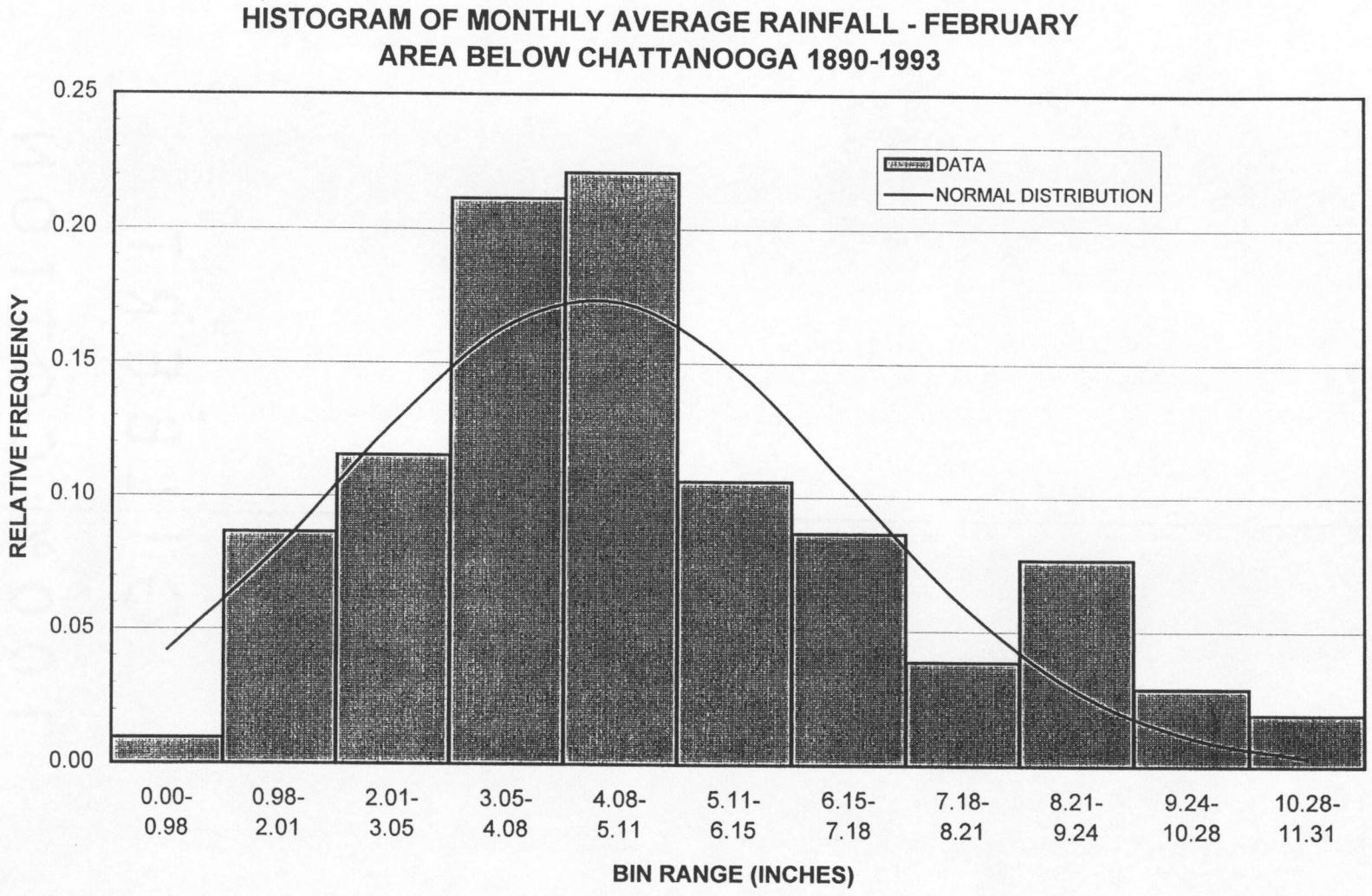
A.46. Frequency Analysis (November). Area Above Chattanooga.



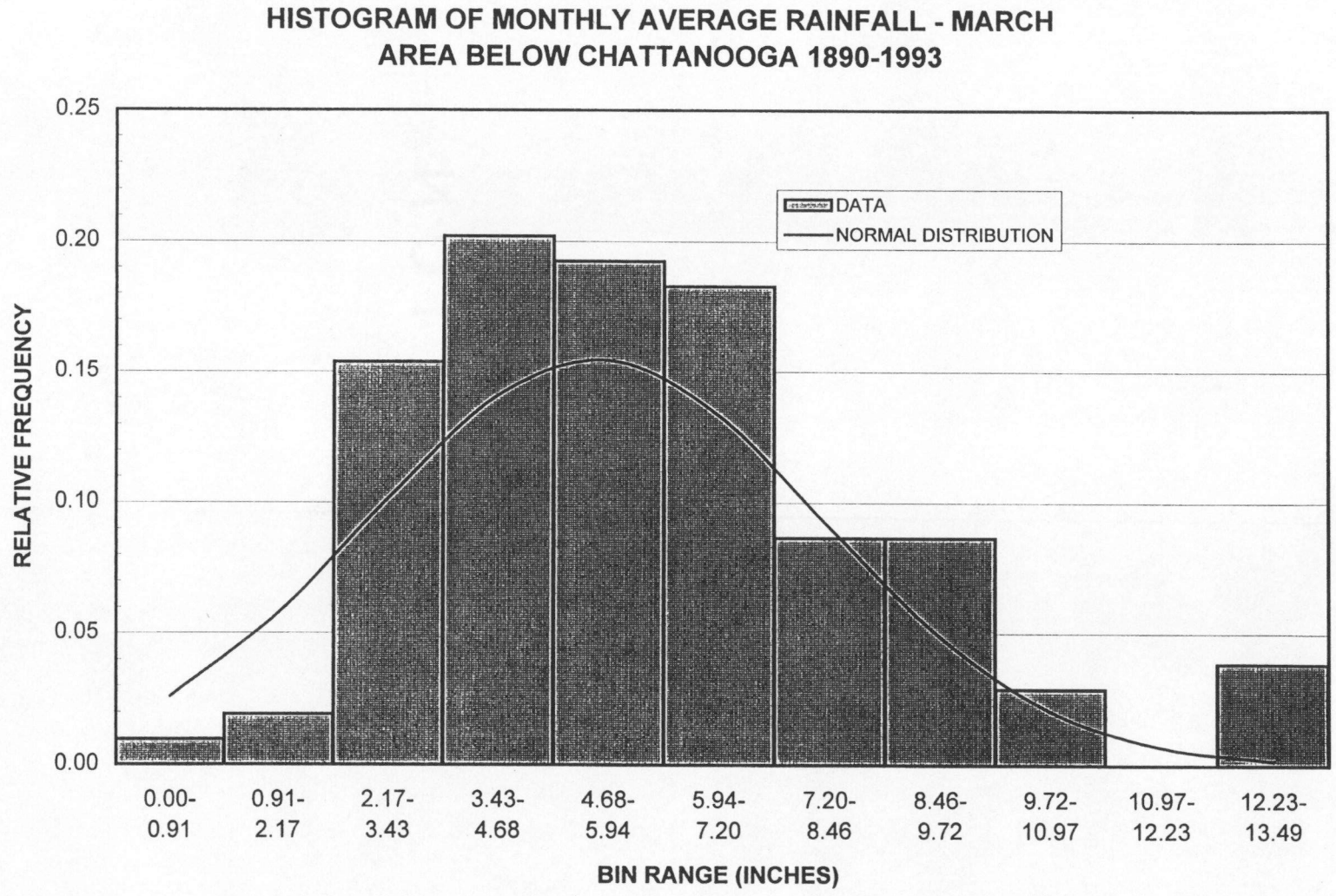
A.47. Frequency Analysis (December). Area Above Chattanooga.



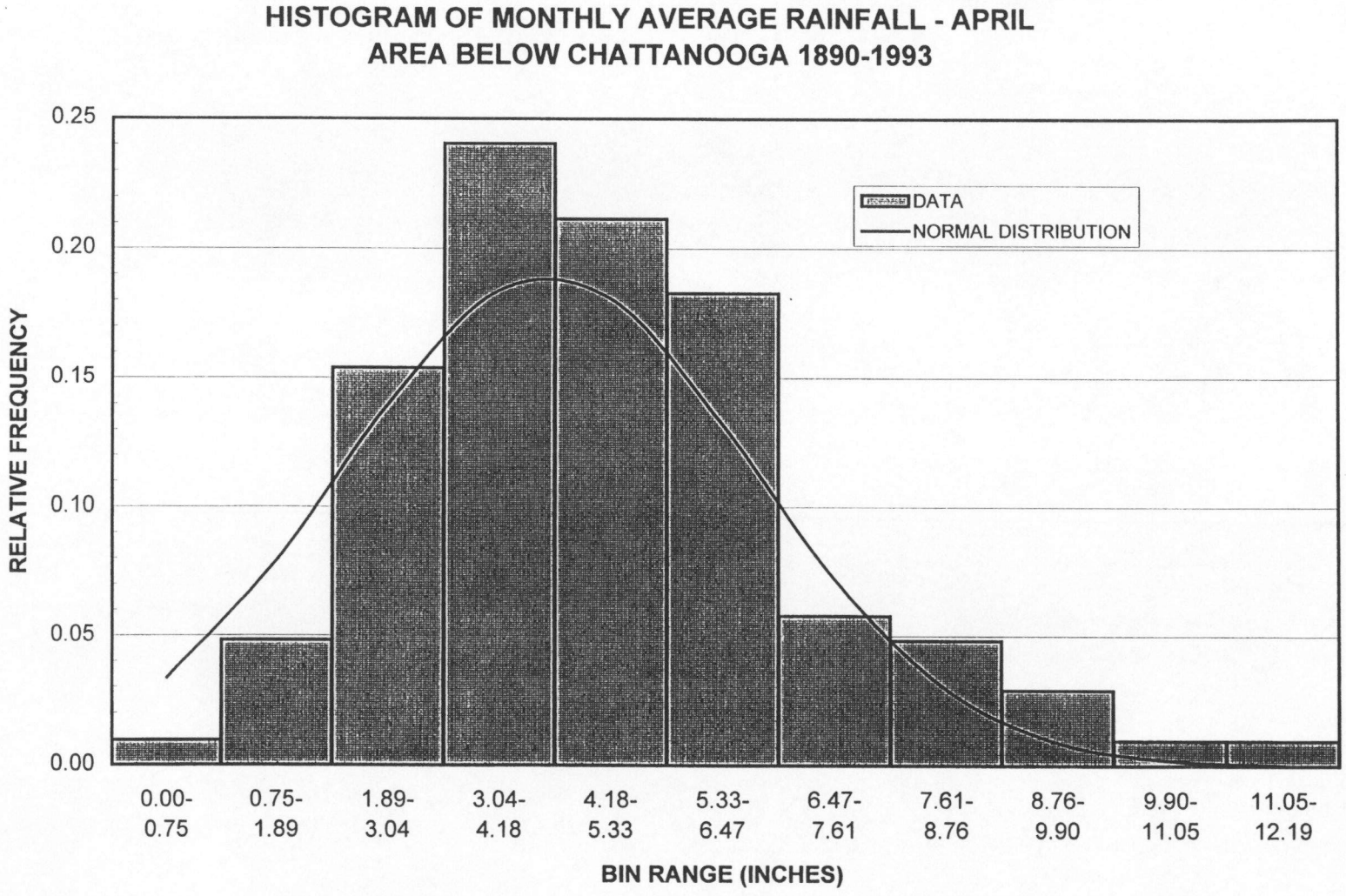
A.48. Frequency Analysis (January). Area Below Chattanooga.



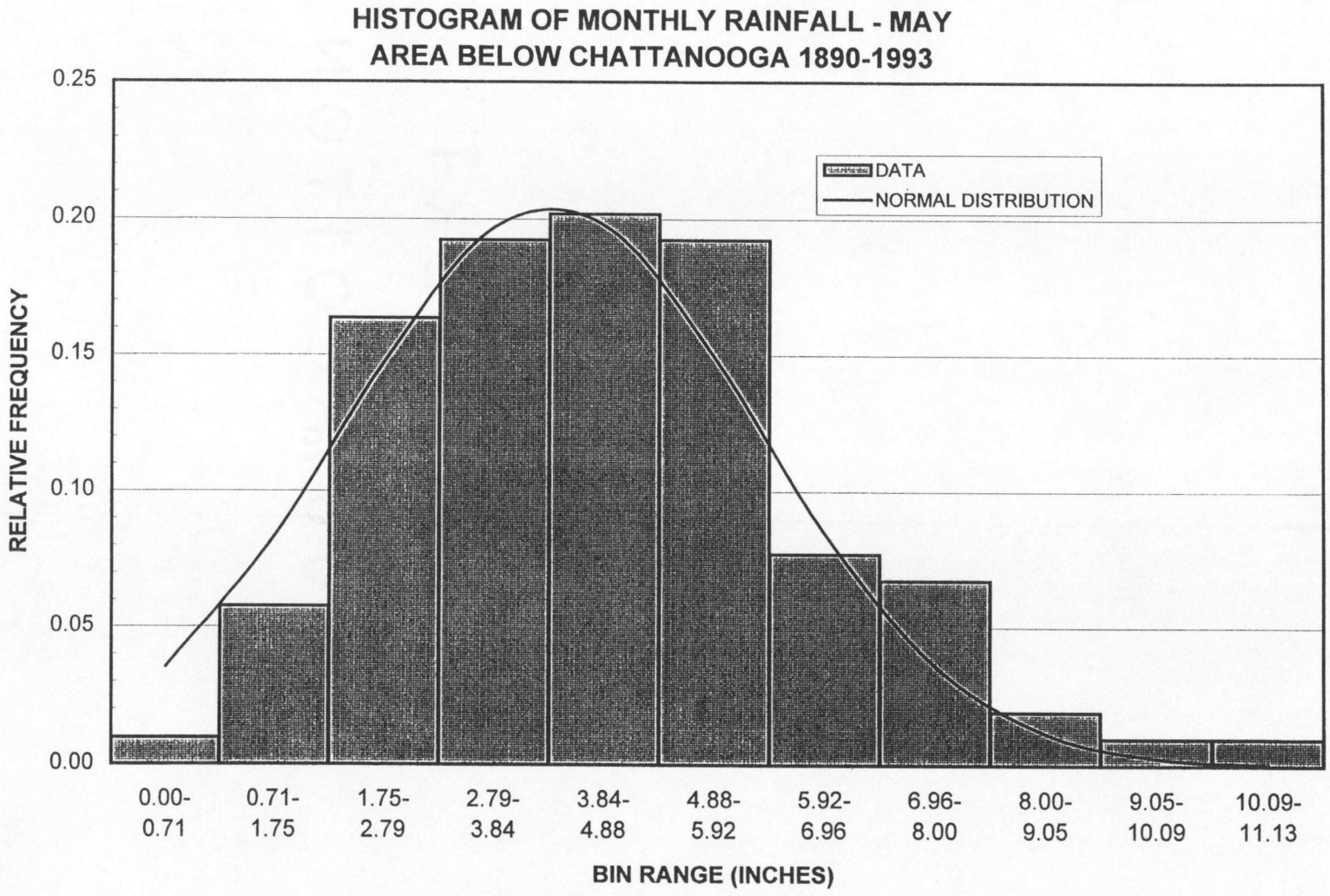
A.49. Frequency Analysis (February). Area Below Chattanooga.



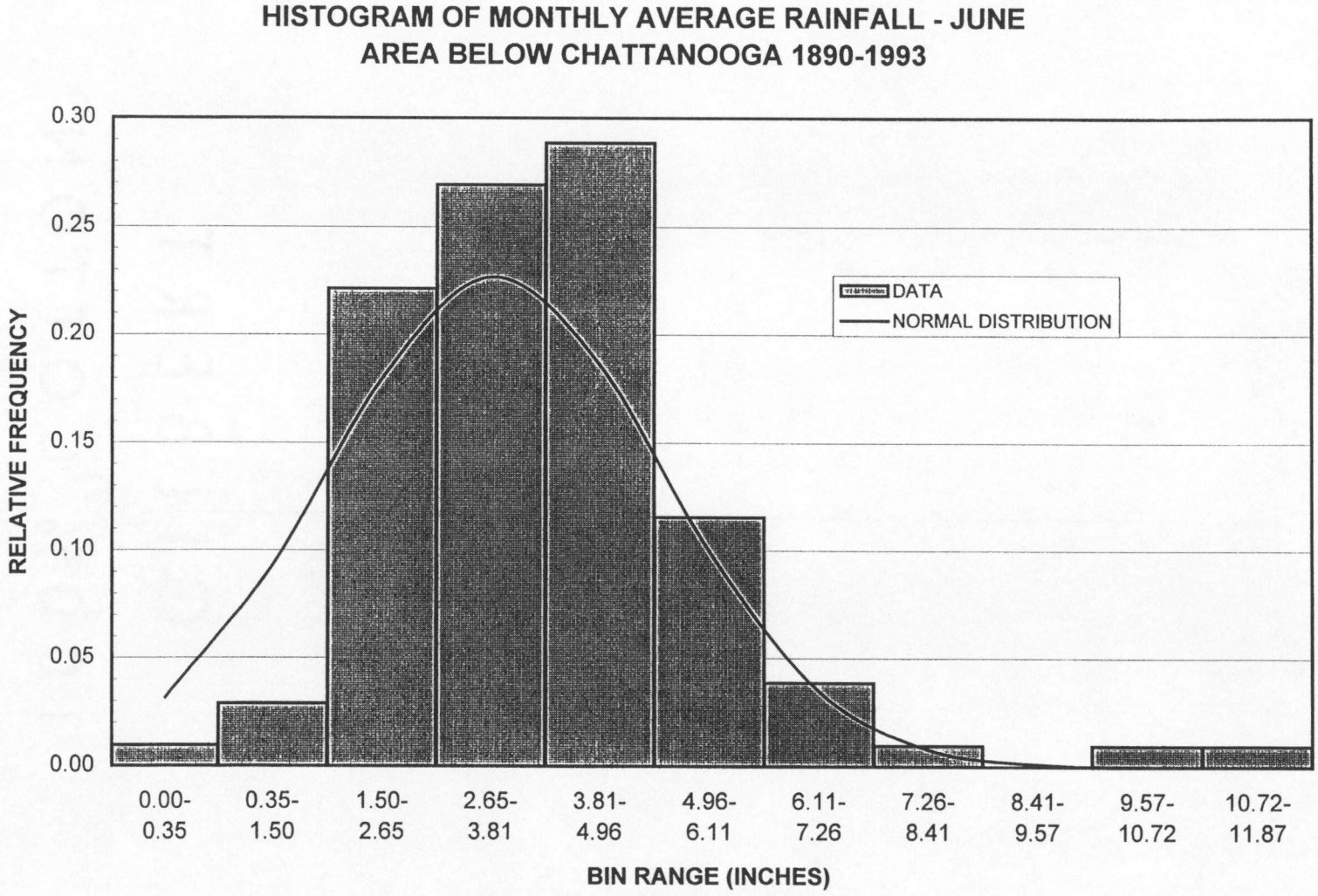
A.50. Frequency Analysis (March). Area Below Chattanooga.



