Tennessee Water Resources Research Center Annual Technical Report FY 2010

Introduction

Introduction

Water Resources Issues and Problems of Tennessee

Tennessee is fortunate to have what many consider to be an abundant and good quality water supply. Historically, federal government agencies, such as the Tennessee Valley Authority (TVA), Corps of Engineers, Soil Conservation Service, U.S. Geological Survey and others, have been the primary contributors to the management and monitoring of water resources. In recent years, however, the State, through the Tennessee Departments of Environment and Conservation, Wildlife Resources, Agriculture and others, have begun to develop a more active and aggressive role in the management and protection of these resources. The State has moved to establish an integrated and coordinated policy and administrative system for the management of water resources in Tennessee.

While the situation is improving, there remain many of the additional types of water problems. Although the overall supply of water is adequate, the distribution is still not optimal. Local shortages occur during dry periods. The summer of 2007 was a particularly hot and dry one. During this period over 35 water districts out of a total of 671 public systems in Tennessee experienced lesser degrees of difficulty in supply water. Beginning in 2006 and continuing on through the summer of 2008, Tennessee experienced another major drought period which severely strained the water supplies of many communities across the state. In recent years, many of the small municipal water suppliers and utility districts that rely on wells, springs, or minor tributaries for their water sources continue to face severe water shortage problems. All across the state many private, domestic, and commercial use wells have become severely strained, forcing users to seek alternative sources of water. Providing an adequate supply of water for industrial, commercial, and domestic uses and the protection of these surface and groundwater resources are of major concern in all regions of the state and vital to the economic development and growth of the state.

Groundwater presents a particular challenge in Tennessee. Over 50% of the population of Tennessee depends on groundwater for drinking water supply. In West Tennessee, nearly all public suppliers, industries, and rural residents use groundwater. However, not enough is known about the quality and quantity of groundwater in the state, and consequently, maximum benefit from and protection of this resource cannot be easily accomplished. More information about the quality of the state's groundwater, particularly about the potential impact of recharge areas, is needed in order to develop an effective management and protection program for this valuable resource.

There is also the problem of potential contamination of groundwater from agricultural and urban non-point sources. The "fate and transport" of agricultural chemicals (herbicides and pesticides) and toxic substances in groundwater is a problem area that must be addressed if the state's groundwater protection strategy is to be effective in protecting this vital resource.

Although the danger of large-scale, main-stem flooding is controlled by mainstream and tributary dams that have been constructed by TVA and the Army Corps of Engineers, localized flooding and even general flooding in unregulated watersheds remain substantial problems across the state. A lack of effective local floodplain management land-use controls is apparent in West Tennessee, where related problems of excessive erosion, sedimentation, drainage, and the loss of wetlands constitutes what many consider to be the greatest single water resource issue in the state from an economic and environmental point of view. Effective regulation of private levee design, construction, maintenance, and safety is needed.

Water quality problems continue to persist from past industrial practices, from the surface mining of coal and other minerals (especially from abandoned mines), from agricultural and urban nonpoint sources and from improperly planned, designed and operated waste disposal sites. As has been the situation in the past, the state program for the construction of municipal wastewater treatment facilities and improved operation and management of the facilities have experienced numerous set-backs due to shortfalls in funding and administrative delays. In major urban areas that have combined storm and sanitary sewers, urban storm water runoff causes increased pollution and, during periods of wet weather, bypasses treatment facilities, which allows raw sewage to enter receiving waters untreated. Tennessee cities, both large and small, are concerned about current (and future) impacts of the new NPDES storm water discharge permit requirements on clean up needs and costs. In certain regions of the state, failing septic fields and the practice of blasting bedrock for new septic fields are serious threats to surface and groundwater resources.

There are existing programs which can address many of these problems. However, some problems do not have easy solutions. Additional research can also play a role in understanding and solving these problems, but the greatest impediments are the lack of agreement between competing interests and a shortage of financial support for existing programs. From the viewpoint of the State government, the legal, institutional, and administrative aspects of water management are major concerns. The state is still working to develop new policy and to refine administrative structure for the effective management of its water resources.

To address the problems and issues of effective water resources management in the state of Tennessee, a truly interdisciplinary and well-coordinated effort is necessary. The Tennessee Water Resources Research Center has the capability and organization that can call upon the diverse set of disciplinary expertise necessary to address the key water issues of the state and region.

The Tennessee Water Resources Research Center: Overview of Program Objectives and Goals:

The Tennessee Water Resources Research Center serves as a link between the academic community and water-related organizations and people in federal and state government and in the private sector, for purpose of mobilizing university research expertise in identifying and addressing high-priority water problems and issues and in each of the respective state regions.

The Tennessee Water Resources Research Center, located at the University of Tennessee, is a federally-designated state research institute. It is supported in part by the U.S. Geological Survey of the U.S. Department of Interior under the provisions of the Water Resources Research Act of 1984, as amended by P.L. 101-397 and 10 I - 1 47. The Act states that each institute shall:

I. plan, conduct or otherwise arrange for competent research that fosters the entry of new research scientists into the water resources fields; the training and education of future water scientists, engineers and technicians; the preliminary exploration of new ideas that address water problems or expand understanding of water and water-related phenomena, and the dissemination of research results of water managers and the public.

II. cooperate closely with other colleges and universities in the state that have demonstrated capabilities for research, information dissemination, and graduate training, in order to develop a statewide program designed to resolve state and regional water and related land problems.

In supporting the federal institute mandate, the TNWRRC is committed to emphasizing these major goals:

1. To assist and support all the academic institutions of the state, public and private, in pursuing water resources research programs for addressing problem areas of concern to the state and region.

2. To provide information dissemination and technology transfer services to state and local governmental bodies, academic institutions, professional groups, businesses and industries, environmental organizations and others, including the general public, who have an interest in water resources matters.

3. To promote professional training and education in fields relating to water resources and to encourage the entry of promising students into careers in these fields.

4. To represent Tennessee in the Universities Council on Water Resources, the American Water Resources Association (including Tennessee Section), the Water Environment Federation, the American Water Works Association, the International Erosion Control Association, the Soil and Water Conservation Society, the Lower Clinch Watershed Council, the ORNL-TVA-UT Research Consortium and the National Institutes for Water Resources (NIWR). To work with these and other associations and with state, local and federal government agencies dealing with water resources in identifying problems amenable to a research approach and in developing coherent programs to address them. Particularly, to cooperate with the other state institutes and their regional groupings for assisting the U.S. Geological Survey in developing a national water resources strategy.

In fulfilling the Center's major goals indicated previously, TNWRRC emphasizes the application of Section 104 grant and required matching funds for primarily supporting the research and training/education needs of the state. While the information dissemination and technology transfer portion of the Center's overall program does not receive direct or significant section 104 funding, this is accomplished primarily from the research and training activities of the Center from other funding sources--state, private, or non-profit. The Center recognizes that education and training, research, and information transfer are not independent objectives or are not mutually exclusive. Instead these goals are achieved through the administration of a coordinated, fully-integrated program within the limitations of the resources available to the Center.

Research Program Introduction

None.

Effect of Wastewater Strength on Soil Physical Properties when using Subsurface Drip Irrigation

Basic Information

Title:	Effect of Wastewater Strength on Soil Physical Properties when using Subsurface Drip Irrigation
Project Number:	2008TN52B
Start Date:	3/1/2008
End Date:	8/31/2010
Funding Source:	104B
Congressional District:	TN Second
Research Category:	Water Quality
Focus Category:	Waste Water, Treatment, Water Quality
Descriptors:	
Principal Investigators:	John R. Buchanan

Publication

1. Hillenbrand, Boone,2010,An Investigation for the Need of Secondary Treatment of Residential Wastewater when Applied with a Subsurface Drip Irrigation System,"MS Dissertation", Department of Biosystems Engineering and Soil Science, Insitute of Agriculture, the University of Tennessee, Knoxville, TN.,pp 164.

(6) Nature, Scope and Objectives of Research:

The specific objectives of this project were to:

a) Determine whether biomat forms around drip tubing, and to determine whether the quality of the wastewater influences biomat formation around drip tubing.

b) Determine the extent of soil moisture saturation (if any) around the drip tubing.

c) Determine the renovation of the water at various depths below the point of application.

d) Determine the reduction in nutrients, and organic carbon as water moves through the soil.

e) Publish the new information generated by this project.

7) Methodology and Accomplishments to Date:

Experimental Setup

A consistent supply of primary and secondary treated domestic wastewater was required for this project. Jackson Bend subdivision, located in Blount County, Tennessee, has a decentralized wastewater management system. Wastewater from each home is collected by a Septic Tank Effluent Pump (STEP) system that transfers effluent to a recirculating media filter for secondary treatment. The highly renovated effluent is then subsurface applied using drip irrigation. This location allowed the P.I to collect primary treated water out of the STEP system and collect secondary treated water out of the recirculating sand filter. Two separate subsurface wastewater drip dispersal fields were established. Each field has 305 m of subsurface drip line. Each drip field is composed of 10 parallel rows that are 15.24 m long. The drip lines were plowed-in 0.6 m on center. Specifications for drip line include pressure-compensated emitters rated at approximately 2.27 L/h with the emitters spaced every 0.6 m along the tubing. One drip field received septic tank effluent (primary treatment) and the second field received secondary quality effluent.

Approximately 1,514 L of domestic wastewater per day is applied each day. This includes 757 L of septic tank effluent and 757 L of secondary quality effluent. The dispersal field is 372 m^2, and thus the application rate was 4 $L/m^2/d$.

Data Collection

As of this writing, four rounds of samples have been collected from the experimental location. With Tennessee Water Resources Research Center Program funding, a graduate student was employed to conduct sampling and analyses. Two-inch diameter soil cores were extracted from selected locations within each field. The soil solution from these cores was analyzed for total organic carbon (TOC), total nitrogen, and total phosphorus. A second set of soil cores were extracted and evaluated for saturated hydraulic conductivity.

Soil core samples were taken at two depths, 0.3 and 0.6 m below the drip emitter elevation. Six sets of cores were pulled. Core 1 was at a emitter, core 2 was along the drip tubing, but between emitters, core 3 was at the emitter but between the drip lines (to the right in the direction of flow), core 4 was at the emitter but between the drip lines (to the left in the direction of flow) core 5 was both between emitters and between the drip tubing to the right, and core 6 was between the emitters and tubing to the left. As controls, two cores with samples from 0.3 and 0.6 m were taken from the native soil outside of the drip dispersal area. This procedure was repeated in both fields: The field receiving primary quality effluent and the field receiving secondary quality effluent.

The goal of the chemical analysis was not to extract all of the carbon, nitrogen and phosphorus out of the sample. Rather, this was an attempt to simulate saturated soil conditions and determine the constituent concentration that would be expected to percolate through to the groundwater. Soil chemical properties were analyzed by drying and then grinding the soil sample. Thirty grams of dry soil was mixed with 20 g of tap water and placed on a shaker table for 24 hours. This mixture was then centrifuged for 10 minutes at 3,500 rpm. A sample of the supernatant was extracted and subjected to chemical analyses.

Data Analysis

All of these samples will be analyzed to look for differences in soil solution quality and water movement as the two types of effluent pass through the soil profile. The null hypothesis is that the soil will be able to renovate and move the septic tank effluent equally well as the secondary-treated effluent. Statistical analysis was performed on the data to verify this hypothesis.

(8) Principal Findings and Significance:

The Jackson Bend site has been in operation since June 19, 2006. In that time, just over 6,000 L of effluent per m^2 has been applied. No significant differences have been found in the data concerning the concentrations of total nitrogen, nitrate-nitrogen, and total carbon from the two fields. There does appear to be a difference in saturated hydraulic conductivity.

The hydraulic conductivity differences at Jackson Bend with the primary and secondary treatments were not significantly different however the secondary side did have a significantly lower Ksat than the control. The estimated Ksat values for primary, secondary, and the control are as follows: 0.041, 0.036, and 0.073 cm/day respectively. The Ksat differences for 1-ft and 2-ft depths were not significant (0.049 and 0.050 cm/day respectively).

Jackson Bend shows no significance for nitrate with the primary, secondary, and control treatments. Depth was a significant factor for nitrate concentration with the concentration getting higher nearer the emitter (3.970 mg/kg at 1-ft and 2.602 mg/kg at 2-ft).

The concentration of total carbon for the primary treatment was lower than with the secondary and control treatments but not significant due to the variability in the data. This is counter-intuitive because one would expect there to be significantly more carbon on the primary side. It is speculated that uniform effluent application, and dose and resting cycles allowed by the drip irrigation promoted enhanced organic carbon degradation.

The total nitrogen concentration was not significantly different between the 3 treatments. The treatment means ranged from 6.4 to 8.4 mg/kg. The control at the 1-ft depth has a significantly higher concentration of TN than at the 2-ft depth but these concentrations are not significantly different than the primary and secondary samples at either depth.

The overall treatment differences in TP were not significantly different but there were differences when the trt*depth interactions are examined. The control samples at the 1-ft depth are significantly higher than the primary and secondary samples. The means for secondary are higher than the means for primary but are not significant.

(9) Summary and Conclusions:

The purpose of this study was to evaluate two strengths of wastewater (primary and secondary) being applied by subsurface drip dispersal to determine the need for secondary treatment. The purpose was not to evaluate the performance of subsurface drip dispersal as a whole. The soil has a tremendous ability to treat wastewater but its full potential may be retarded by the use of a costly secondary treatment. Physical and chemical properties of the soil were measured to make the comparison. It was found that the pore water in the soil that had been irrigated with the low strength wastewater was of slightly higher quality than the pore water in the primary treated side. At Jackson Bend, the hydraulic conductivity of the primary side show significant reduction as compared to the secondary and control areas; and within reason, this is beneficial for the treatment of the wastewater – more contact time with the soil. Nitrate and total nitrogen were significantly higher in the primary treated areas but showed a decrease with depth. TC and TP showed no significant differences. The benefits of a secondary treatment are not enough to make it necessary when using subsurface drip dispersal. The soil acts much the same as the secondary wastewater treatment plant and drip irrigation is designed to fully utilize these characteristics.