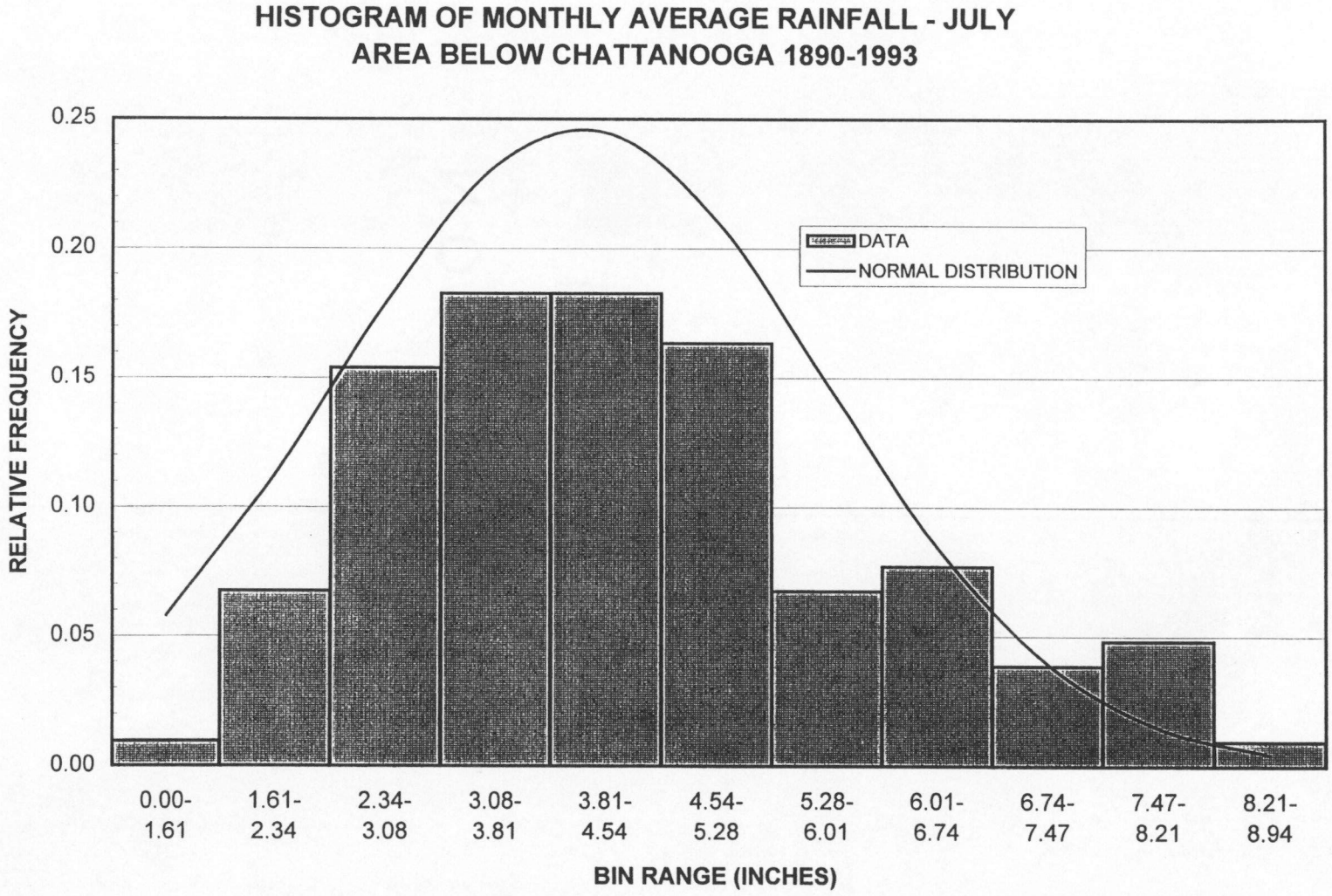
A.51. Frequency Analysis (April). Area Below Chattanooga.



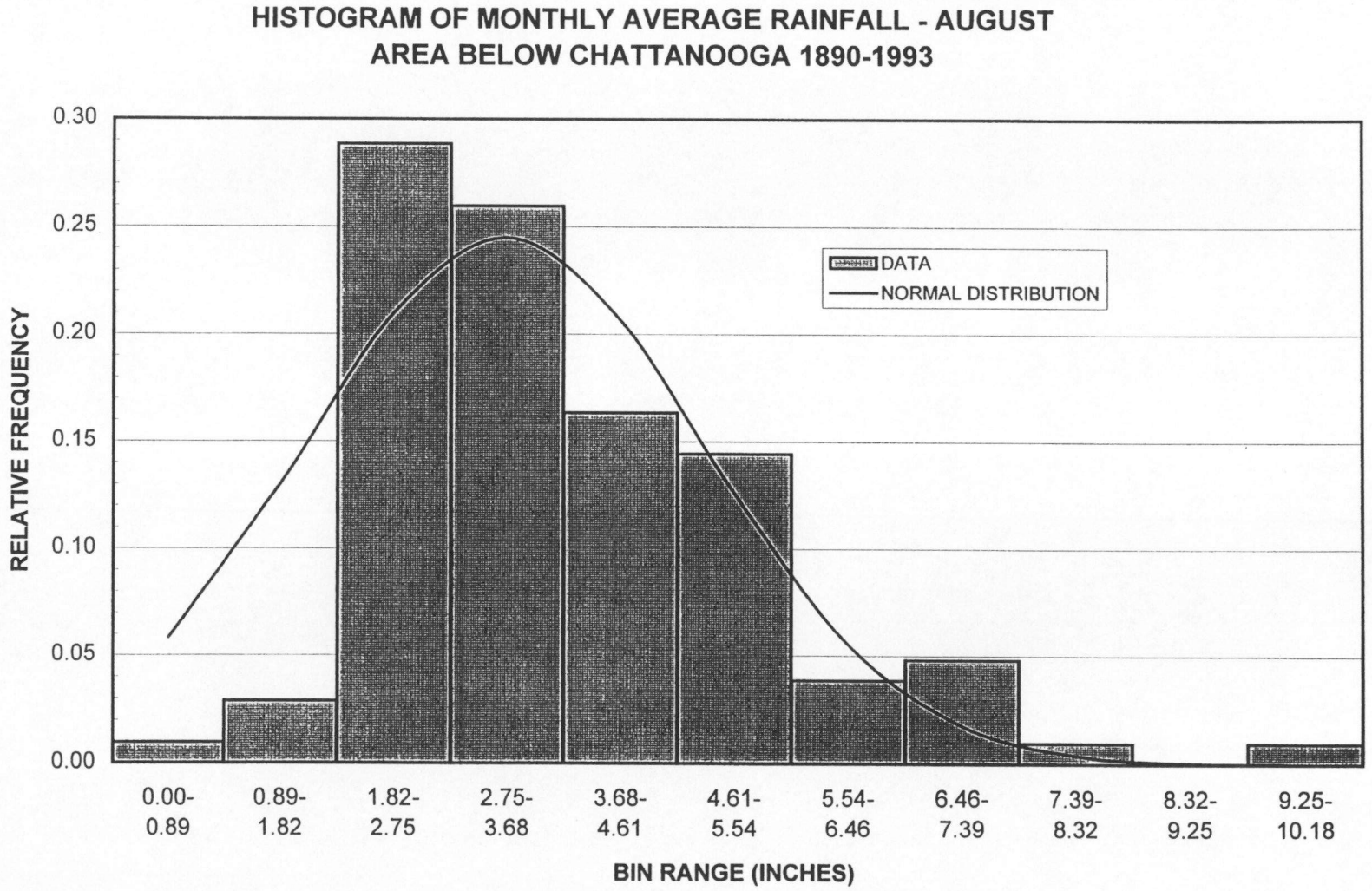
A.52. Frequency Analysis (May). Area Below Chattanooga.



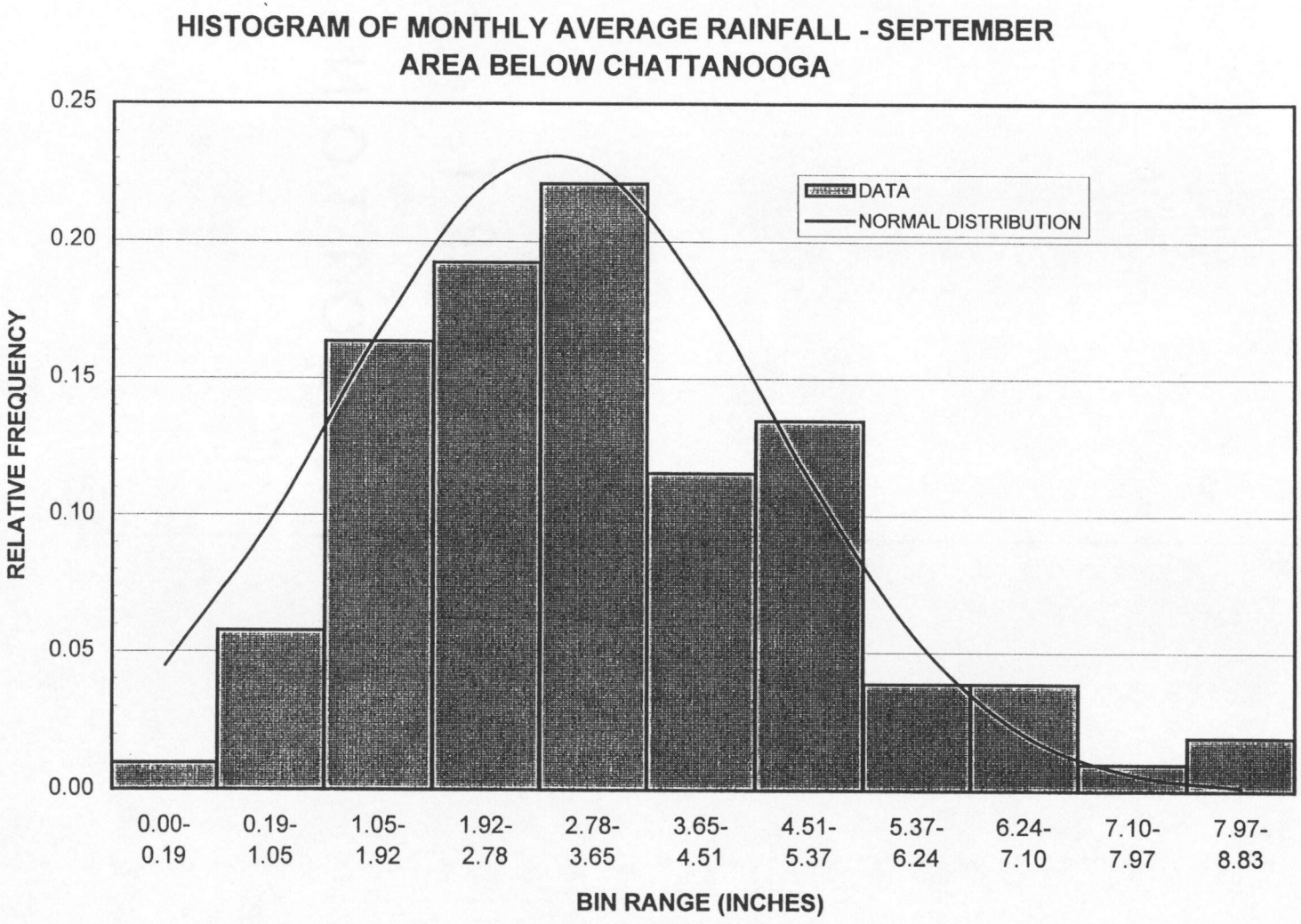
A.53. Frequency Analysis (June). Area Below Chattanooga.



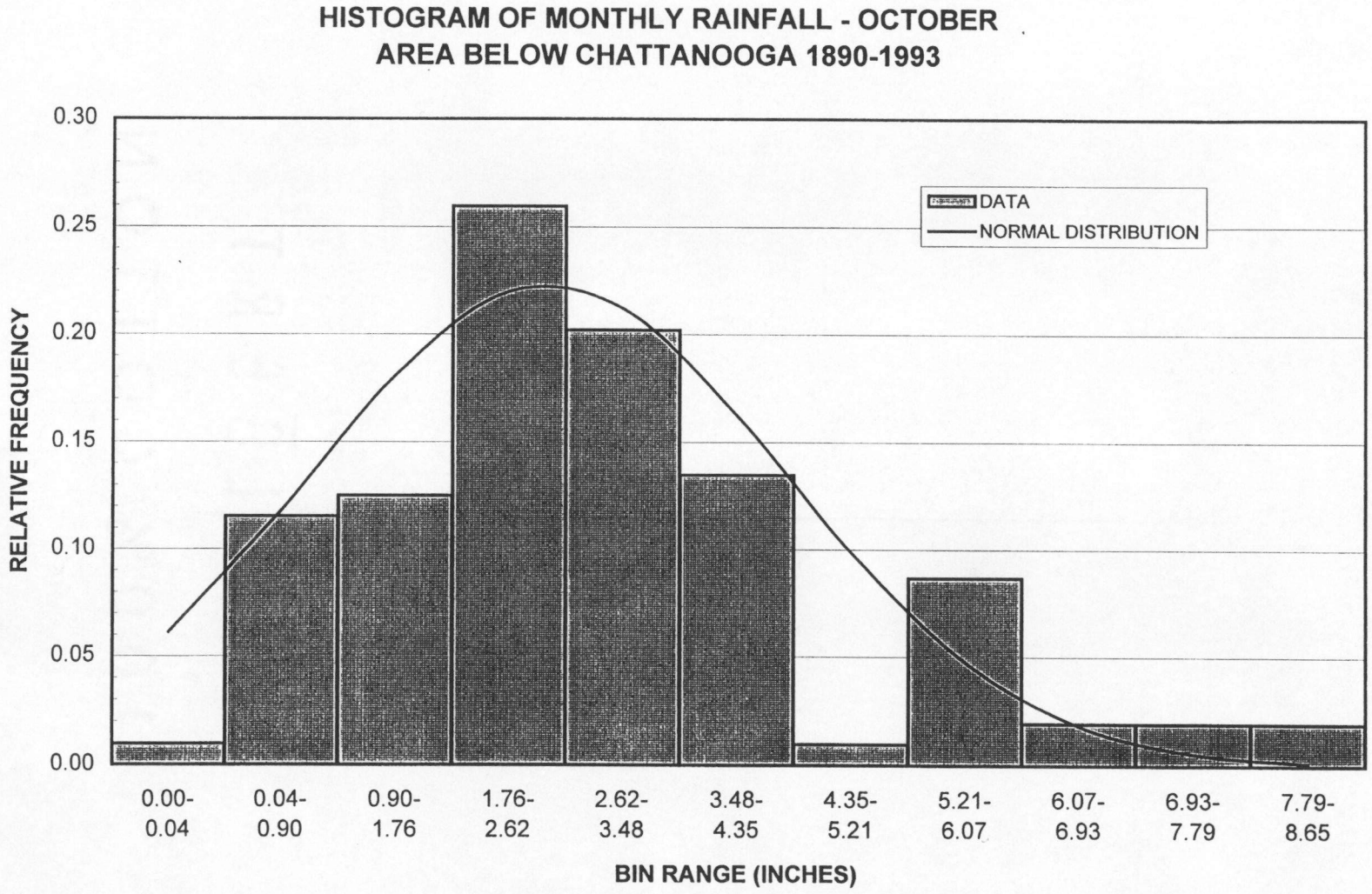
A.54. Frequency Analysis (July). Area Below Chattanooga.



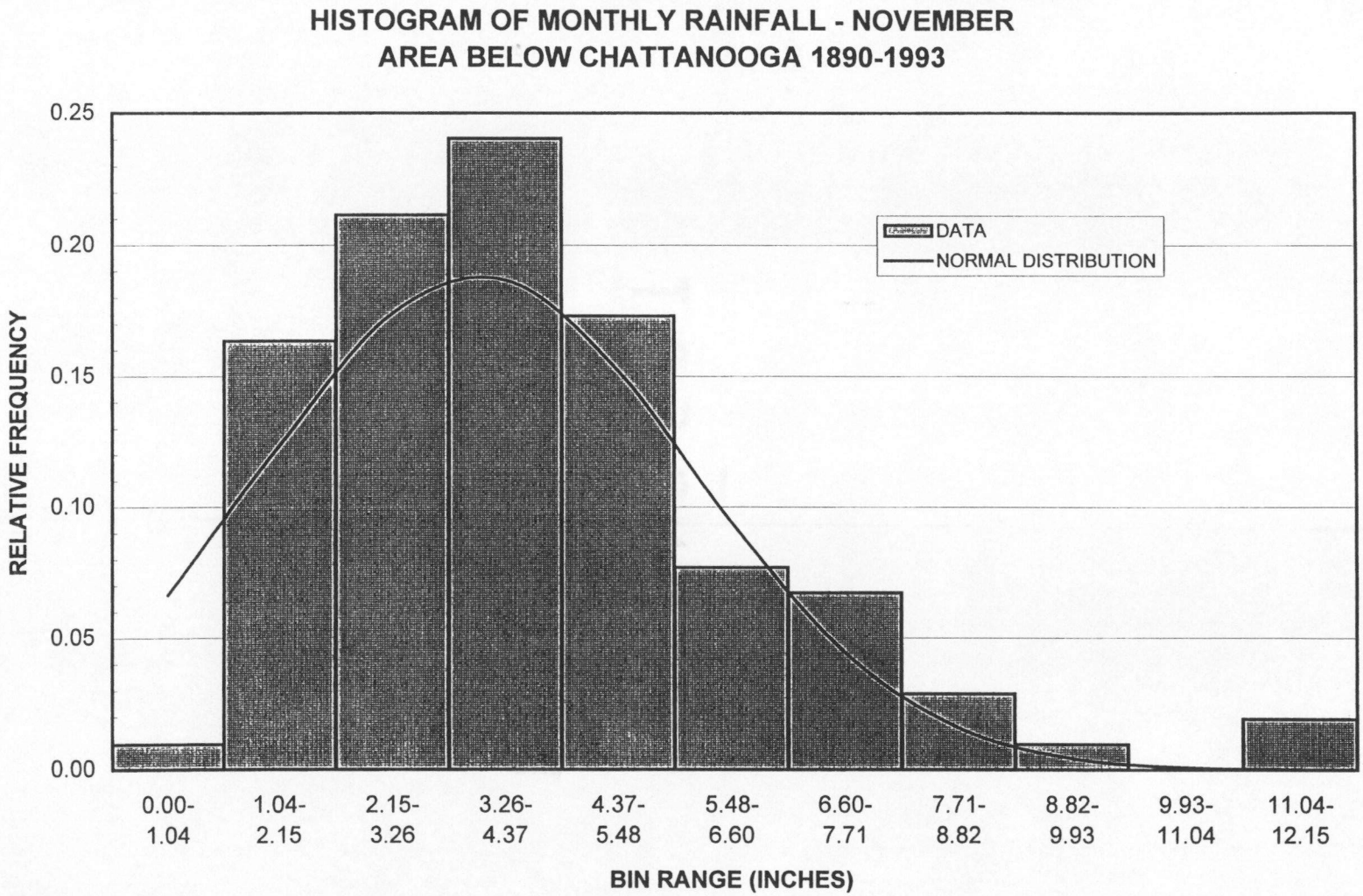
A.55. Frequency Analysis (August). Area Below Chattanooga.