(10) Publications from this Effort

This work has produced a Master's Thesis. "An Investigation for the Need of Secondary Treatment of Residential Wastewater when applied with a Subsurface Drip Irrigation System" was written by Boone Hillenbrand for the partial fulfillment of the requirement of a M.S. degree in Biosystems Engineering. Boo

Drought Variability in Reconstructed Streamflow

Basic Information

Title:	Drought Variability in Reconstructed Streamflow
Project Number:	2009TN61B
Start Date:	3/1/2009
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	Second
Research Category:	Climate and Hydrologic Processes
Focus Category:	Drought, Climatological Processes, Hydrology
Descriptors:	Climate, Drought, Streamflow Reconstruction, Atmospheric/Oceanic Influences, Tree-rings,
Principal Investigators:	Glenn A Tootle, Henri D Grissino-Mayer

Publications

1. Moser, C., G. Tootle, and V. Lakshmi, 2011. A Comparison of SNOTEL and AMSR-E Snow water Equivalent Datasets in Western U.S. Watersheds, International Journal of Remote Sensing, In Press.
2. Soukup,T., O., Aziz, G. Tootle, S. Wulff and T. Piechota, 2009, Incorporating Climate into a Long Lead-Time Non-parametric Streamflow Forecast. Journal of Hydrology, 368(2009) 131-142.
3. Geren, Tate, 2010, Streamflow Reconstruction in the Tennessee Valley, MS Dissertation, Department of Civil and Environmental Engineering, College of Engineering, The University of Tennessee, Knoxville, TN. 138 pp.
4. Ogle, Ross, 2010, Streamflow Reconstruction in Headwaters of the Southern Applachians, MS Dissertation, Department of Civil and Environmental Engineering, College of Engineering, The University of Tennessee, Knoxville, TN. 173 pp.

Executive Summary and Research Results

On behalf of the graduate research assistants (Cody Moser, Tate Geren and Ross Ogle), Co-PI (Henri Grissino-Mayer) and the PI (Glenn Tootle), we hereby submit our final report *Reconstructions of Tennessee Valley Precipitation and Streamflow*.

The scientific objectives of the two-year research project were to:

1. Evaluate available tree-ring chronology data and identify streamflow gages of interest. (Year 1)
2. Evaluate methodologies used to reconstruct streamflow. (Year 1)
3. Examine linkages between reconstructed streamflow and large scale oceanic / atmospheric phenomena that act at interannual and interdecadal time scales. (Year 2)
4. Develop probabilistic forecasts of droughts, and frequency / duration analysis of droughts. (Year 2)

The research provided outstanding training and support for the above mentioned graduate students. Cody Moser completed his Ph.D. in May 2011 while Tate Geren and Ross Ogle completed their Master's degree(s) in December 2010.

The results of the research were presented at the 2010 American Geophysical Union Fall Meeting:

Moser, C., R. Ogle, A. Bowen and G. Tootle. A Tree-Ring Reconstruction of Precipitation in the Tennessee Valley. Presentation at *American Geophysical Union (AGU) Fall Meeting*, December 12-18, 2010, San Francisco, California.

The research is currently under review in the *Journal of the American Water Resources Association* (pages 3 thru 30 below) and is in preparation for submittal to *Tree Ring Research* (pages 31 thru 51 below).

The results of the research made several contributions including the improvement of reconstructions of precipitation in the Tennessee Valley and the first successful reconstructions of streamflow in the Tennessee Valley. Literature review, data, methods, results and conclusions are provided below.

A TREE-RING RECONSTRUCTION OF PRECIPITATION IN THE TENNESSEE VALLEY

Cody L. Moser[1], Henri D. Grissino-Mayer[2], and Glenn A. Tootle[3]

ABSTRACT

A considerable record of past climate has been reconstructed for the southwestern United States (U.S.), but little knowledge exists about the history of climate in the southeastern part of the country. We investigate the dendroclimatic potential of a critical flood control and hydropower region in the southeastern U.S. (Tennessee Valley) using climate division precipitation and regional tree-ring chronology datasets. Predictors (i.e., tree-ring chronologies) are pre-screened using correlation ($p \leq 0.05$) with regional precipitation to ensure a practical and reliable reconstruction. Model calibration was based on the period 1895–1980 and a rescaling technique was applied to create the reconstruction. Tennessee Valley spring-summer (May–July) precipitation was reconstructed from 1692 to 1980 (289 years) using a stepwise linear regression model. The reconstruction model explains 56% of the variance in spring-summer precipitation records while the reduction of error (RE) statistic indicates valuable information exists in the reconstruction. The Weibull technique, which is frequently used in the field of hydrology, was applied to the field of dendroclimatology to visualize problematic areas (i.e., frequency regimes) of the climate reconstruction. The Weibull analysis illustrates that the Tennessee Valley reconstruction model developed generally underestimates extreme precipitation and

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overestimates average precipitation. The reconstruction reveals 15 drought periods in which Tennessee Valley spring-summer rainfall was below average for at least three consecutive years. The longest May–July drought occurred over 10 consecutive years (1827–1836). Instrumental records indicate that the two most recent droughts rank second and third in severity in the past three centuries. The reconstruction provides valuable climatic variability information that can be used to assess current conditions and manage water resources in the region. This information is especially valuable given the reservoir operation of the Tennessee Valley Authority (TVA).

(KEY TERMS: Tennessee Valley; dendrochronology; tree rings; precipitation; climate variability; water supply; time series analysis.)

INTRODUCTION

Dendroclimatology is the science of extracting climatic information from the annual growth layers of woody plants, and assumes that these growth layers contain the environmental conditions under which they were formed (Fritts, 1971; Hughes *et al*., 1982). Tree-ring widths can provide a proxy for gauge records because the same climatic factors, primarily precipitation and evapotranspiration, control the growth of moisture-limited trees (Meko *et al*., 1995). Since all forest sites are not equally influenced by interannual variations in the regional climate, dendroclimatologists search for the particular marginal forest sites where precipitation and temperature variations strongly limit tree growth (Stahle and Cleaveland, 1992). The recovery of valid climate information from tree-ring data relies upon the regular formation of distinctive annual-growth layers, the selection of trees from climate-sensitive forest sites, and on the accurate cross-dating of annual rings to their exact year of formation (Douglass, 1941; Stokes and Smiley, 1968; Fritts, 1976).

Annual tree-ring data are uniquely suited for high-resolution climate reconstructions and have been widely used to reconstruct climatic conditions and atmospheric oscillations. Valuable reconstructions of drought (Girardin *et al*., 2006; Cook *et al*., 2007; D'Arrigo *et al*., 2008), climate indices (Cook *et al*., 2002; Gray *et al*., 2004; Braganza *et al*., 2009), precipitation (Stahle and Cleaveland, 1994; Dettinger *et al*., 1998), streamflow (Meko *et al*., 2007; Watson *et al*., 2009; Barnett *et al*., 2010), and temperature (Wiles *et al*., 1998; Yadav *et al*., 1999; Cook *et al*., 2000) provide important baseline information for evaluating current trends in climate and for placing possible future changes within a historical context. Given the great age and extensive spatial coverage of tree-ring chronologies in the temperate latitudes of the Northern Hemisphere, tree rings can provide one of the best sources of information on natural climate fluctuations to measure the anticipated climate changes of the future (Stockton *et al*., 1985; Stahle and Cleaveland, 1992). Moisture-sensitive trees species are ideal in dendroclimatic research and the arid and semi-arid conditions of the southwestern U.S. offers the opportunity to create statistically skillful tree-ring reconstructions of climate variables. However, in the southeastern U.S., many misconceptions still linger among scientists that tree-ring research simply is not possible because of high decomposition and decay rates and a lack of trees that are long-lived or have sensitive patterns of tree rings to facilitate crossdating (Grissino-Mayer, 2009).