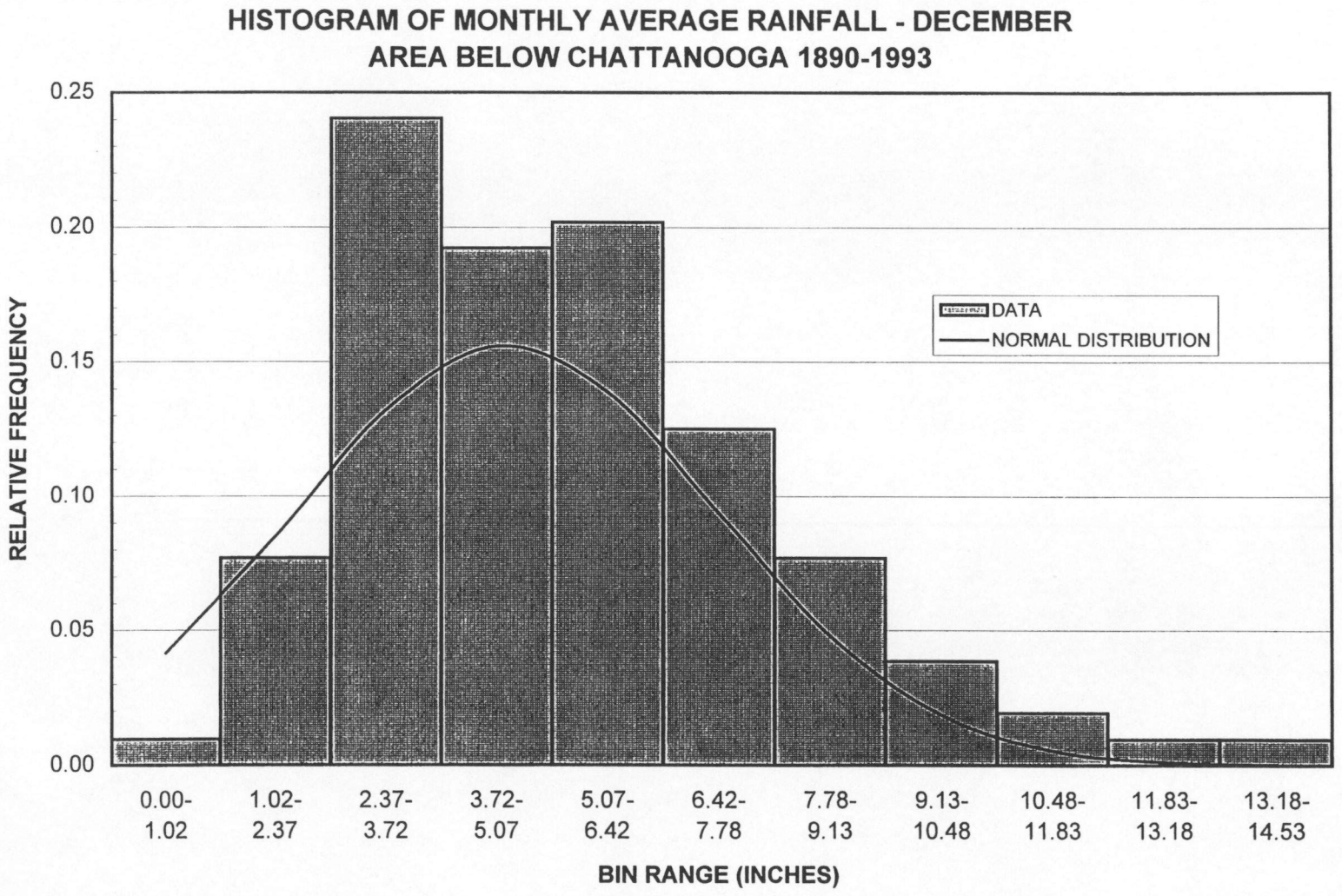
A.56. Frequency Analysis (September). Area Below Chattanooga.



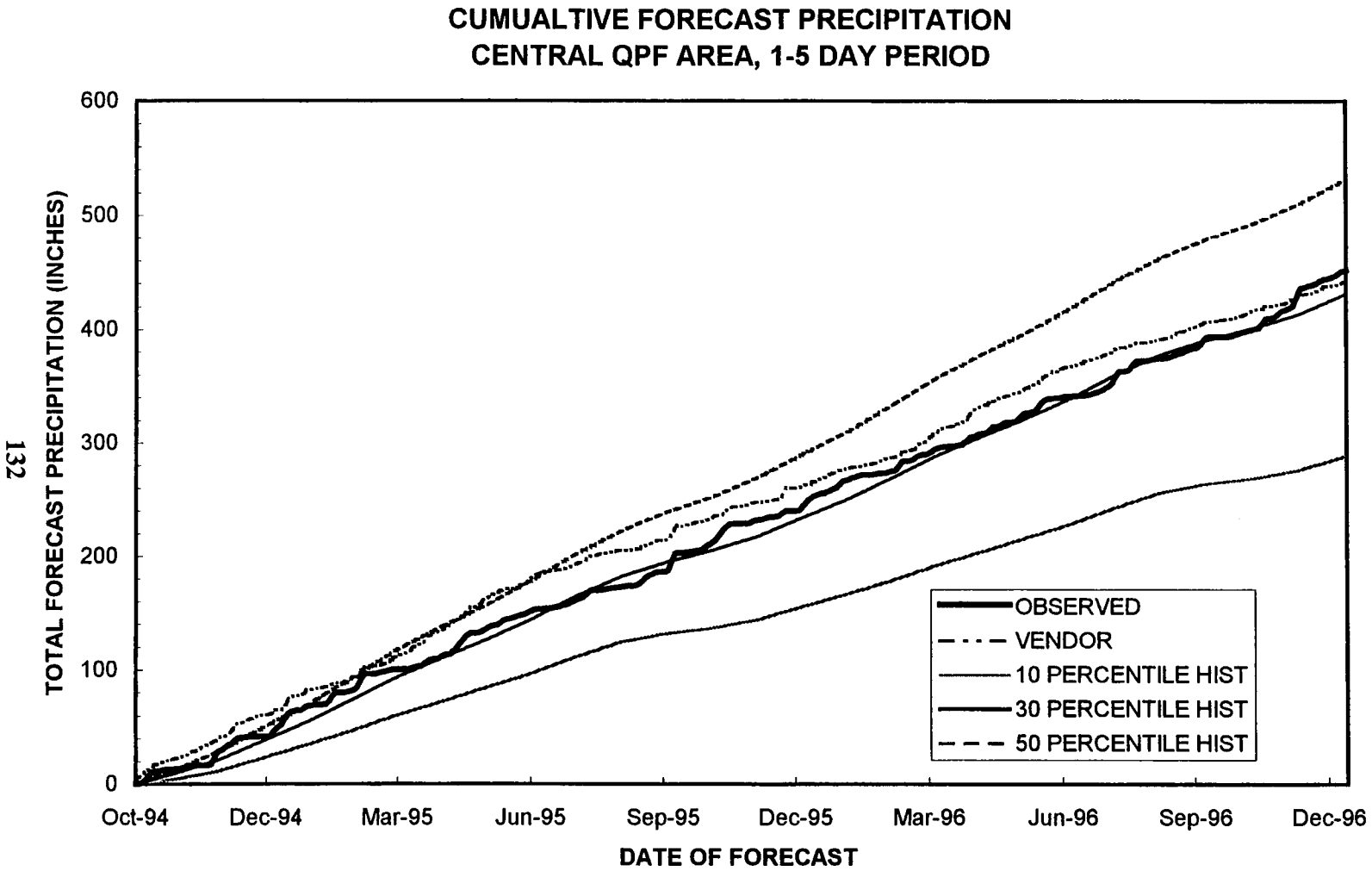
A.57. Frequency Analysis (October). Area Below Chattanooga.



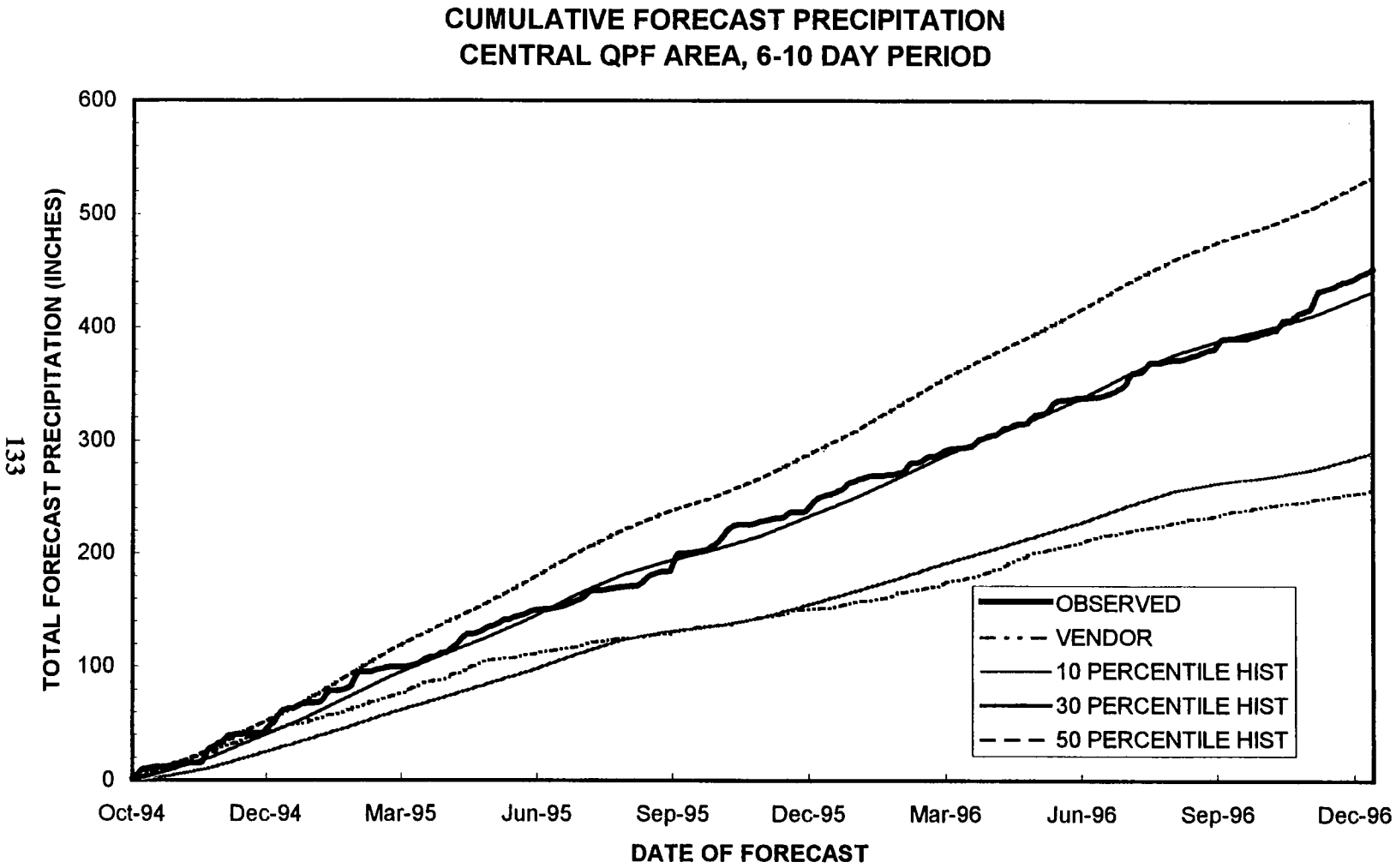
A.58. Frequency Analysis (November). Area Below Chattanooga.



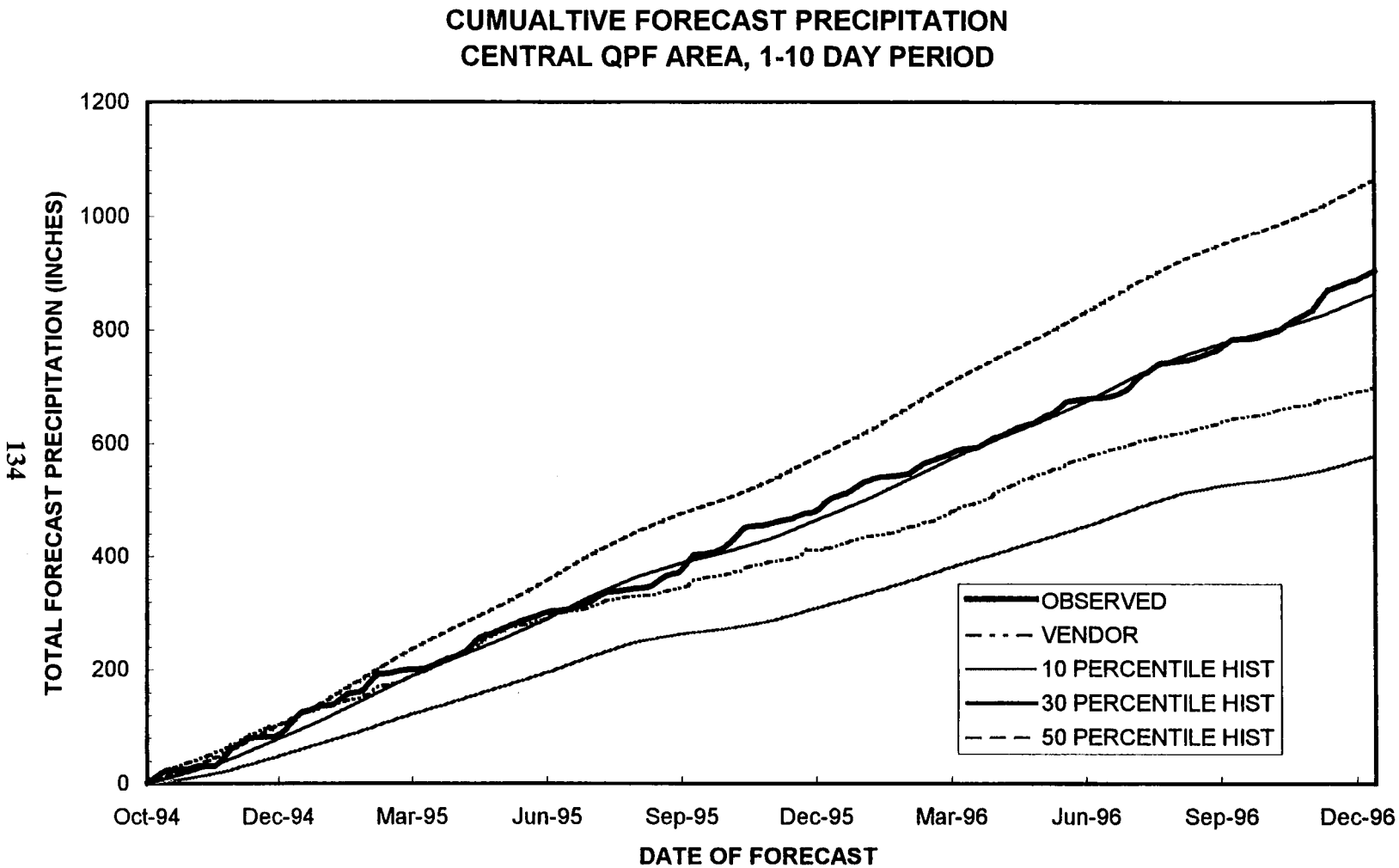
A.59. Frequency Analysis (December). Area Below Chattanooga.



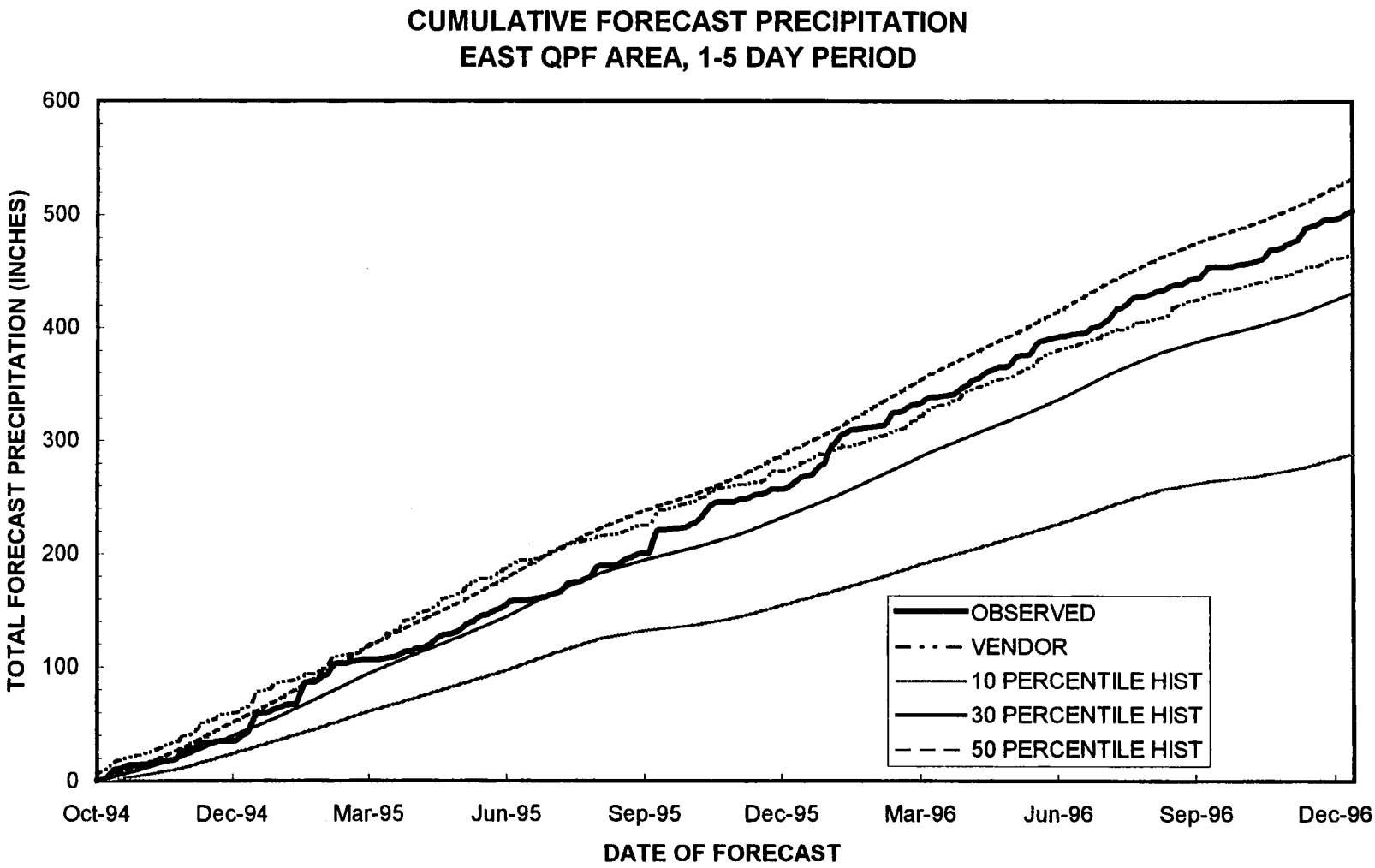
A.60 Cumulative Volume Analysis (1 to 5-Day Period). Central QPF Area.



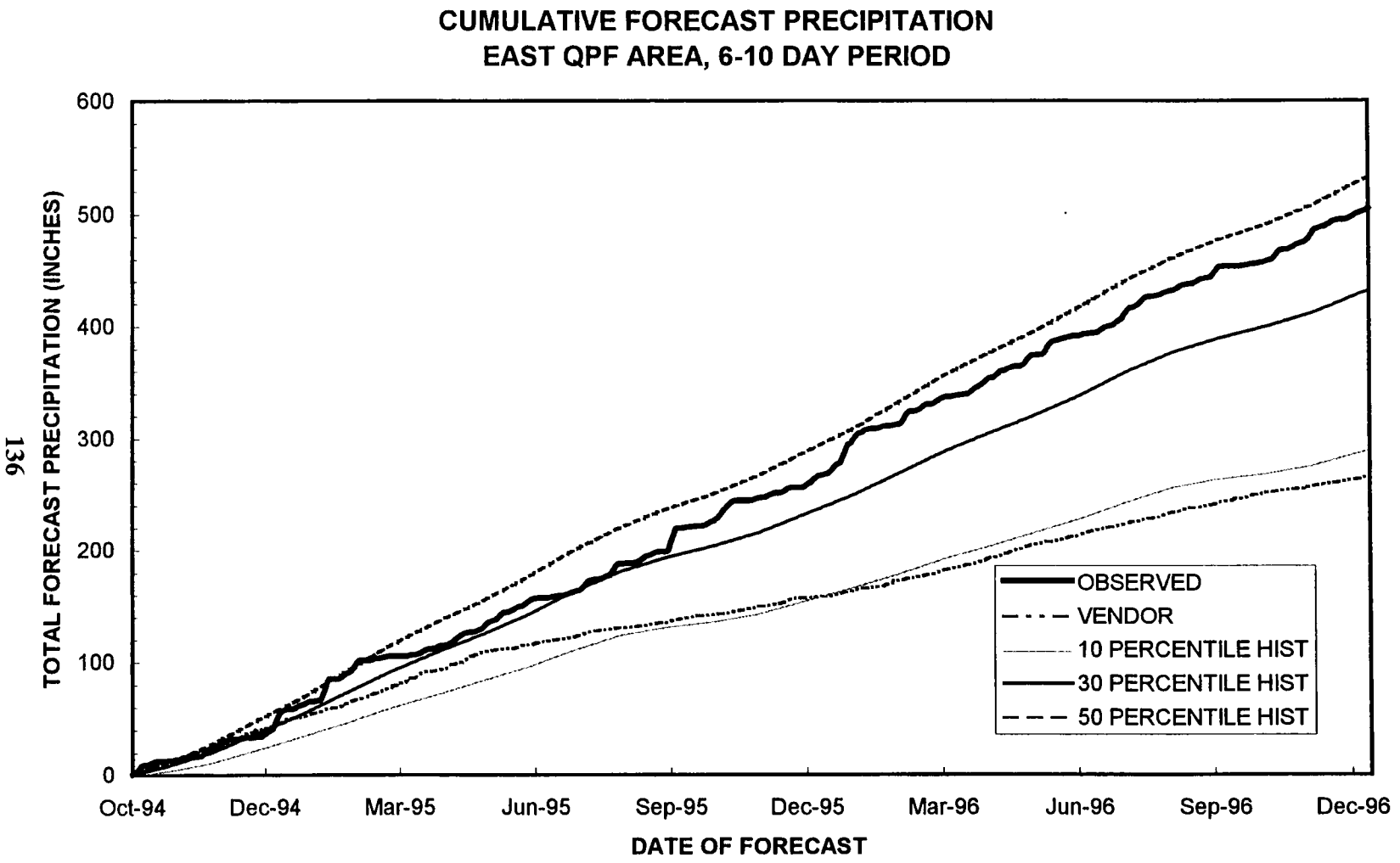
A.61. Cumulative Volume Analysis (6 to 10-Day Period). Central QPF Area.



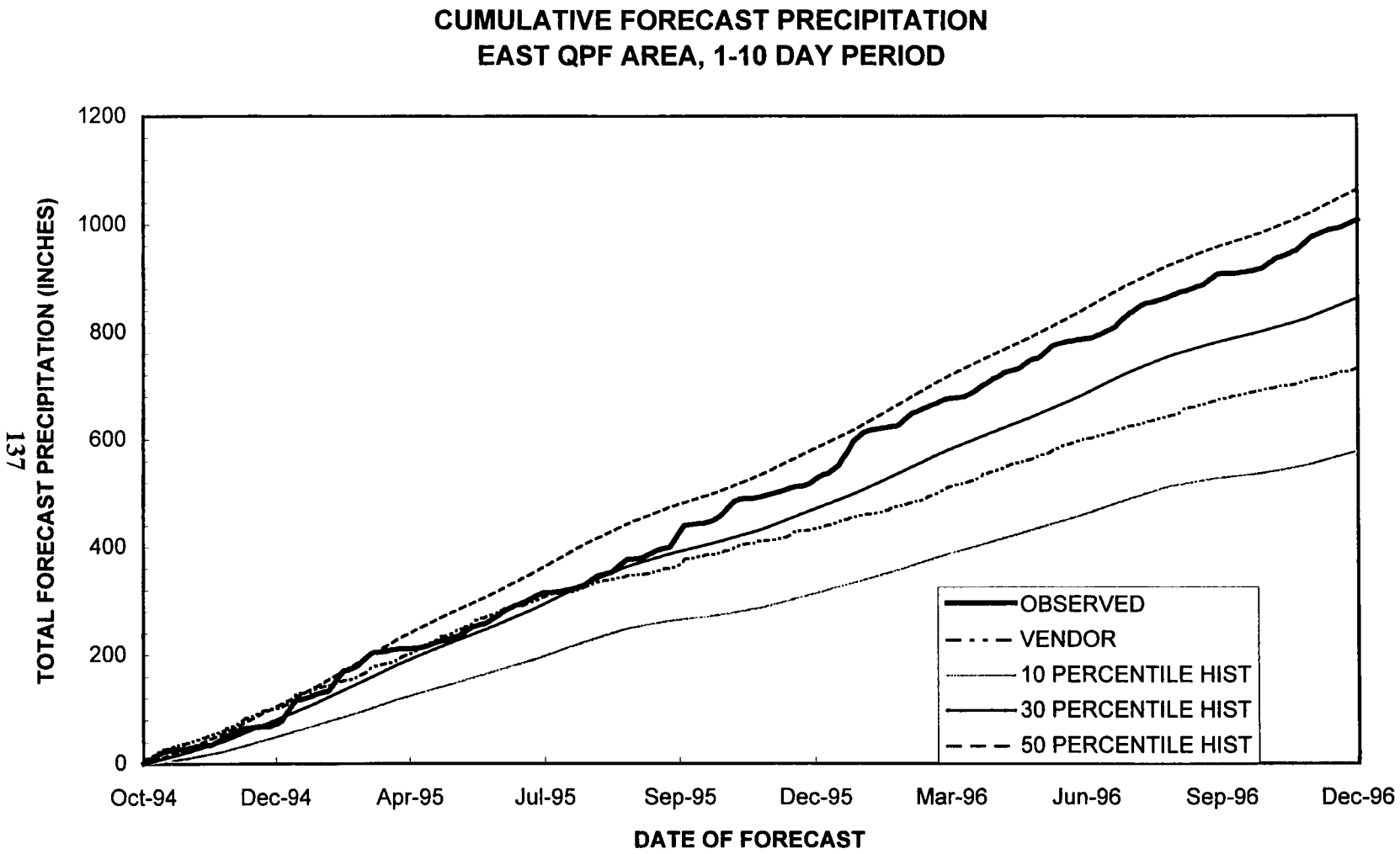
A.62. Cumulative Volume Analysis (1 to 10-Day Period). Central QPF Area.



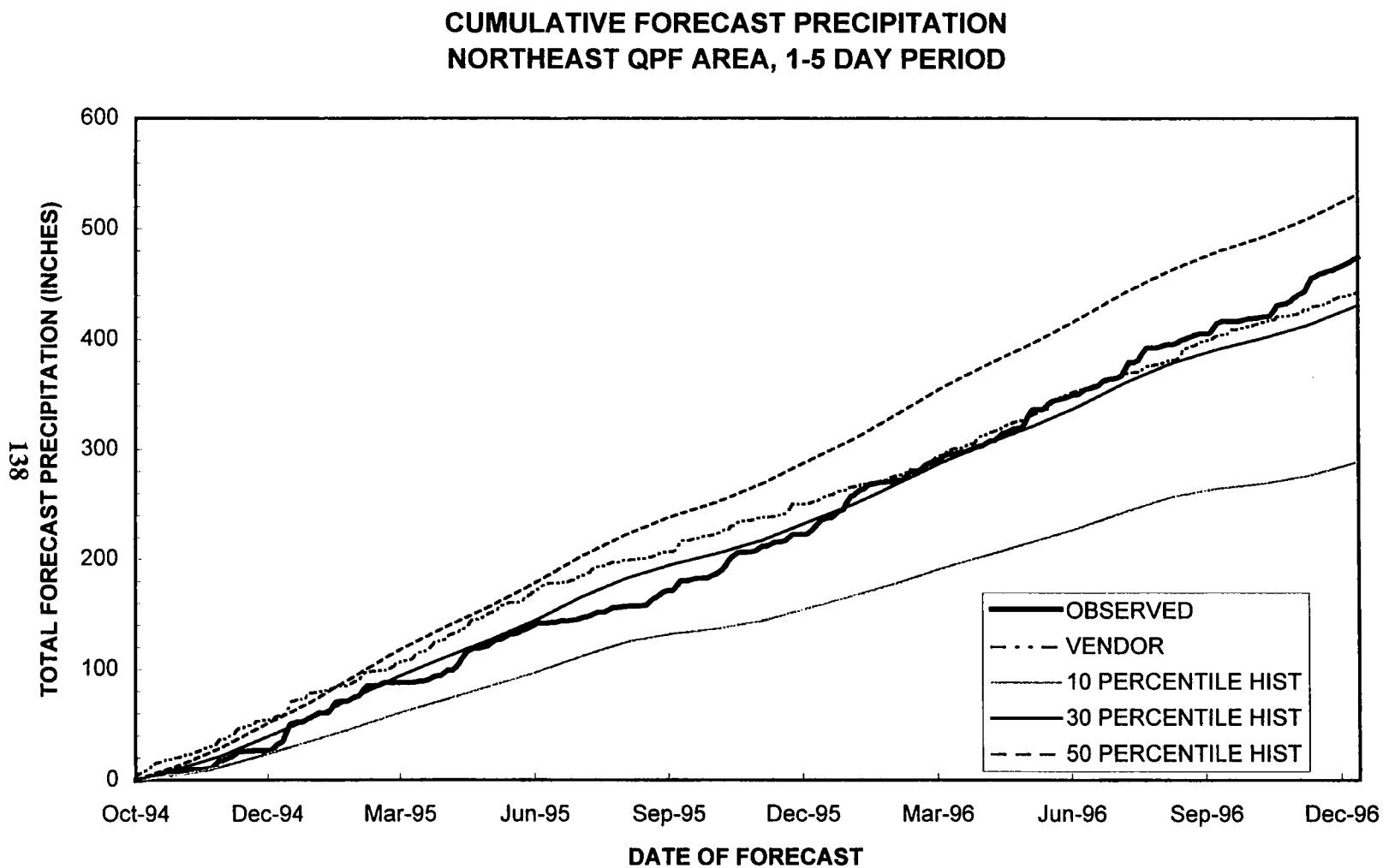
A.63. Cumulative Volume Analysis (1 to 5-Day Period). East QPF Area.



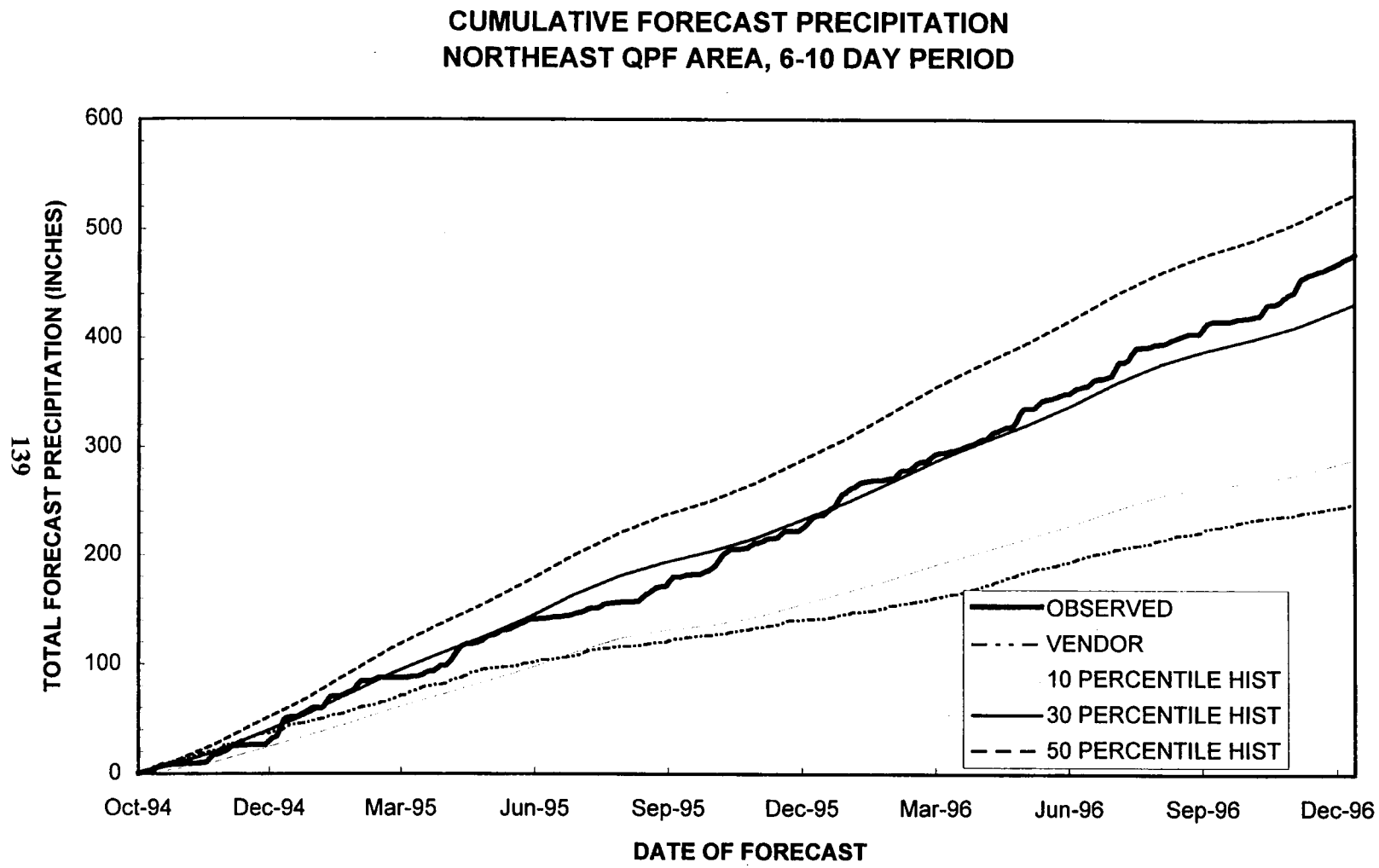
A.64. Cumulative Volume Analysis (6 to 10-Day Period). East QPF Area.



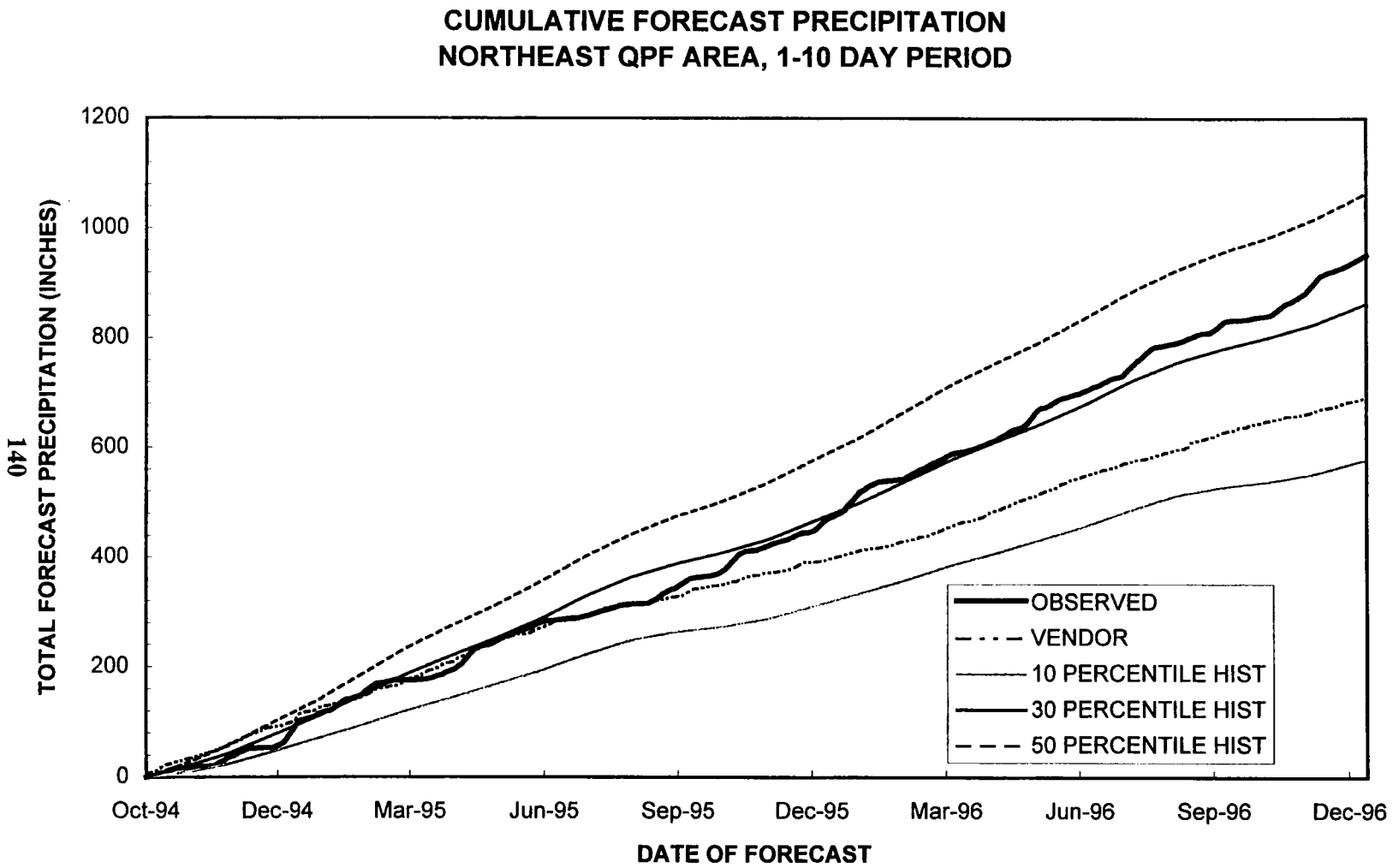
A.65. Cumulative Volume Analysis (1 to 10-Day Period). East QPF.



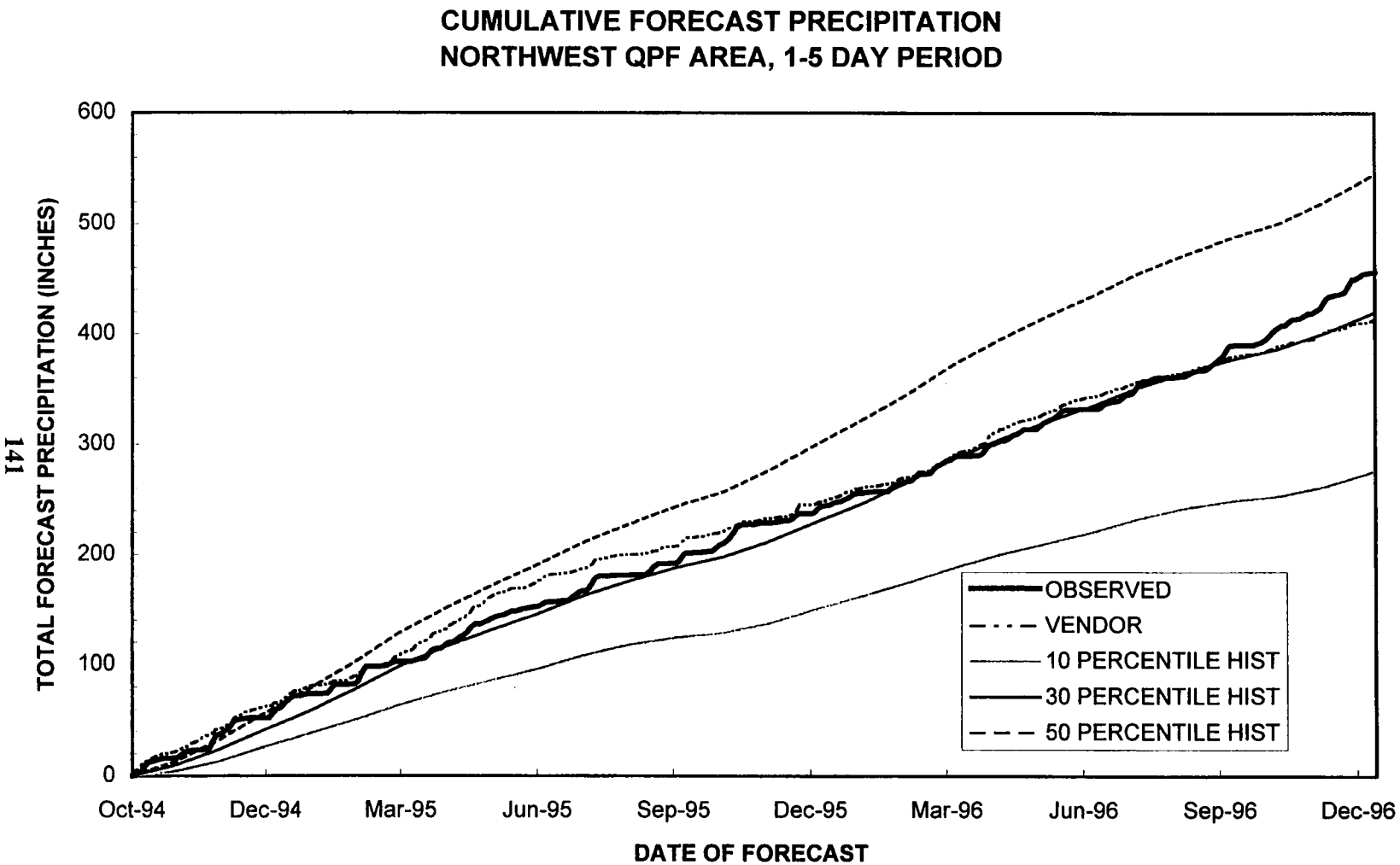
A.66. Cumulative Volume Analysis (1 to 5-Day Period). Northeast QPF Area.