While dendroclimatology has a long history in the southwestern U.S., the science in the southeastern U.S. has been discontinuous, largely because the forests of the region are more mesic and have been extensively cleared or impacted by management practices (Grissino-Mayer, 2009). Although misconceptions still exist regarding the applicability of dendroclimatology in the Southeast, tree rings in the region have been used to investigate the relationships between climate and tree-growth. Using seven tree-ring chronologies, Phipps (1983) reconstructed April–August streamflow in Virginia. Tainter *et al*. (1984) used dendrochronology to investigate red oak species decline within the western North Carolina Nantahala Mountains. The 1,000-year spring-summer precipitation reconstruction created by Stahle and Cleaveland (1992) was found to replicate most of the multidecadal variability apparent in the available instrumental rainfall data within North Carolina, South Carolina, and Georgia. These studies form the foundation to dendroclimatology in the southeastern U.S. However, it is evident that very little dendroclimatology research has been conducted within the southeast U.S. during the past 20 years.

Our first objective evaluates the dendroclimatic potential in the Tennessee Valley using tree-ring chronologies. Blasing *et al*. (1981) attempted the first tree-ring reconstruction within the Tennessee Valley. Updating the reconstruction will provide valuable graphical and statistical information about regional climatic drivers and patterns. We hypothesize that the research of Blasing *et al*. (1981) can be improved statistically, spatially, and graphically with the incorporation of modern statistical software, visualization tools, and mapping capabilities. Next, a Weibull exceedance probability technique is applied. The presented Weibull technique is a new contribution to the field of dendroclimatology. The method can be used to visualize problematic areas of a climate reconstruction and determine the validity of a reconstruction. Finally, we examine the long-term hydrologic variability in the Tennessee Valley and determine drought phases based on the reconstruction. Analyzing the multidecadal variability of precipitation on a timescale longer than the instrumental record provides valuable water availability information to Tennessee Valley water resource planners and managers.

SITE DESCRIPTION

The Tennessee Valley Authority (TVA) operates and maintains water resources in the Tennessee Valley. TVA works to support economic development and serves as an environmental steward of the nation's fifth largest river system. Dams operated by TVA store the water needed to generate clean, efficient electric power and help prevent hundreds of millions of dollars in flood damage. Our study area encompasses eastern Tennessee and western North Carolina (Figure 1) within the Southern Appalachian region and the Great Smoky Mountains National Park (GSMNP). The crest of the Smoky Mountains forms the boundary between Tennessee and North Carolina and elevations range from 250 to 2,000 meters (NPS, 2010). GSMNP has a moderate climate, typified by mild winters and hot, humid summers. GSMNP experiences more annual rainfall (90 to 180 cm) than anywhere else in the country except the Pacific Northwest and the relative humidity in the park during the growing season is about twice that of the Rocky Mountain region (NPS, 2010). Both of these climatic factors provide exceptional growing conditions. Almost 95% of the GSMNP is forested, and about 25% of that area is old-growth forest making it one of the largest blocks of deciduous, temperate, old-growth forests in North America (NPS, 2010).

DATA AND METHODS

Tree-Ring Chronologies

Tree-ring chronology data are available from the International Tree-Ring Data Bank (ITRDB, 2010) (http://www.ncdc.noaa.gov/paleo/treering.html). Datasets are maintained by the National Oceanic and Atmospheric Administration (NOAA) Paleoclimatology Program and the World Data Center for Paleoclimatology. Available data include ring width measurements, wood density measurements, and site chronologies. Tree-ring chronology datasets within and around the eastern Tennessee Valley were collected. All ring width series were uniformly processed and standardized using the ARSTAN program (Cook, 1985). Conservative detrending methods (negative exponential/straight line fit or a cubic spline two thirds the length of the series) were used to combine all series into a single site chronology (Cook *et al*., 1990). Low-order autocorrelation in the chronologies that may, in part, be attributed to biological factors (Fritts, 1976) was removed, and the resulting residual chronologies were used for analysis. Because the reconstruction length and moisture sensitivity of eastern U.S. tree species was unknown at the time of data collection, approximately 70 regional chronologies were collected (Figure 1).

Precipitation

NOAA provides monthly climatic datasets (i.e., temperature, precipitation, and Palmer Drought Severity Index) for each U.S. climate division. Climate division datasets are regional representations based on multiple weather stations located across the region. Datasets do not reflect localized phenomena which may be characteristic of the climatic record at a single station. Four climate divisions were used in our study; two located in Tennessee (Eastern and Cumberland Plateau) and two within North Carolina (Southern Mountains and Northern Mountains) (Figure 1).

Identifying Similar Precipitation Regions

We use a rotated principal components technique similar to Timelsena and Piechota (2008) to regionalize the climate division precipitation datasets. Principal components analysis (PCA) is a widely used technique in meteorology and climatology (Baeriswyl and Rebetz, 1997) and is sometimes used to reduce the size of climate datasets without losing critical information. Spatial regionalization based on the principal components of climate variables is called S-Mode PCA (Richman, 1986). Following Timelsena and Piechota (2008), a principal component factor loading cutoff value of 0.6 was used to establish statistically similar climatic regions. As an alternative to reconstructing the precipitation for each climate division, S-Mode PCA determines if regional precipitation can be reconstructed, thus providing increased value. Blasing *et al*. (1981) concluded that it was generally true that division data, and possibly other regionally averaged data, are superior to single-station data for dendroclimatic studies and recommended that exploratory studies in such regions involve calibrations with regionally averaged data. S-Mode PCA results provided the basis for the regionalization of the reconstruction area.

Seasonal Reconstruction

We use correlation between various seasons for regional (as identified by PCA) precipitation and yearly residual with measurements for tree-ring chronologies (in and adjacent to the precipitation region) to identify the precipitation season most influential to tree growth and therefore most suitable for reconstruction. Arguably, the concept of correlation can be viewed as the foundation of both basic statistics (e.g., t-test) and advanced statistics (e.g., multivariate analysis of variance), because these other tests either explicitly or implicitly describe relationships or associations among variables of interests (Chen and Popovich, 2002). Due to varying climatological and biological influences in the region, a 95% (positive) significance level ($p \leq 0.05$) was chosen. Blasing *et al*. (1981) discovered tree rings in the region contain the highest moisture signal with May-June precipitation. We consider the relationship between tree growth and ten different precipitation seasons of various durations. Three-month seasonal precipitation periods investigated include January–March, April–June, May–July, July–September, and October–December. Six-month seasonal precipitation periods include January–June, April–September, and July–December. May-June and annual precipitation are also considered. We retain significant, positive r-values for analysis.