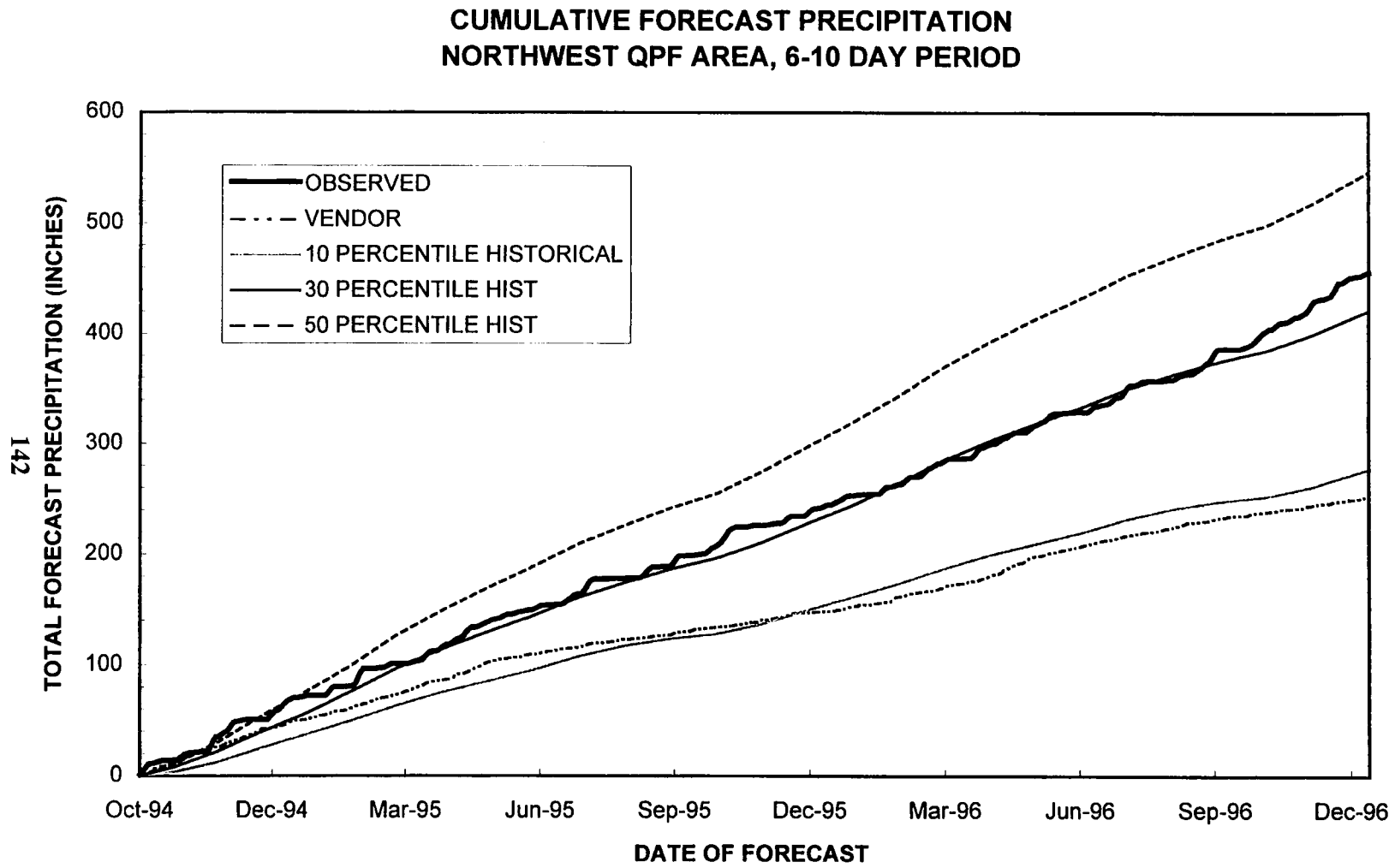
A.67. Cumulative Volume Analysis (6 to 10-Day Period). Northeast QPF Area.



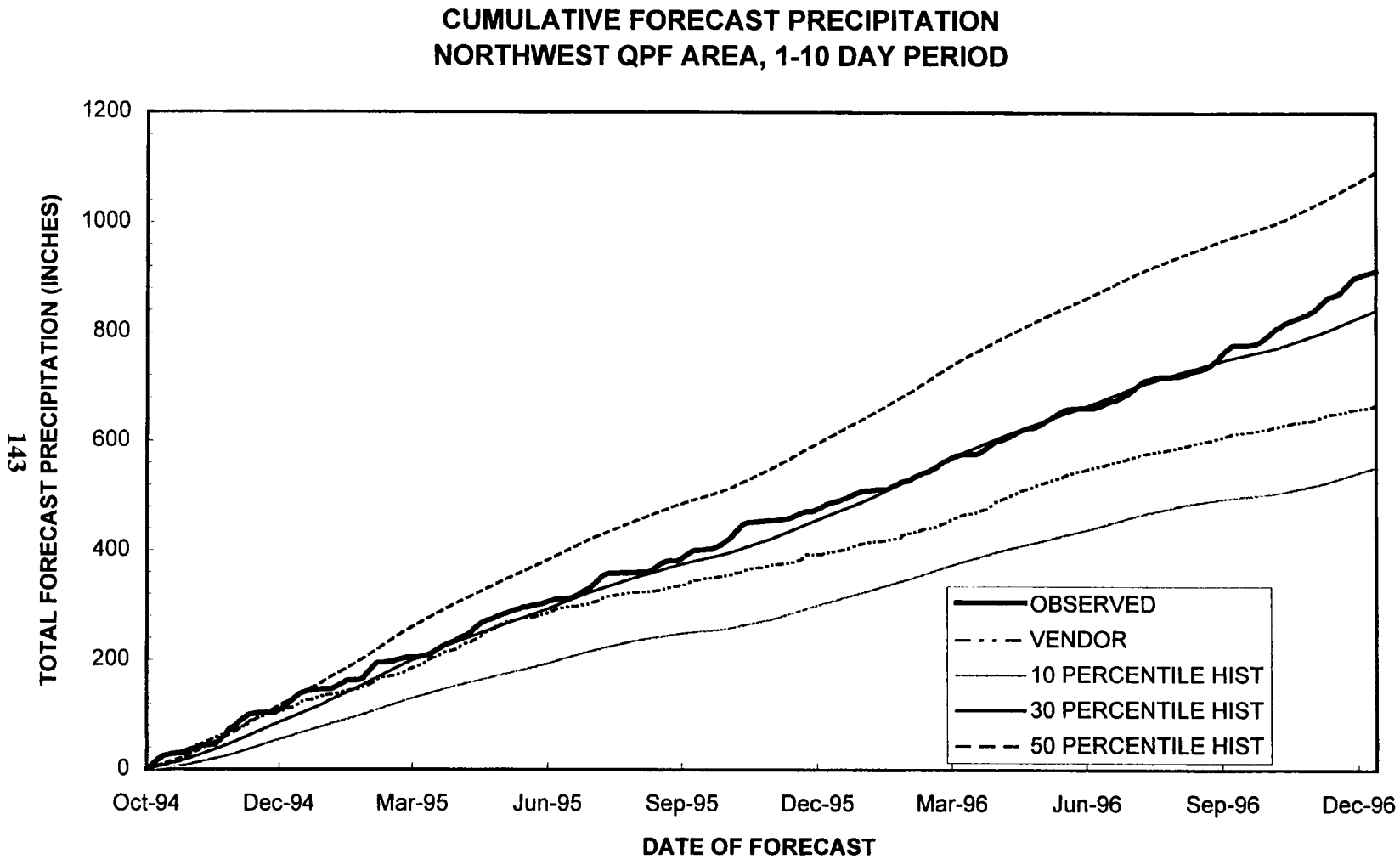
A.68. Cumulative Volume Analysis (1 to 10-Day Period). Northeast QPF Area.



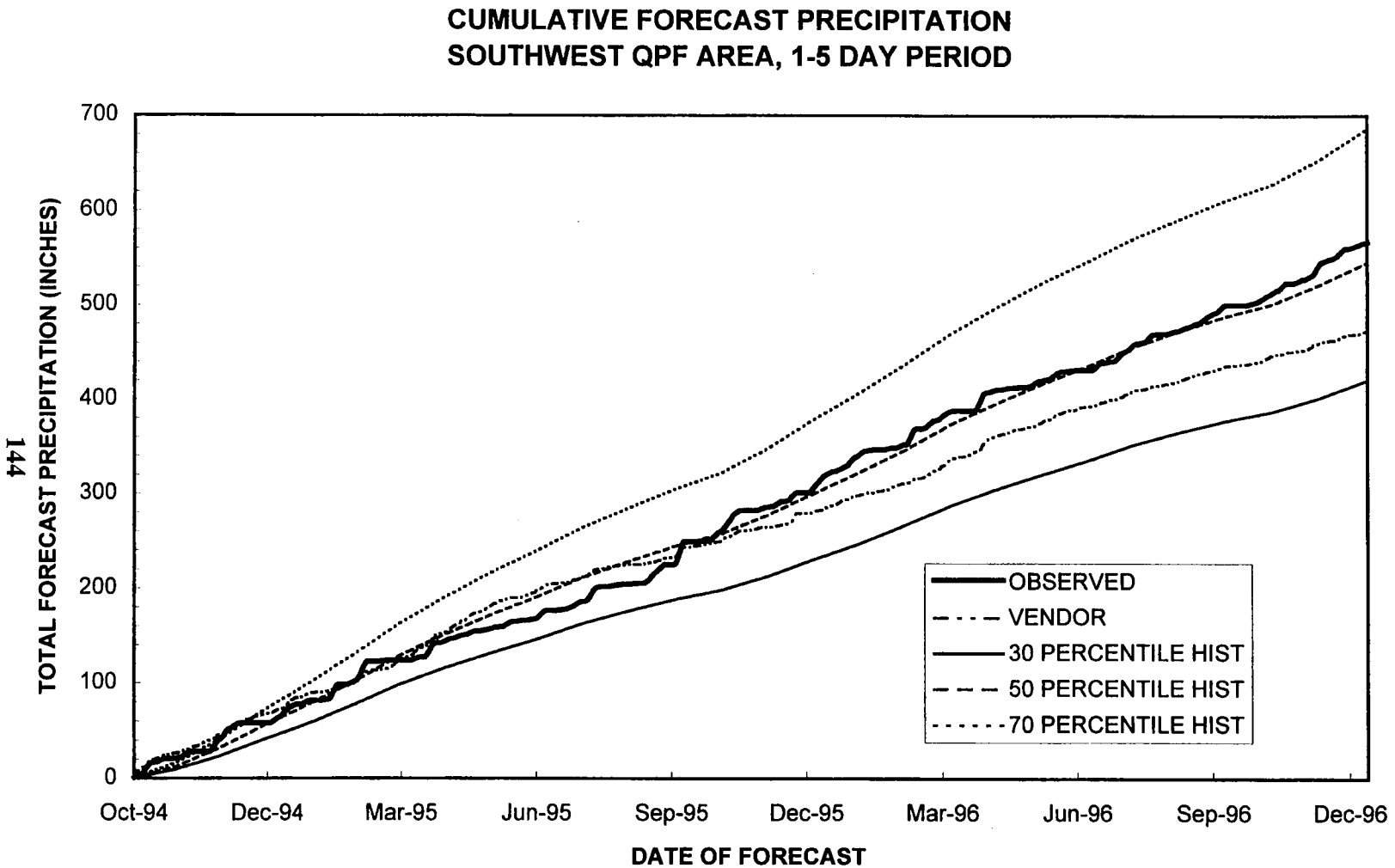
A.69. Cumulative Volume Analysis (1 to 5-Day Period). Northwest QPF Area.



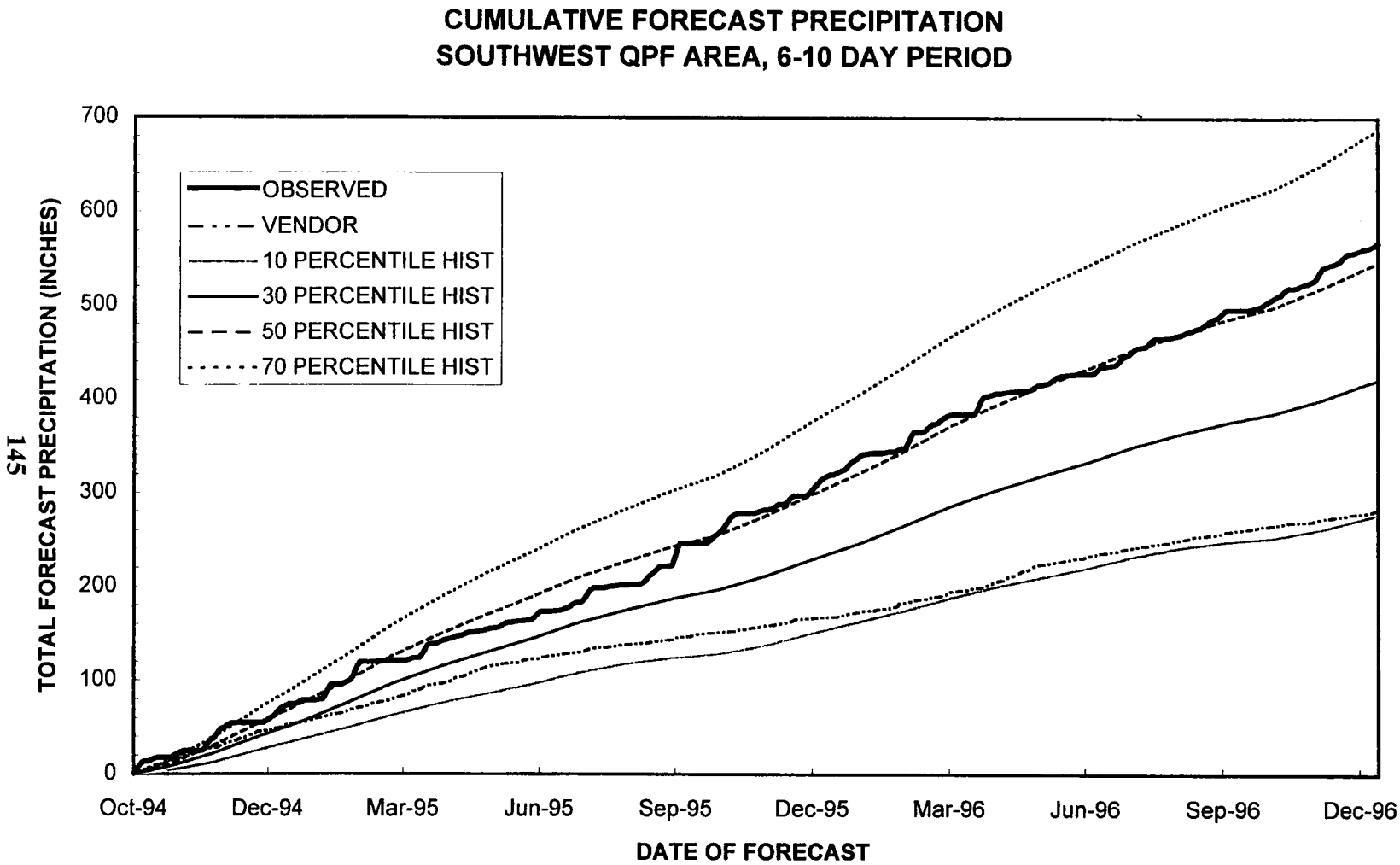
A.70. Cumulative Volume Analysis (6 to 10-Day Period). Northwest QPF Area.



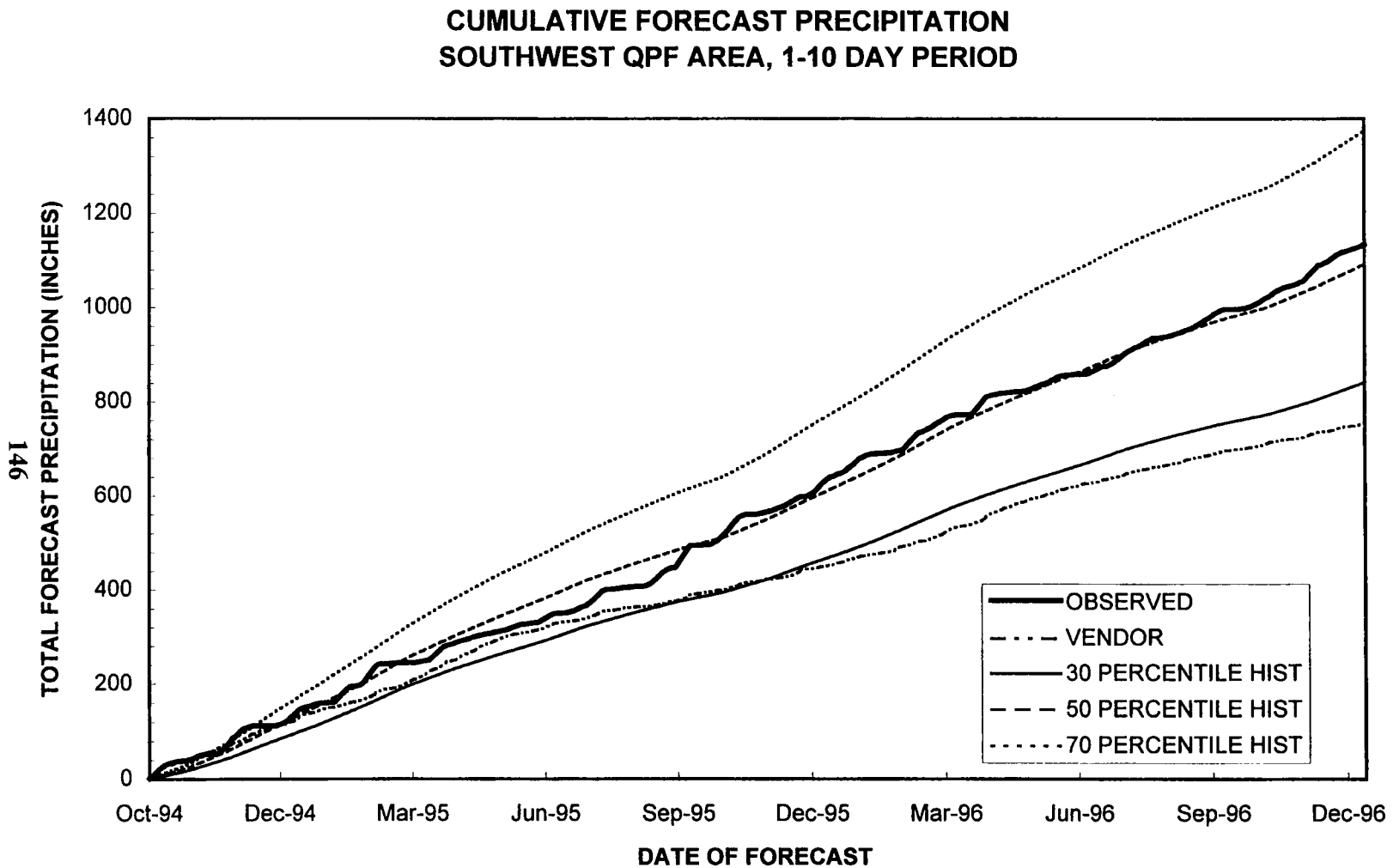
A.71. Cumulative Volume Analysis (1 to 10-Day Period). Northwest QPF Area.