Reconstruction Methodology

Model calibration and verification in the region was based on the period from 1895 to 1980 (n = 86). Regression approaches are the most common statistical method in climate reconstructions. In the simplest case, a linear regression equation is used to reconstruct past values of a single climatic variable from ring-width indices of a single tree-ring chronology, or from a mean of two or more chronologies which have been merged to form a single chronology (Blasing *et al*., 1981). Following the procedure of Woodhouse *et al*. (2006), the F-level for a predictor had a maximum p-value of 0.05 for entry and 0.10 for retention in our stepwise regression model.

Next, the ability of the variables to predict precipitation was tested using a split sample calibration-verification scheme (Meko and Graybill, 1995; Woodhouse, 2003). The same variables to predict precipitation were used in a regression equation to predict precipitation in the first half of the period 1895–1937 (n = 43), and the resulting regression equation was tested on the second half of the period 1938–1980 (n = 43). The variables were then calibrated with the second half of the period and tested on the first half. The split sample scheme is an alternative method to calibrate and verify models and will confirm or deny the results from stepwise regression.

Graumlich (1987) and Grissino-Mayer *et al*. (1989) discovered that the final climatic reconstruction has less variability than the original climate data used in the regression analysis. In our study, predicted values from the regression model were rescaled to have the same variance as the instrumental record. First, the mean of the predicted series was subtracted from each predicted value. Next, each centered observation was multiplied by a scaling factor, k, defined as:

$$k = \frac{s_x}{s_p} \qquad (1)$$

where s_x and s_p are the standard deviations of the original and predicted values, respectively. Finally, the mean was added back to each predicted value. The rescaling method results in a more realistic climate reconstruction without affecting the overall skill of the model.

Statistics calculated to assess model skill and proficiency include overall variance explained (R^2), R^2-predicted, reduction of error (RE), and the Durbin-Watson statistic. While R^2 measures the patterns of similarity between two time series, it does not account for the magnitudes of the differences between observed values and their estimates. RE accounts for differences in magnitudes between observed and predicted values by testing the ability of the regression model to estimate precipitation compared to estimates based on the calibration period mean. RE ranges from minus infinity to + 1.0 and a positive RE value indicates the model has predictive skill (Lorenz, 1956; Fritts, 1976; Woodhouse, 2003). R^2-predicted was calculated from the Predicted REsidual Sums of Squares (PRESS) statistic. PRESS is based upon a leave-one-out cross-validation in which a single year or observation is removed when fitting the model. As a result, the prediction errors are independent of the predicted value at the removed observation (Garen, 1992). The Durbin-Watson statistic was used to check for autocorrelation in the residuals. For model validation, it was imperative that the predictor chronologies and reconstruction residuals contained similar autocorrelation structures. Root mean square error (RMSE), a measure of the differences between predicted and observed values, was also calculated and provided an additional measure of model skill.

Weibull Exceedance Probability

The Weibull equation is the most efficient formula for computing plotting positions for unspecified distributions (Viessman and Lewis, 2003).

$$P = \frac{m}{(n+1)} \qquad (2)$$

P is an estimate of the probability of values being equal to or greater than the ranked value, *m* is the rank of descending values, and *n* is the number of values. Weibull exceedance probability plots provide water managers comprehensive estimates of average precipitation, flows, and extreme events. We calculate the Weibull distribution separately for the reconstruction and observed datasets. Our novel approach plots the Weibull distributions together and provides a visualization tool for the accuracy of the reconstruction model over the full range of precipitation values during the calibration period (1895 to 1980). The evaluation of reconstructed precipitation values before the instrumental record was based on the errors associated with the Weibull plot. The presented Weibull technique may be applied to compare any two time-series of similar lengths (i.e., observed and modeled).

RESULTS

Seasonal Reconstruction and Identification of Similar Precipitation Regions

Similar to Blasing *et al*. (1981), our correlation analysis between seasonal precipitation data and regional chronologies indicates tree-ring sensitivity to climate conditions from spring-summer moisture. DendroClim 2002 from Biondi and Waikul (2004) indentifies a significant correlation with May, June, and July precipitation, with May and June showing the strongest moisture signal. Henderson and Grissino-Mayer (2009) found positive relationships between spring-summer precipitation and tree growth in the Southeastern Coastal Plain and Stahle and Cleaveland (1992) found that April–June precipitation had the strongest relationship with tree growth in North Carolina, South Carolina, and Georgia, which further confirm our results. Large quantities of tree-ring chronologies were statistically significant with May-June, April–June, and May–July precipitation (Figure 2). The three-month precipitation seasons of January–March, July–September, October–December and six-month season of July–December were insignificant (i.e., very few moisture sensitive chronologies). Several tree-ring chronologies were significant with respect to the precipitation seasons of January–June, April–September and January–December (annual). However, this was observed because these periods contain the highly sensitive period of April through July within their time-series, making these periods unsuitable to reconstruct. May–July contains a stronger moisture signal compared to April–June. Rather than reconstructing May-June precipitation as performed in Blasing *et al*. (1981), we elect to reconstruct May–July precipitation because reconstructing a three-month season provides more climatic variability and temporal information. May-June precipitation reconstructed in Blasing *et al*. (1981) accounts for 15–20% of total annual precipitation while 25–35% of total annual precipitation occurs in May–July.

Correlation analysis indicates that all four climate division precipitation datasets are highly related (significant at $p < 0.01$) to each other. Following Timilsena and Piechota (2008), S-Mode PCA reveals that all four climate division precipitation datasets also exceed the factor loading cutoff value of 0.6. Therefore, the four climate divisions were merged (averaged) similar to Woodhouse (2003). The reconstruction region contains 42 tree-ring chronologies that were significant with May–July precipitation (Figure 2). To further investigate and better understand the dendroclimatic potential of the southeastern U.S., tree-ring chronologies that were significant (95%) with spring-summer precipitation were analyzed by species (Figure 3). Within the southeastern U.S., the ITRDB contains more oak chronologies than any other species. Approximately 60% of the oak chronologies in the region were significant with May–July precipitation. While fewer bald cypress and hemlock chronologies have been cored in the region, they contain a similar moisture signal (~60%). All tulip and cedar chronologies in the region contain a significant spring-summer moisture signal although very few (less than 5) of these species have been collected. Spruce and pine species contain the weakest moisture signal in the region (Figure 3).

Calibration and Verification of the Reconstruction Model

A spring-summer (May–July) precipitation reconstruction dating back to 1692 was most feasible in this region. We base feasibility on the balance between reconstruction length and predictability of the calibration model. Five tree-ring chronologies (Table 1) within and around the reconstruction region were retained in the stepwise regression model. The Scotts Gap chronology is a tulip poplar, Mt. Collins a spruce, and the Land Between the Lakes an oak species. Two Bald Cypress chronologies (Lassiter Swamp and Black River) from Stahle and

Cleaveland located near the Atlantic coast were also retained in the reconstruction model (Figure 1). Although the five chronologies are not all located within our reconstruction region, the stepwise regression results indicate that this was the set of chronologies that best reflects the regional climate conditions and also influence spring-summer precipitation in the region.

Model calibration and verification results in our study significantly exceed those of Blasing *et al*. (1981). The overall variance explained in regional May-June precipitation from the Blasing *et al*. (1981) calibration model never exceeded 29%. Our Tennessee Valley spring-summer reconstruction model explained 56% of the total variance (Figure 4). Predicted precipitation values were correlated at $p \leq 0.001$ with instrumental values from 1895 to 1980. The Durbin-Watson statistic for the regression model was 2.15, indicating no signs of autocorrelation and validating the use of residual chronologies. Residuals from the regression equation display no trends with the predictor variables and were approximately normally distributed, meeting the assumptions of multiple linear regression. The calibration model had a reduction of error value of 0.50, indicating valuable information exists in the reconstruction, and the RMSE of the rescaled ($k = 1.34$) calibrated reconstruction model was 5 centimeters (14% of the mean). Model statistics (Table 2) were calculated using the rescaled reconstruction.

Results from the split sample method confirm the findings of stepwise regression. Overall variance explained was similar to that of stepwise linear regression. The period from 1895 to 1937 resulted in better model calibration and verification (65% of the variance explained), compared with 40% of the variance being explained using the period from 1938–1980. These results suggest that tree growth had an improved response to May–July precipitation during 1895–1937 in the region. The Weibull plot (Figure 5) shows that the reconstruction model generally underestimates extreme precipitation (wet and dry) and overestimates average precipitation. The average absolute difference between reconstructed and observed spring-summer precipitation for the Weibull plot was 3.5%, confirming a reasonably accurate and realistic reconstruction.

DISCUSSION OF RECONSTRUCTED TENNESSEE VALLEY PRECIPITATION AND LONG-TERM HYDROCLIMATIC VARIABILITY

The stepwise linear regression model was used to reconstruct May–July Tennessee Valley precipitation for the years of the tree-ring record, dating back to 1692 (Figure 6). The full precipitation reconstruction average was 36 centimeters. Based on the calibrated model and validation statistics, the reconstruction accurately replicates the annual variability apparent in instrumental rainfall data (r = 0.75). Instrumental records can be evaluated in the context of a longer period based on climate reconstructions. This is useful in determining whether planning based on the instrumental record incorporates the range of variability and extremes that is representative of long-term natural variability (Woodhouse, 2003). Extreme 5, 10, and 25-year periods were calculated using percentage of overall normal for the reconstruction and recent instrumental records (Table 3). In all cases, the reconstruction revealed more variability in May–July precipitation has occurred compared to what has been observed in instrumental records. The largest difference was found in the 5-year driest periods. While the driest 5-year period based on instrumental records was 16.5% below normal, the driest 5-year period based on the reconstruction was nearly 26% below normal.

In general, tree-ring reconstructions are conservative estimates of the observed values, and there is a tendency in moisture-sensitive trees for dry extremes to be better replicated than wet extremes (Woodhouse, 2003). We define a drought as a period of at least three consecutive years in which the spring-summer precipitation was below the overall (i.e., reconstruction) average. Following the procedure in Woodhouse (2003), the severity of these dry phases was quantified by calculating the cumulative departures of the below-average years and dividing this total by the number of consecutively below-average years for a seasonal average severity. One drought occurred in the late 1600s (Figure 7). Six droughts occurred in the 1700s including the most severe drought in the past three centuries (1724–1726) during which the May–July precipitation was nearly 30% below normal. Six droughts also occurred in the 1800s, including the longest spring-summer drought (a duration of ten years from 1827–1836) in the past three centuries. Because the reconstruction ends at 1980, droughts occurring in the past century were broken into two groups: (1) droughts based on the reconstruction (1900–1980) and (2) droughts based on recent instrumental records (1981–2008). Similar to droughts based on the reconstruction, droughts based on instrumental records were determined using the long-term reconstruction mean. A total of four droughts occurred during the past 110 years, two based on the reconstruction period and two based on recent instrumental data. The two most recent May–July droughts (1985–1988 and 2006–2008) were ranked second and third in terms of drought severity in the past 300 years (Figure 7). Since the reconstruction model generally underestimates extreme low precipitation values based on the Weibull plot, it should be noted that droughts were most likely slightly less severe than what is shown in Figure 7.

CONCLUSIONS AND FUTURE WORK

We evaluated the dendroclimatic potential in the Tennessee Valley using precipitation and tree-ring chronologies. Although our reconstruction was not as robust as those found in the western U.S., it exceeds previous research efforts and can provide regional water managers with a visual tool to analyze current and future spring-summer precipitation patterns and extremes within the Tennessee Valley. A Weibull technique new to the field of dendroclimatology was presented and provides a visualization tool for a climate reconstruction. The reconstruction reveals that variability in 1700s and 1900s precipitation had slightly more variability than 1800s precipitation. Furthermore, droughts occurred with similar frequency in each century.

The climatic and biological persistence within the southeastern U.S. makes it difficult to create an accurate climate reconstruction because tree growth is likely driven by a number of environmental variables. Future work may investigate the dendroclimatic potential of reconstructing other regional climate parameters, including temperature. Our results suggest that tree growth in the southeast U.S. is affected by numerous limiting factors, which is an important observation, but causes a problem because an accurate reconstruction of a single climate variable is challenging. Value would be found in the collection of more recent samples from tree species found to contain a significant response to precipitation in our research. Many of the chronologies in the region available on the ITRDB were last cored in the 1980s, making it difficult to compare the recent change in climate with climate of past centuries. It is anticipated that subsequent reconstruction studies will find value in this work by using our study as a foundation when evaluating past climate in the Tennessee Valley.

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LITERATURE CITED

Baeriswyl, P.A. and M. Rebetez, 1997. Regionalization of Precipitation in Switzerland by Means of Principal Component Analysis. Theoretical and Applied Climatology 58:31–41.

Barnett, F., T. Watson, S. Gray, and G. Tootle, 2010. Upper Green River Basin Streamflow Reconstructions. ASCE Journal of Hydrologic Engineering 15(7):567–579.

Biondi, F. and K. Waikul, 2004. DENDROCLIM2002: A C++ Program for Statistical Calibration of Climate Signals in Tree-Ring Chronologies. Computers and Geosciences 30(3):303–311, doi:10.1016/j.cageo.2003.11.004.

Blasing, T.J., D.N. Duvick, and D.C. West, 1981. Dendroclimatic Calibration and Verification Using Regionally Averaged and Single Station Precipitation Data. Tree-Ring Bulletin 41:37–43.

Braganza, K., J.L. Gergis, S.B. Power, J.S. Risbey, and A.M. Fowler, 2009. A Multiproxy Index of the El Niño-Southern Oscillation, AD 1525-1982. Journal of Geophysical Research 114, DO5106, doi:10.1029/2008JD010896.

Chen, P.Y. and P.M. Popovich, 2002. Correlation: Parametric and Nonparametric Measures. Sage Publications, Inc., Thousand Oaks, California.

Cook, E.R, 1985. A Time Series Approach to Tree-Ring Standardization, Ph.D. dissertation. University of Arizona, Tucson.