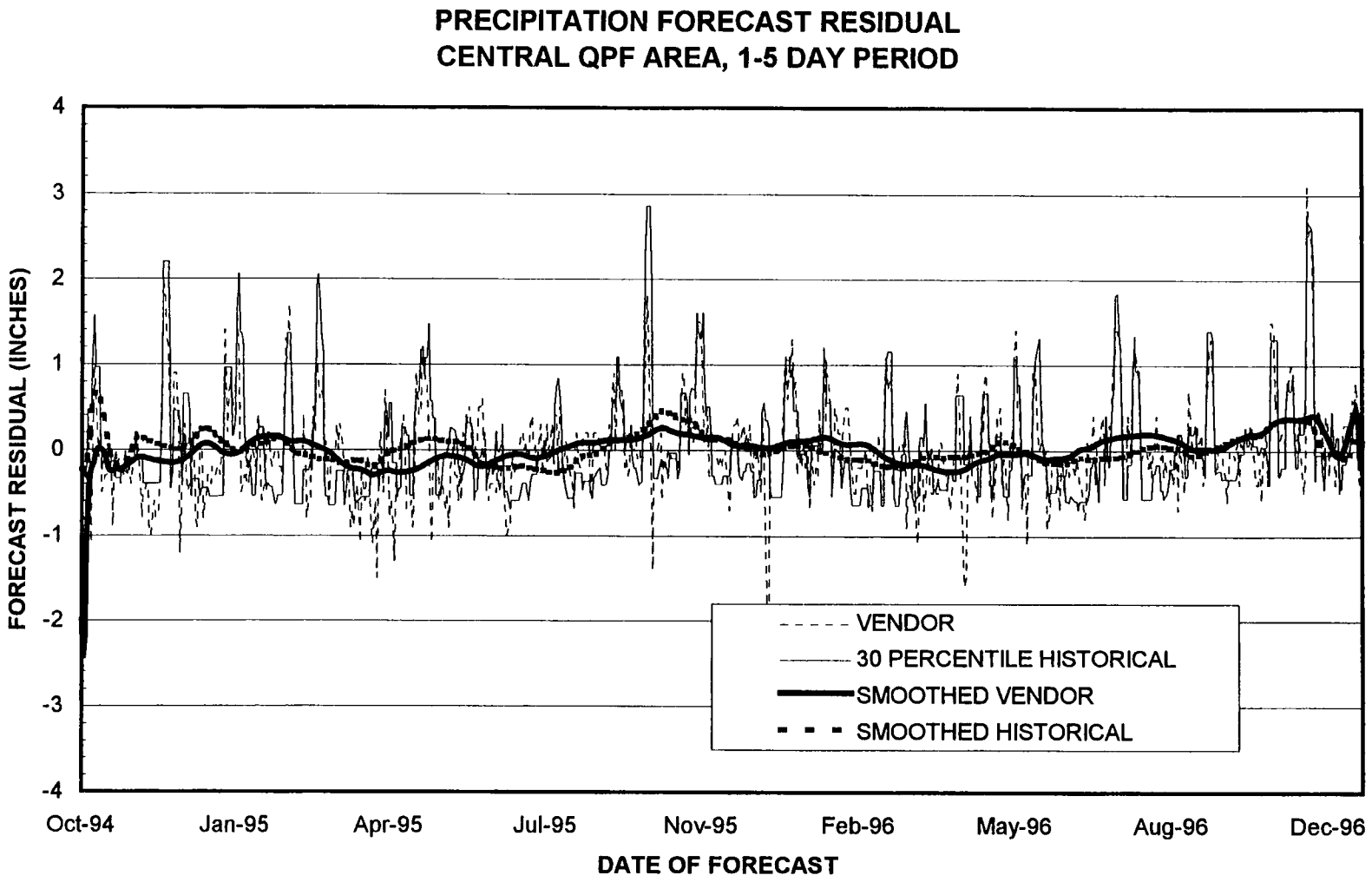
A.72. Cumulative Volume Analysis (1 to 5-Day Period). Southwest QPF Area.



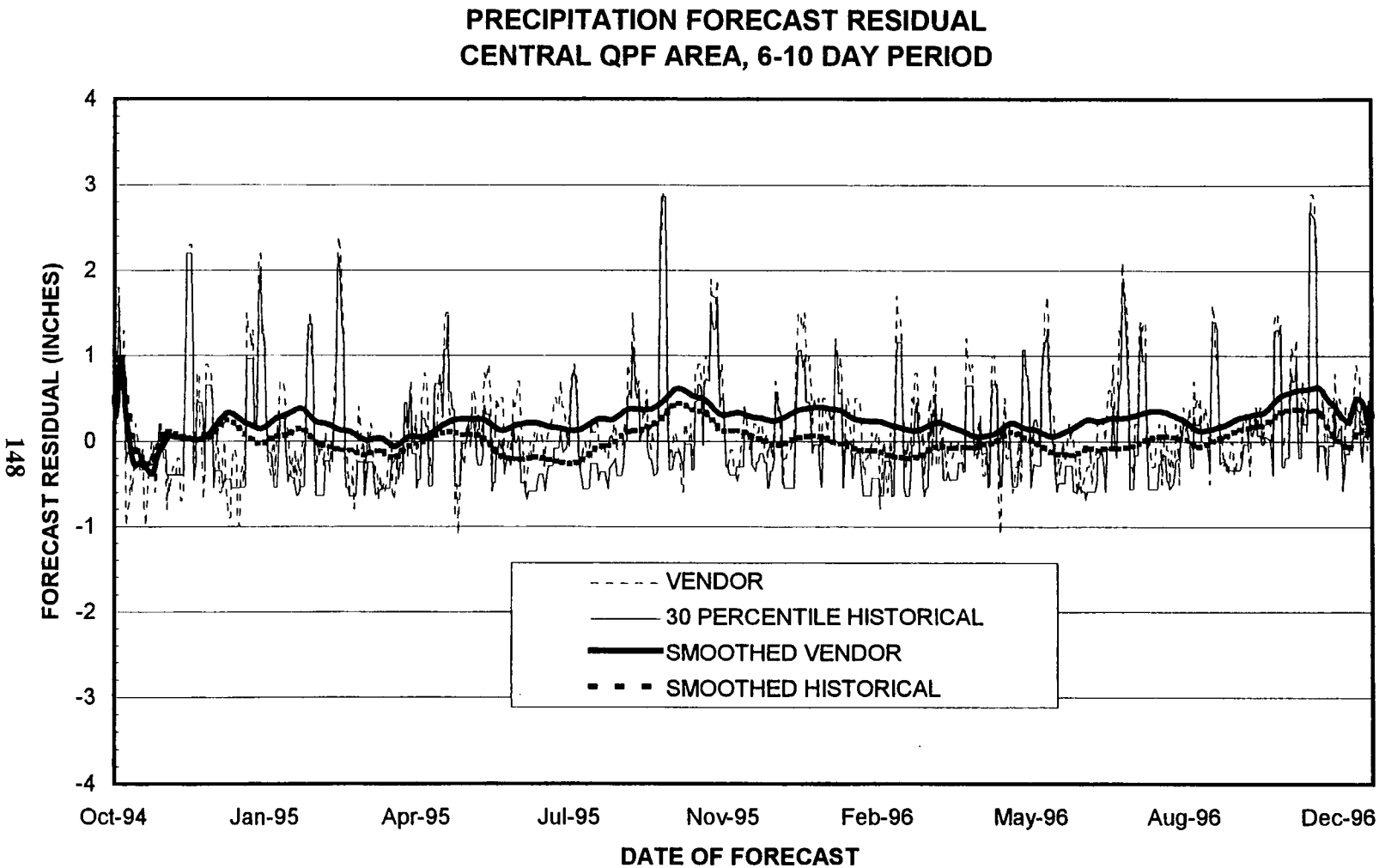
A.73. Cumulative Volume Analysis (6 to 10-Day Period). Southwest QPF Area.



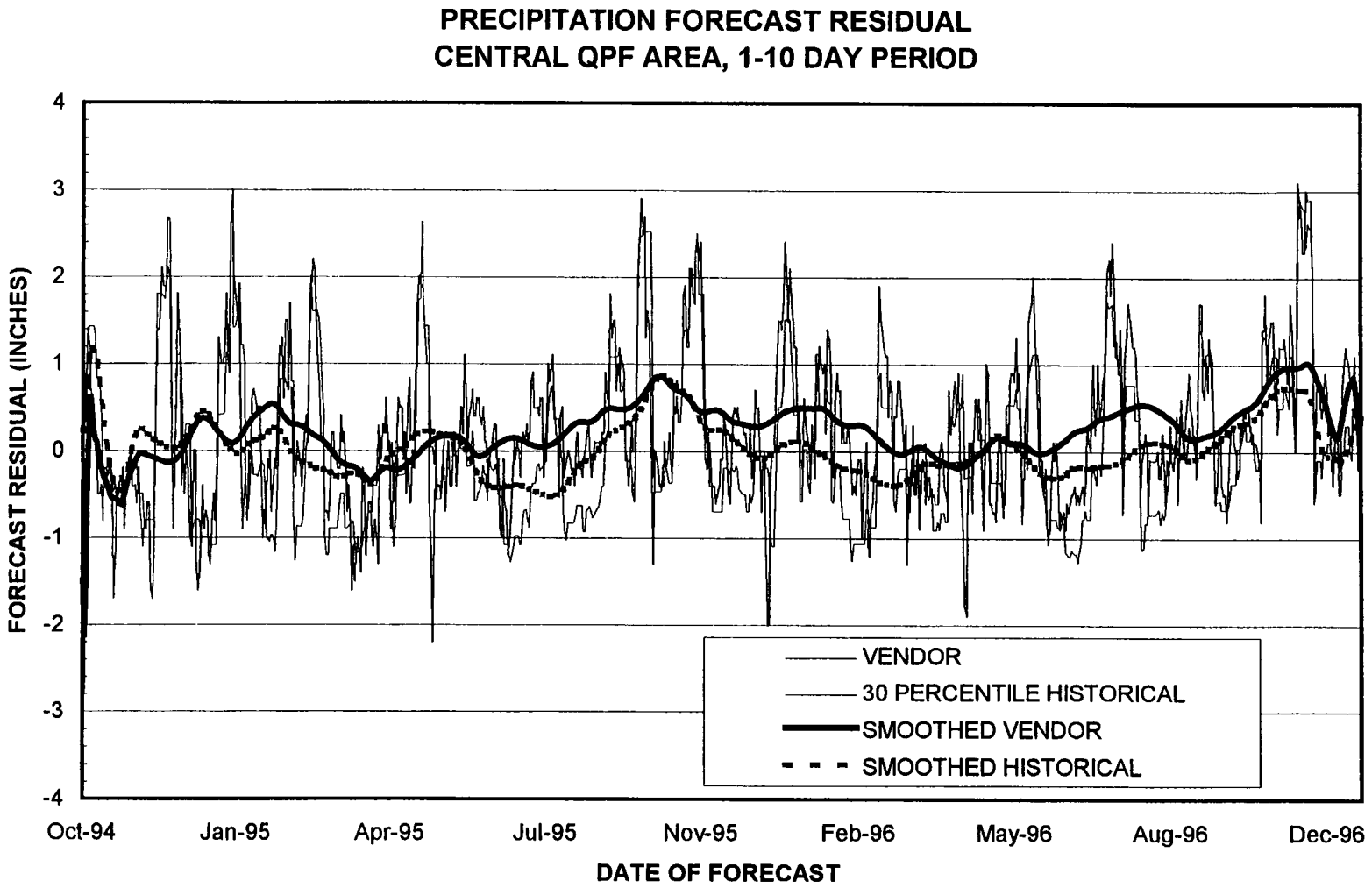
A.74. Cumulative Volume Analysis (1 to 10-Day Period). Southwest QPF Area.



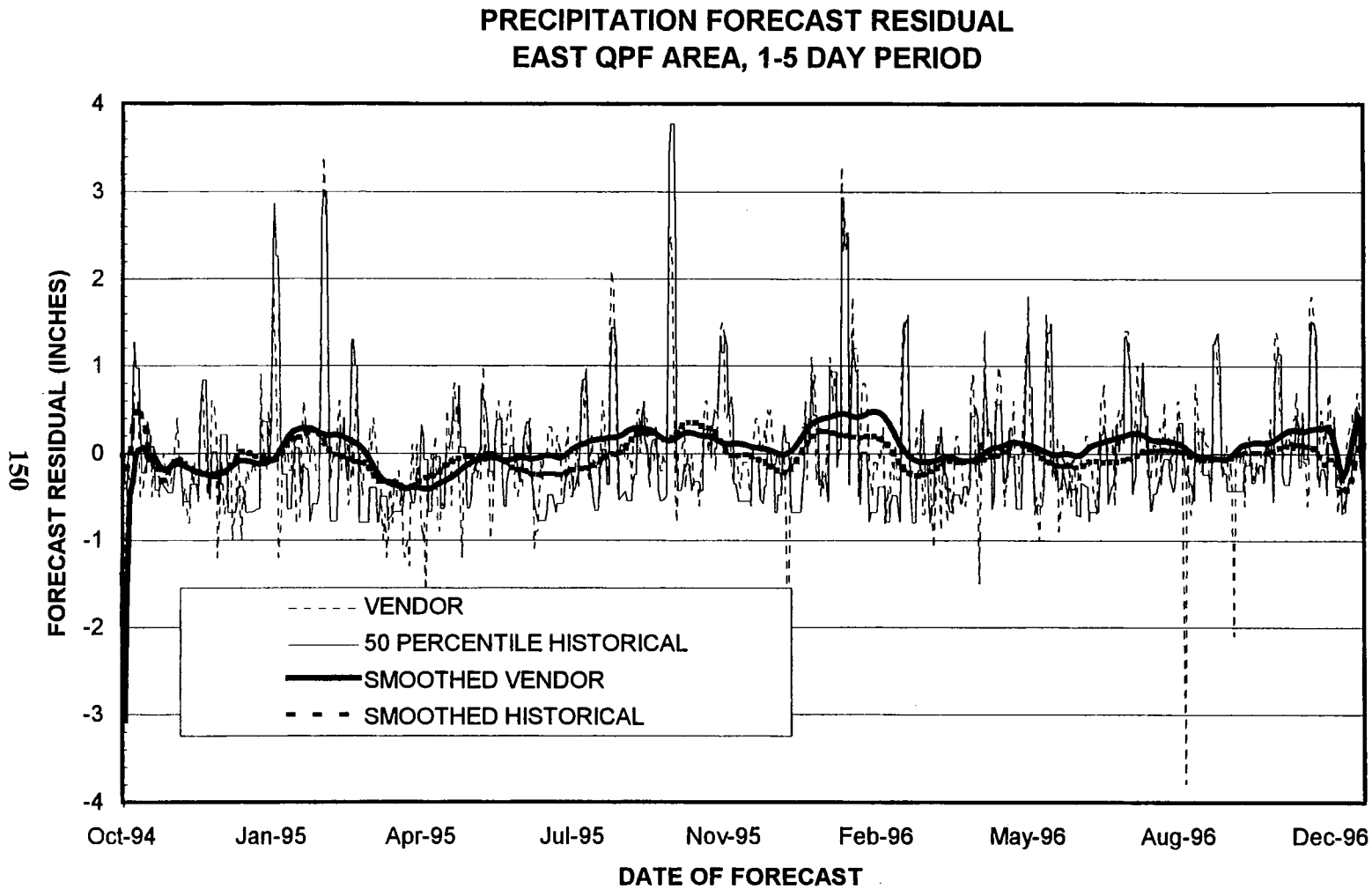
A.75. Residual Analysis (1 to 5-Day Period). Central QPF Area.



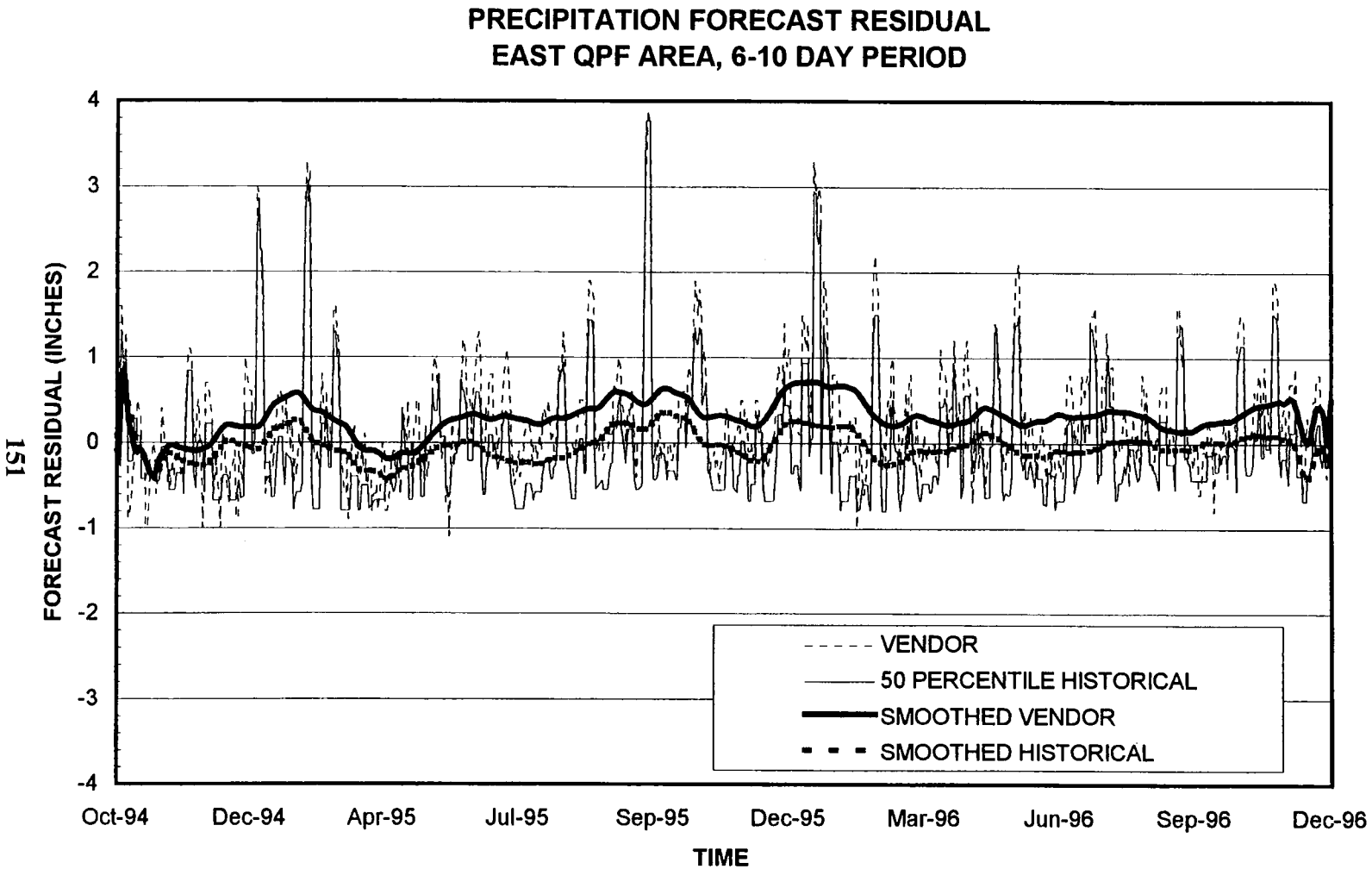
A.76. Residual Analysis (6 to 10-Day Period). Central QPF Area.