Cook, E.R., B.M. Buckley, R.D. D’Arrigo, and M.J. Peterson, 2000. Warm-Season Temperatures Since 1600 BC Reconstructed from Tasmanian Tree Rings and their Relationship to Large-Scale Sea Surface Temperature Anomalies. Climate Dynamics 16(2–3):79–91.

Cook, E.R., K. Briffa, S. Shiyatov, and V. Mazepa, 1990. Tree-Ring Standardization and Growth-Trend Estimation. *In*: Methods of Dendrochronology: Applications in the Environmental Sciences, E.R. Cook and L.A. Kairiukstis. (Editors). Springer, New York.

Cook, E.R., R.D. D’Arrigo, and M.E. Mann, 2002. A Well-Verified, Multiproxy Reconstruction of the Winter North Atlantic Oscillation index Since AD 1400. Journal of Climate 15(13):1754–1764.

Cook, E.R., R. Seager, M.A. Cane, and D.W. Stahle, 2007. North American Drought: Reconstructions, Causes, and Consequences. Earth-Sciences Reviews 81(1-2):93–134, doi:10.1016/j.earscirev.2006.12.002.

D'Arrigo, R., P. Baker, J. Palmer, K. Anchukaitis, and G. Cook, 2008. Experimental Reconstruction of Monsoon Drought Variability for Australia Using Tree Rings and Corals. Geophysical Research Letters 35(12), L12709, doi:10.1029/2008GL034393.

Dettinger, M.D., D.R. Cayan, H.F. Diaz, and D.M. Meko, 1998. North-South Precipitation Patterns in Western North America on Interannual-to-Decadal Timescales. Journal of Climate 11(12):3095–3111.

Douglass, A.E., 1941. Crossdating in Dendrochronology. Journal of Forestry 39(10):825–831.

Fox, J., 1991. Regression Diagnostics: An Introduction. Sage University Paper Series on Quantitative Applications in the Social Sciences 07-079. Sage Publications, Newbury Park, CA, United States.

Fritts, H.C., 1971. Dendroclimatology and Dendroecology. Quaternary Research 1:419–449.

Fritts, H.C., 1976. Tree Rings and Climate. Academic Press, London, United Kingdom.

Garen, D.C., 1992. Improved Techniques in Regression-Based Streamflow Volume Forecasting. Journal of Water Resources Planning and Management 118(6):654–670.

Girardin, M.P., J.C. Tardiff, M.D. Flannigan, and Y. Bergeron, 2006. Synoptic-Scale Atmospheric Circulation and Boreal Canada Summer Drought Variability of the Past Three Centuries. Journal of Climate 19(10):1922–1947.

Graumlich, L.J., 1987. Precipitation Variation in the Pacific Northwest (1675-1975) as Reconstructed from Tree Rings. Annals of the Association of American Geographers 77(1):19–29.

Gray, S.T., L.J. Graumlich, J.L. Betancourt, and G.T. Pederson, 2004. A Tree-Ring Based Reconstruction of the Atlantic Multidecadal Oscillation since 1567 AD. Geophysical Research Letters 31(12), L12205, doi:10.1029/2004GL019932.

Grissino-Mayer, H.D., 1989. Climatic Response in Tree Rings of Loblolly Pine from North Georgia. Physical Geography, 10(1):32–43.

Grissino-Mayer, H.D., 2009. An Introduction to Dendroarchaeology in the Southeastern United States. Tree-Ring Research 65(1):5–10.

Henderson, J.P. and H.D., Grissino-Mayer, 2009. Climate-Tree Growth Relationships of Longleaf Pine (Pinus palustris Mill.) in the Southeastern Coastal Plain, USA. Dendrochronologia 27(1):31–43.

Hughes, M.K., P.M. Kelly, J.R. Pilcher, and V.C. LaMarche, Jr, 1982. Climate from Tree Rings. Cambridge University Press, Cambridge, United Kingdom.

International Tree Ring Data Bank (ITRDB), 2010. Tree-Ring Data – World Data Center for Paleoclimatology, <http://www.ncdc.noaa.gov/paleo/treering.html> (Sep. 25, 2009).

Lorenz, E.N., 1956. Empirical Orthogonal Functions and Statistical Weather Prediction. Statistical Forecasting Rep. 1, Department of Meteorology, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Meko, D.M. and D.A. Graybill, 1995. Tree-Ring Reconstructions of Upper Gila River Discharge. Water Resources Bulletin 31:605–616.

Meko, D.M., C.A. Woodhouse, C.A. Baisan, T. Knight, J.J. Lukas, M.K. Hughes, and M.W. Salzer, 2007. Medieval Drought in the Upper Colorado River Basin. Geophysical Research Letters 34(10), L10705, doi:10.1029/2007GL029988.

Meko, D.M., C.W. Stockton, and W.R. Boggess, 1995. The Tree-Ring Record of Severe Sustained Drought. Water Resources Bulletin 31:789–801.

National Park Service (NPS), 2010. Great Smoky Mountains. < http://www.nps.gov/grsm/naturescience/index.htm> (Aug. 30, 2010).

Phipps, R.L., 1985. Collecting, Preparing, Crossdating, and Measuring Tree Increment Cores. Water-Resources Investigations Report 85-4148. U.S. Geological Survey.

Richman, M.B., 1986. Rotation of Principal Components (review article). Journal of Climatology 6:293–335.

Stahle, D.W. and M.K. Cleaveland, 1992. Reconstruction and Analysis of Spring Rainfall Over the Southeastern United-States for the Past 1000 Years. Bulletin of the American Meteorological Society 73(12):1947–1961.

Stahle, D.W. and M.K. Cleaveland, 1994. Tree-Ring Reconstructed Rainfall over the Southeastern USA During the Medieval Warm Period and Little Ice-Age. Climatic Change 26(2-3):199–212.

Stockton, C.W., W.R. Boggess, and D.M. Meko, 1985. Climate and Tree-Rings. Paleoclimate Analysis and Modeling. A.D. Hecht, Ed., J Wiley & Sons, Inc., 71–161.

Stokes, M.A., and T.L. Smiley, 1968. An Introduction to Tree-Ring Dating. University of Chicago Press. 73 pp.

Tainter, F.H., S.W. Fraedrich, and D.M. Benson, 1984. The Effect of Climate on the Growth, Decline, and Death of Northern Red Oaks in the Western North Carolina Nantahala Mountains. Castanea 49(3):127–137.

Timilsena, J. and T. Piechota, 2008. Regionalization and Reconstruction of Snow Water Equivalent in the Upper Colorado River Basin. Journal of Hydrology 352(1–2):94–106, doi:10.1016/j.jhydrol.2007.12.024.

Viessman, W. and G.L. Lewis, (2003). *Introduction to Hydrology*. 5th ed. Pearson Education, Inc., Upper Saddle River, New Jersey, USA.

Watson, T., F.A. Barnett, S. Gray, and G. Tootle, 2009. Reconstructed Streamflows for the Headwaters of the Wind River, Wyoming, United States. Journal of the American Water Resources Association 45(1):1–13, doi:10.1111/j.1752-1688.2008.00274.x.