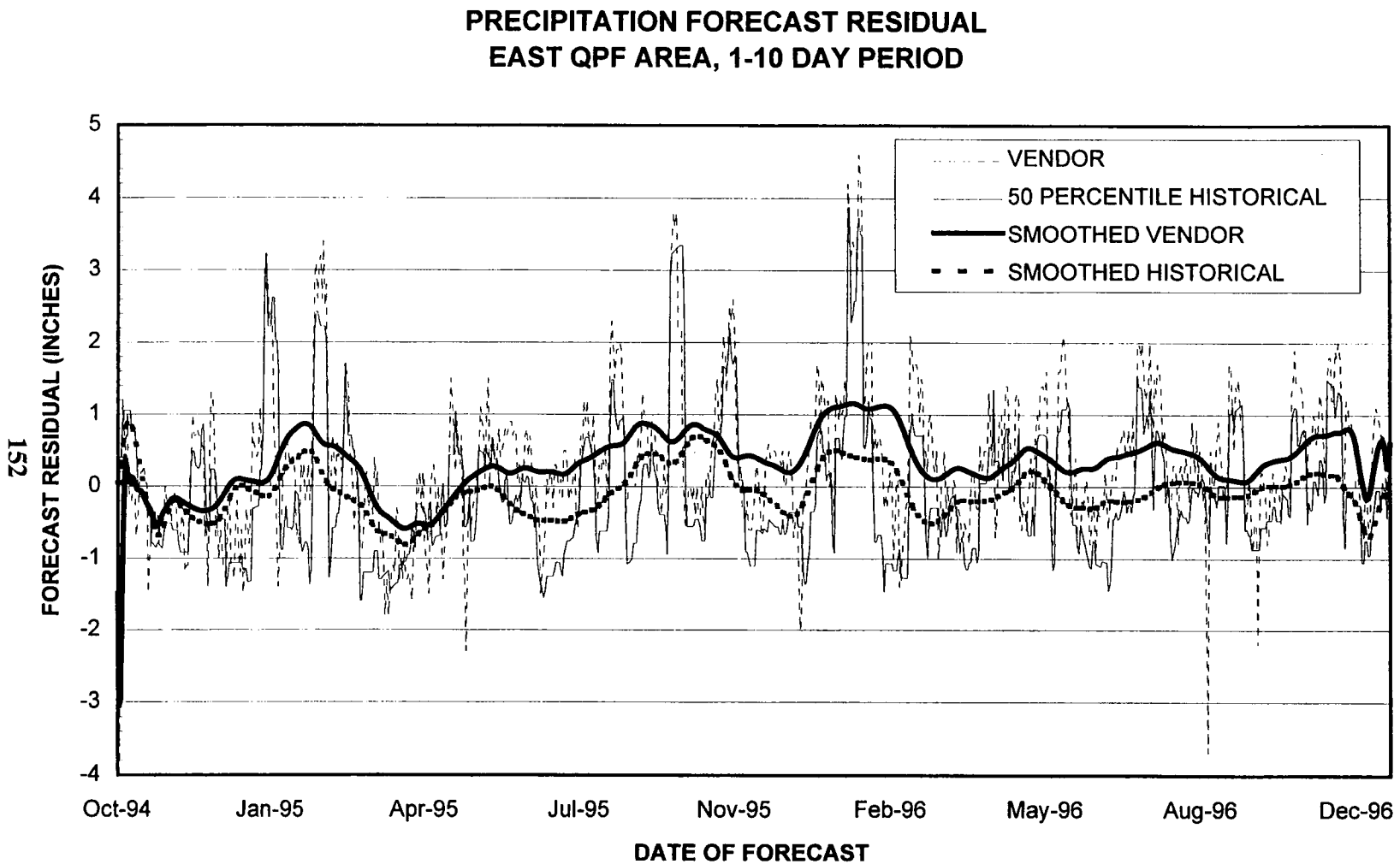
A.77. Residual Analysis (1 to 10-Day Period). Central QPF Area.



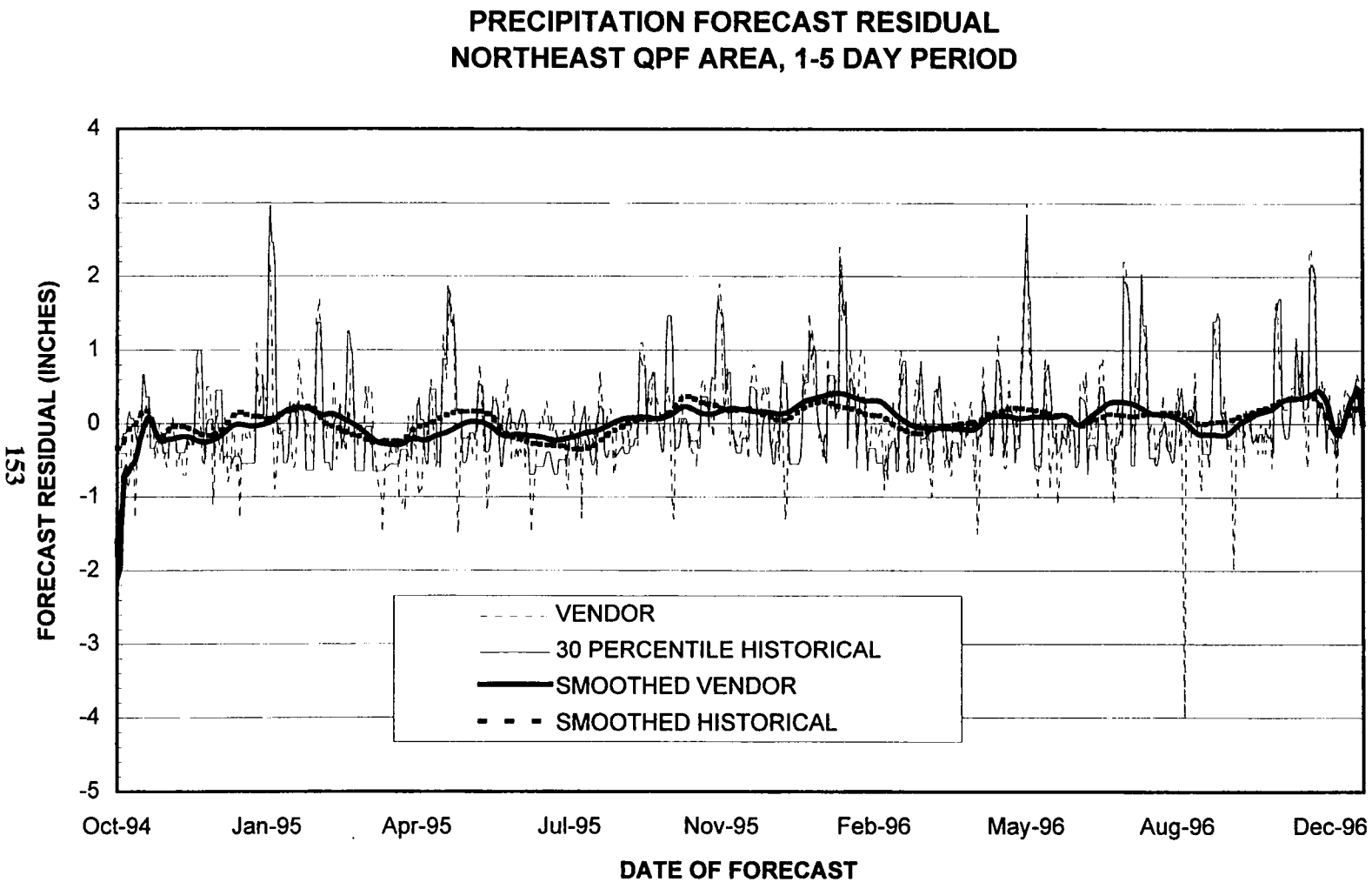
A.78. Residual Analysis (1 to 5-Day Period). East QPF Area.



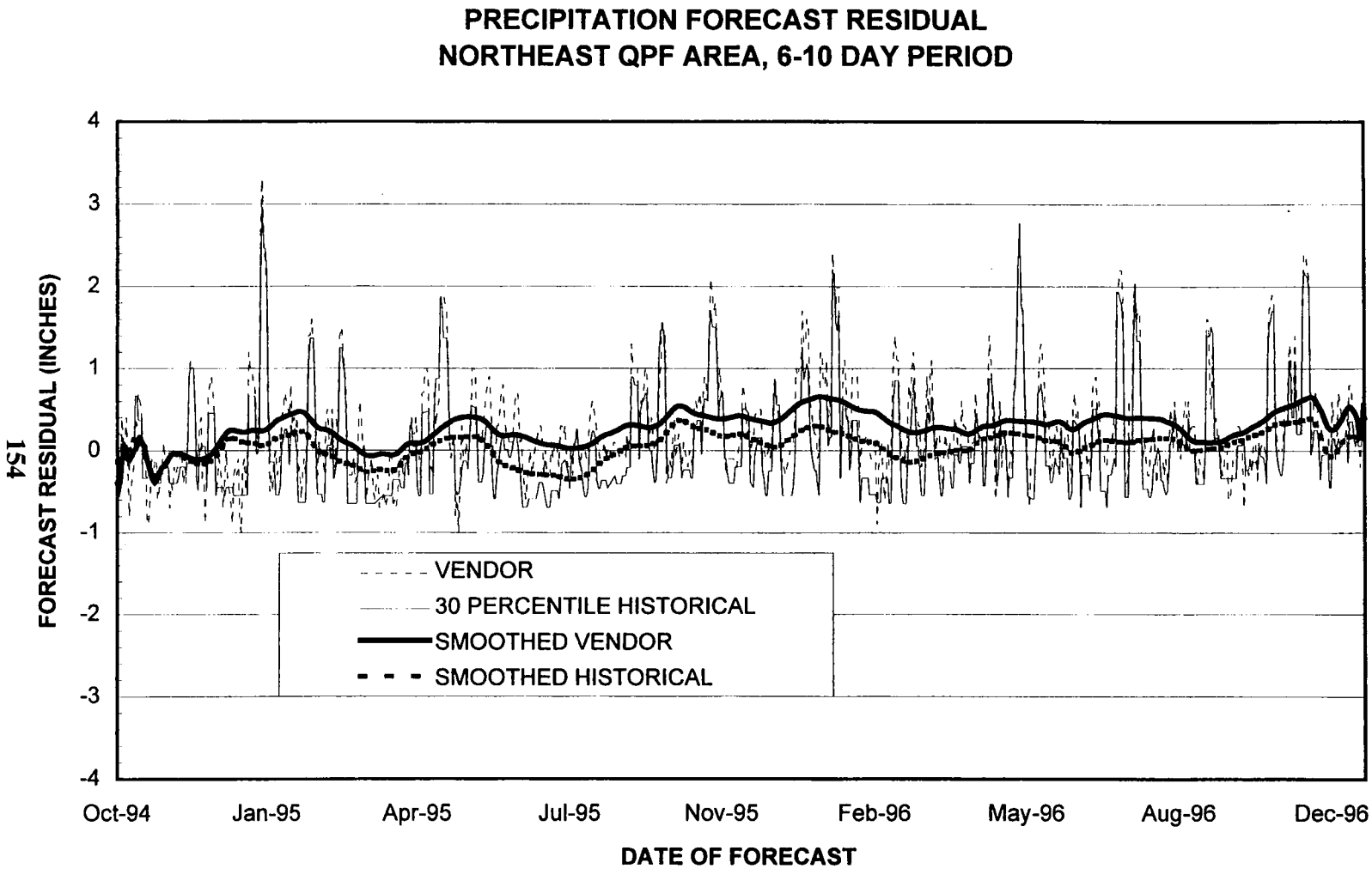
A.79. Residual Analysis (6 to 10-Day Period). East QPF Area.



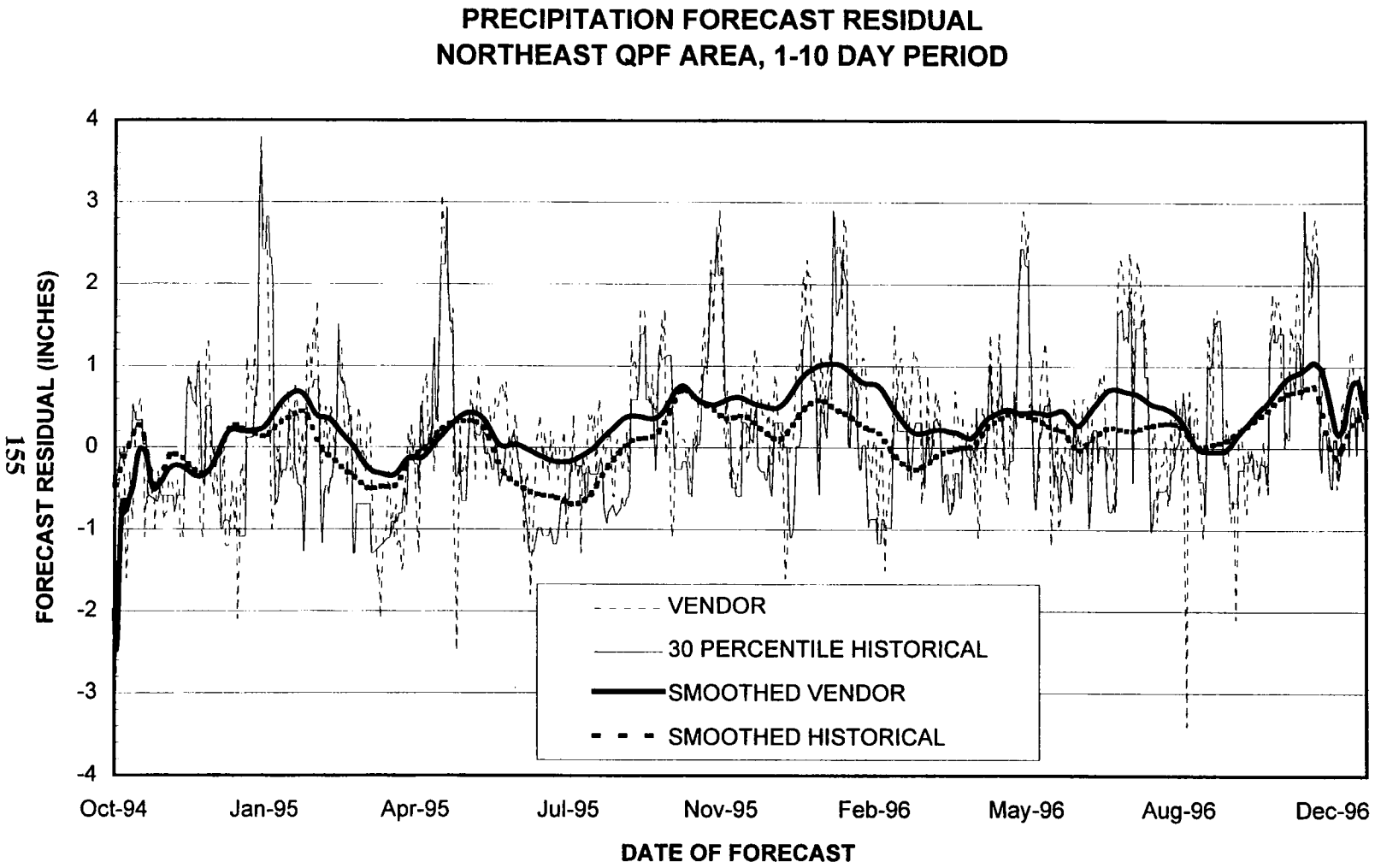
A.80. Residual Analysis (1 to 10-Day Period). East QPF Area.



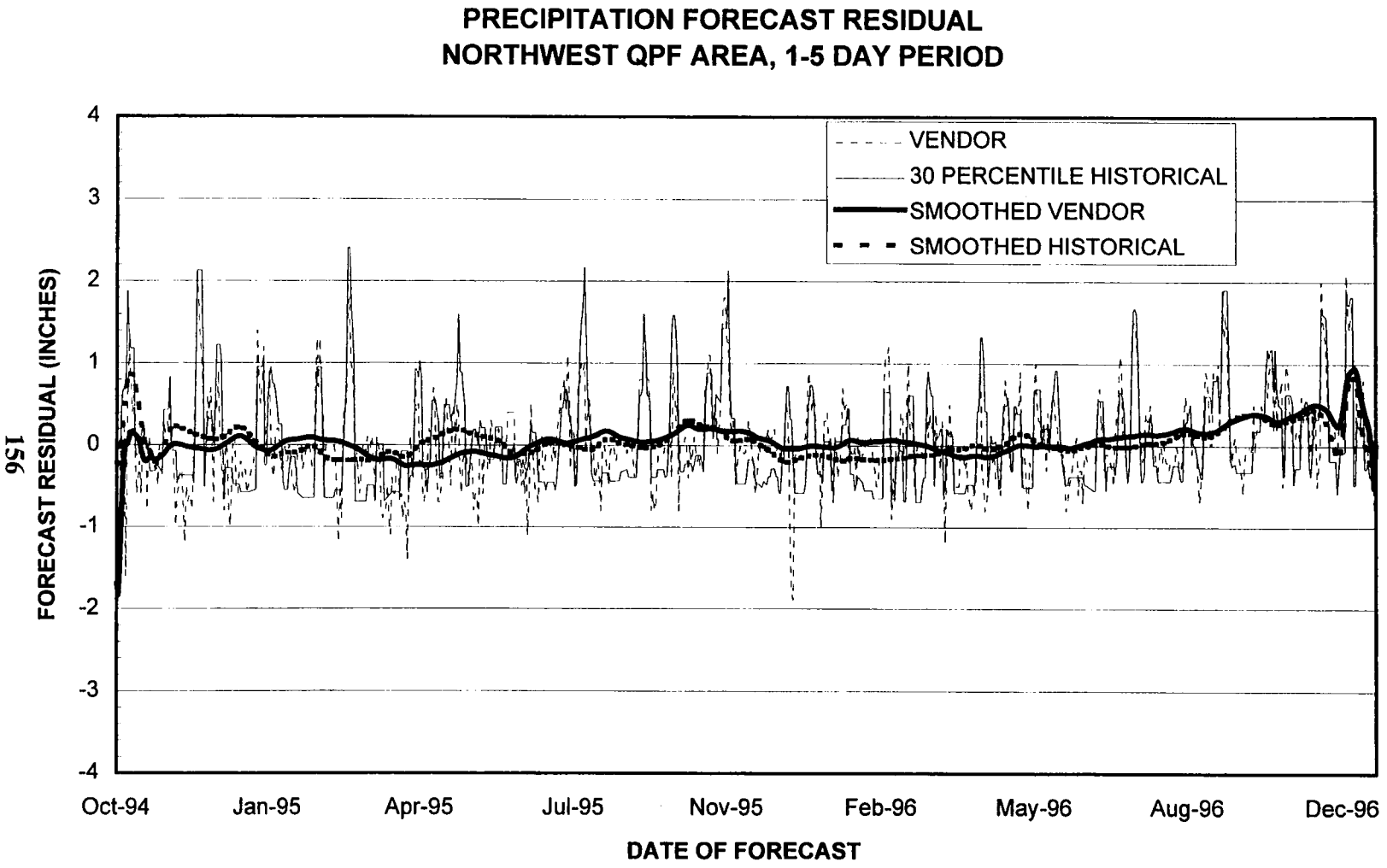
A.81. Residual Analysis (1 to 5 Day Period). Northeast QPF Area.



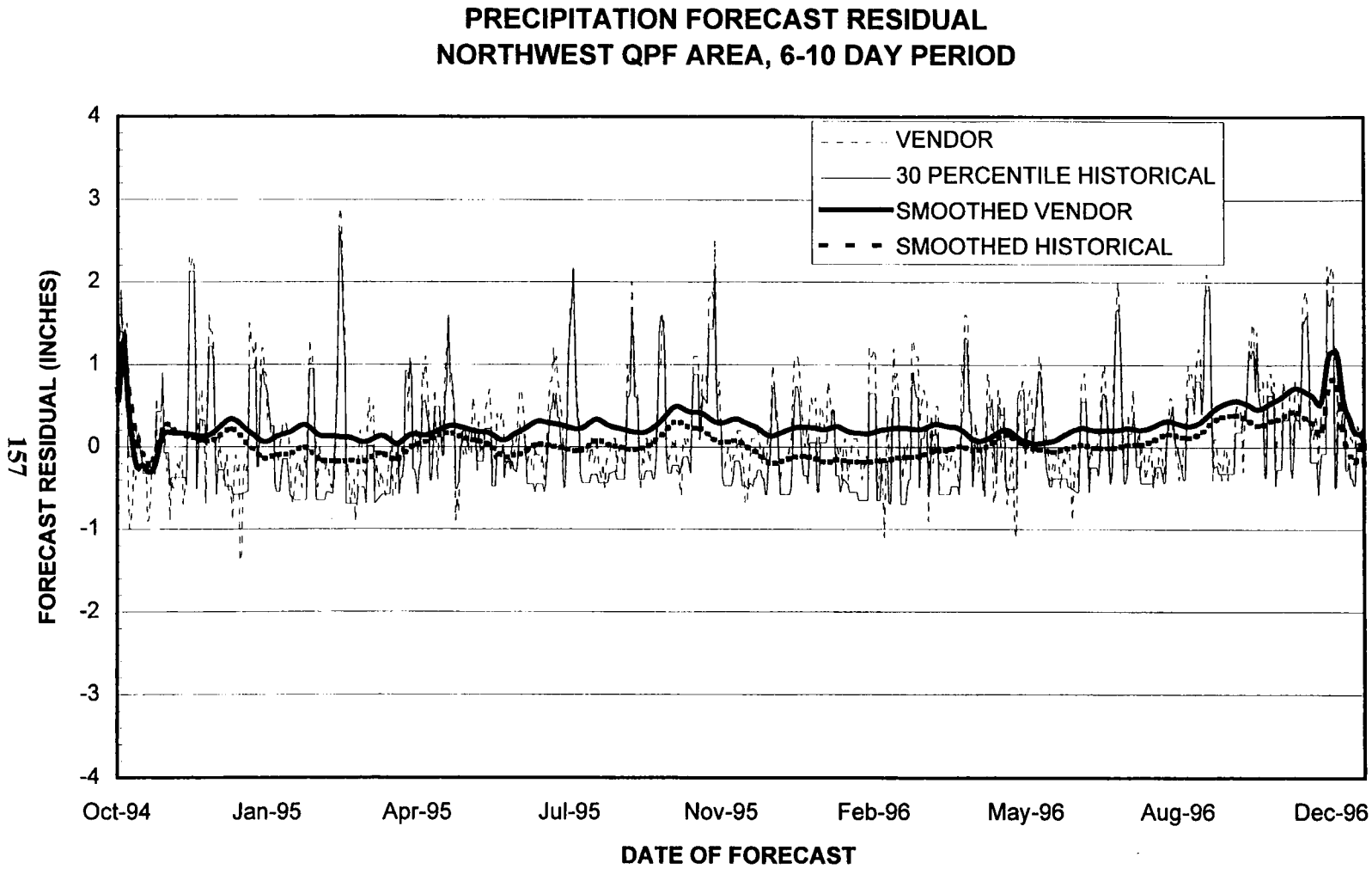
A.82. Residual Analysis (6 to 10-Day Period). Northeast QPF Area.



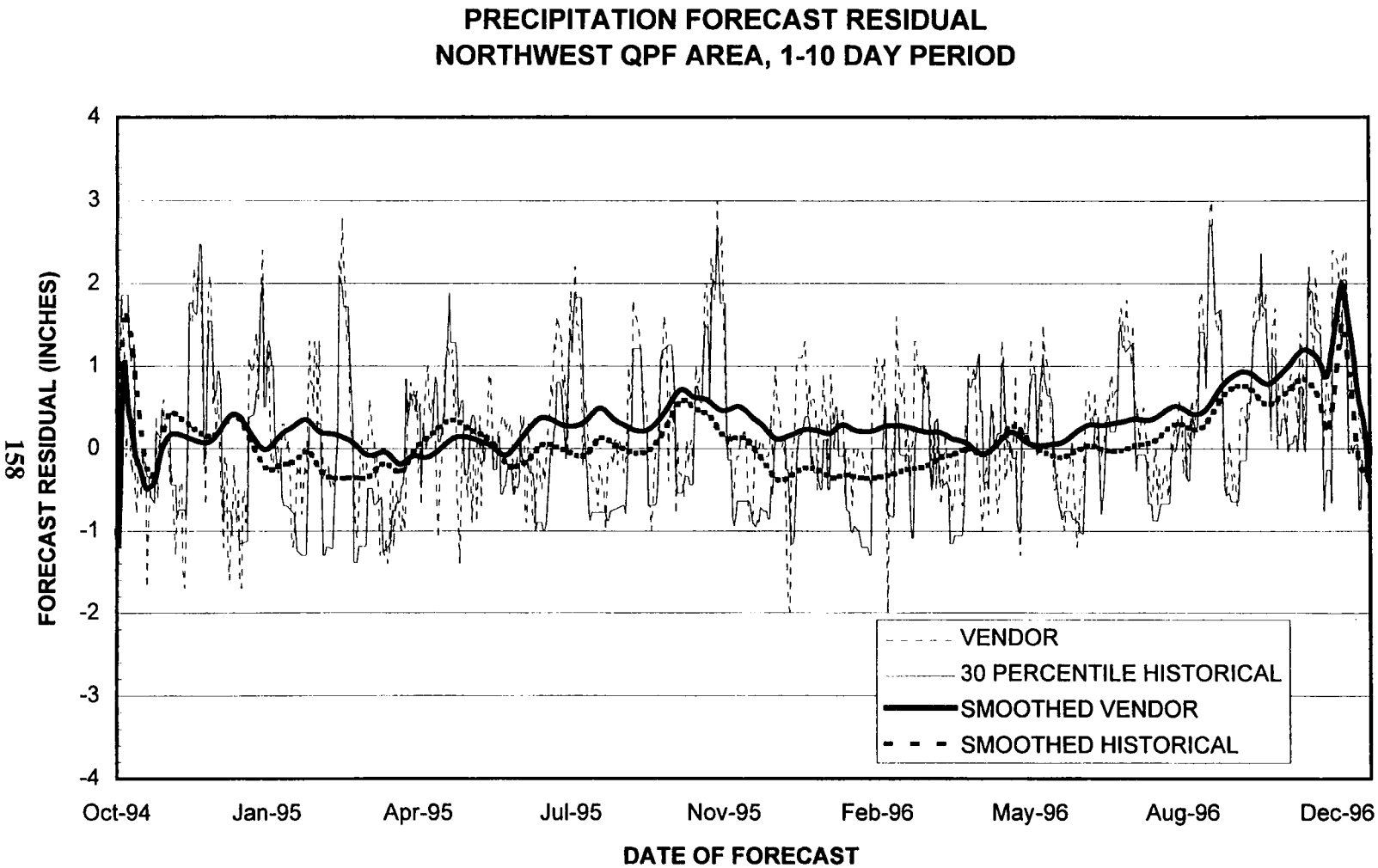
A.83. Residual Analysis (1 to 10-Day Period). Notrheast QPF Area.



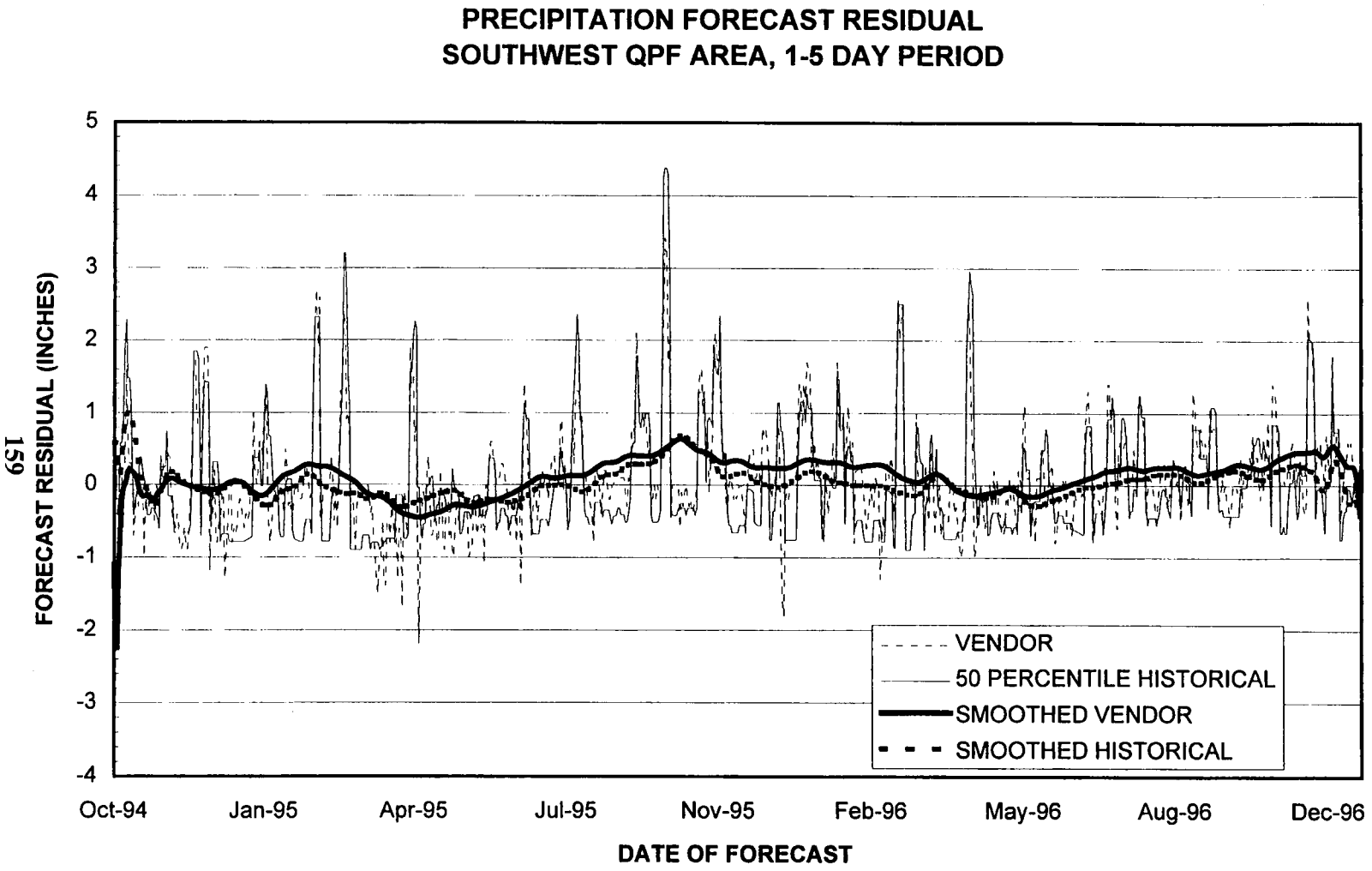
A.84. Residual Analysis (1 to 5-Day Period). Northwest QPF Area.



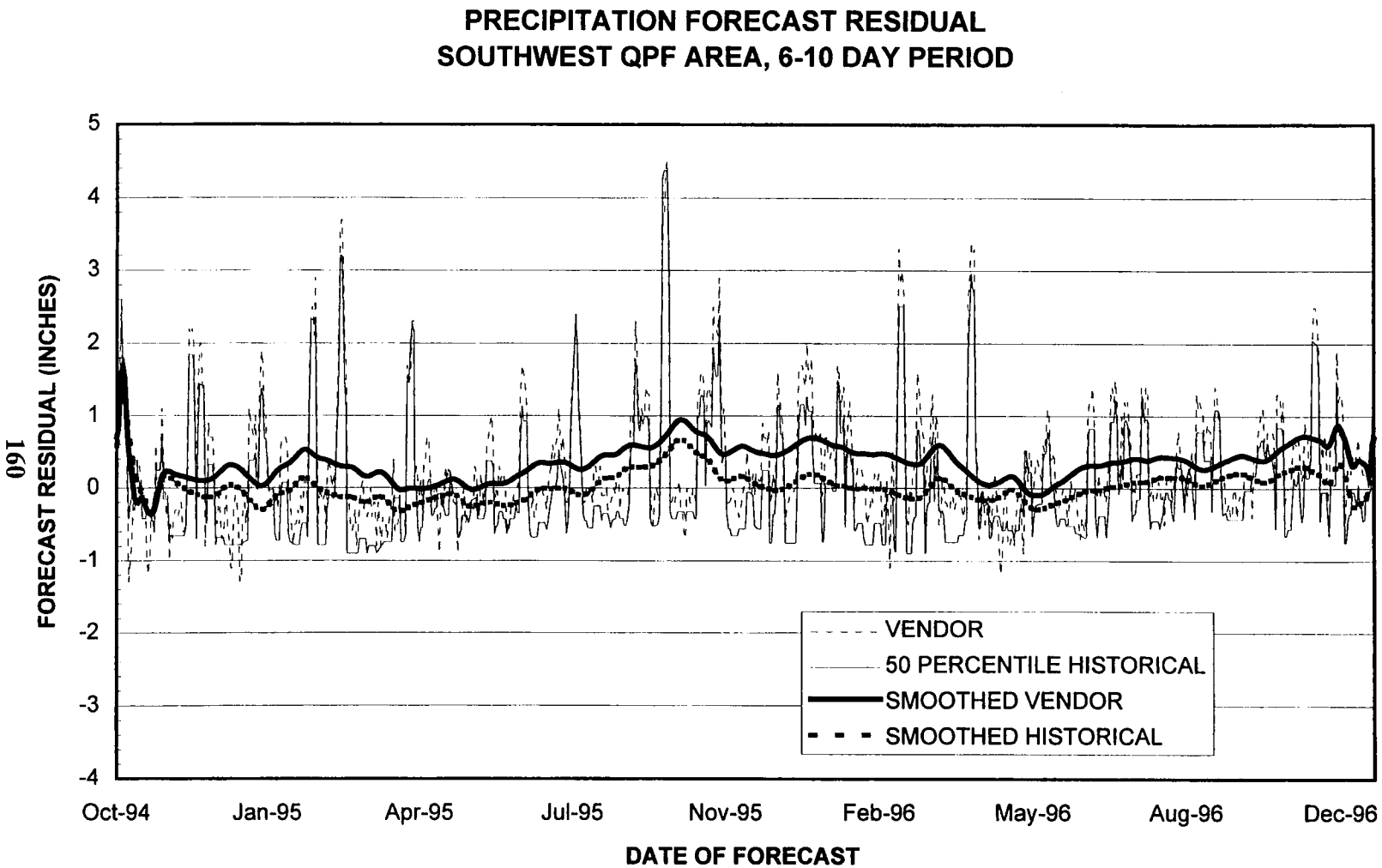
A.85. Residual Analysis (6 to 10-Day Period). Northwest QPF Area.



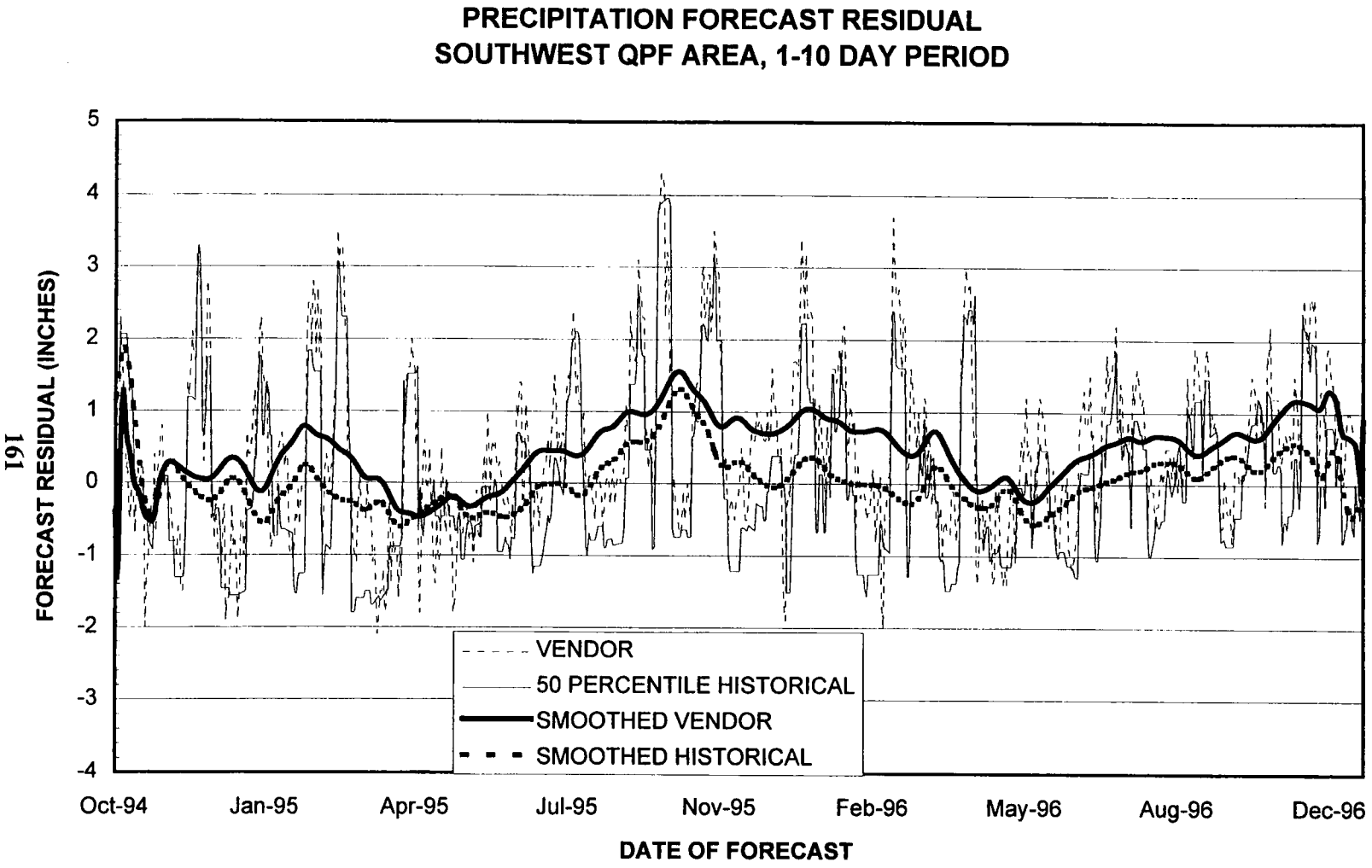
A.86. Residual Analysis (1 to 10-Day Period). Northwest QPF Area.



A.87. Residual Analysis (1 to 5-Day Period). Southwest QPF Area.



A.88. Residual Analysis (6 to 10-Day Period). Southwest QPF Area.



A.89. Residual Analysis (1 to 10-Day Period). Southwest QPF Area.

VITA

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