Wiles, G.C., R.D. D'Arrigo, and G.C. Jacoby, 1998. Gulf of Alaska Atmosphere-Ocean Variability over Recent Centuries Inferred from Coastal Tree-Ring Records. Climatic Change 38(3):289–306.

Woodhouse, C.A., 2003. A 431-yr Reconstruction of Western Colorado Snowpack from Tree Rings. Journal of Climate 16(10):1551–1561.

Woodhouse, C.A., S.T. Gray, and D.M. Meko, 2006. Updated Streamflow Reconstructions for the Upper Colorado River Basin. Water Resources Research 42(5), WO5415, doi: 10.1029/2005WR004455.

Yadav, R.R., W.K. Park, and A. Bhattacharyya, 1999. Spring-Temperature Variations in Western Himalaya, India, as Reconstructed from Tree-Rings: AD 1390-1987. Holocene 9(1):85–90.

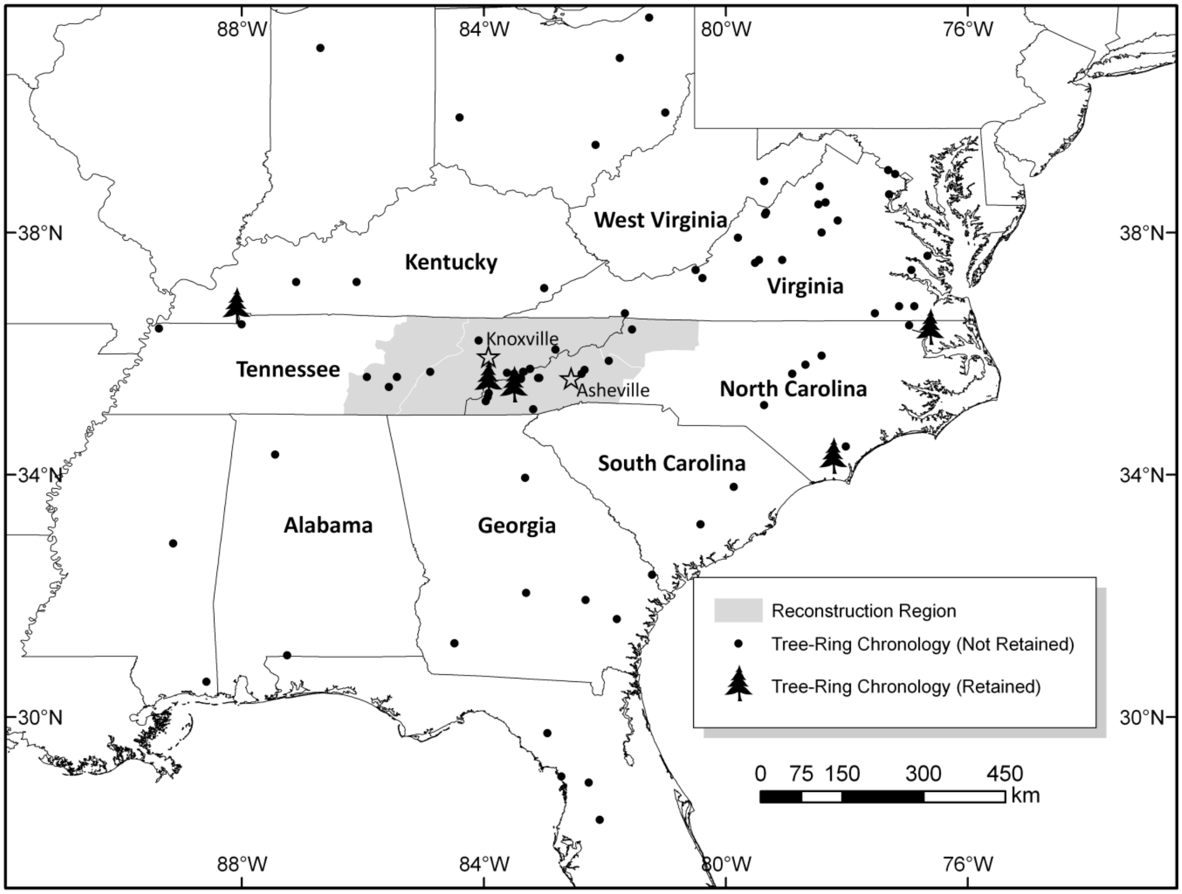

FIGURE 1. Location Map. The reconstruction region and all southeastern U.S. tree-ring chronologies are shown.

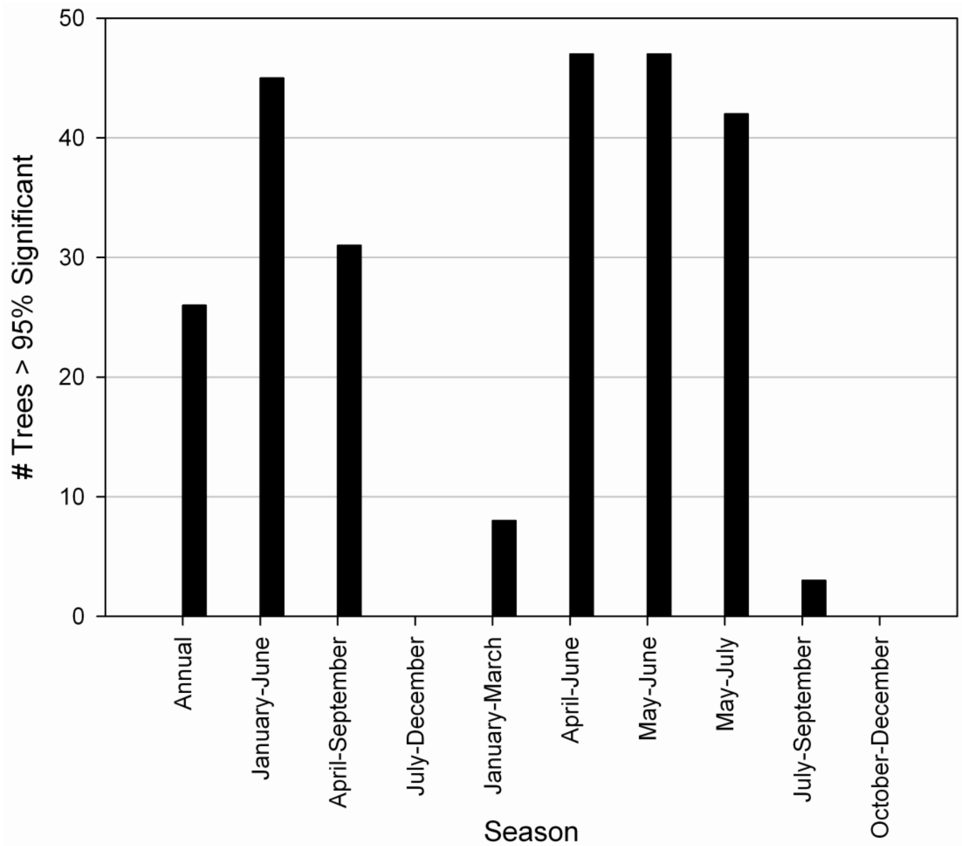

FIGURE 2. Seasonal Correlation Results. A 95% significance correlation level is used. Precipitation is reconstructed for spring-summer (May–July).

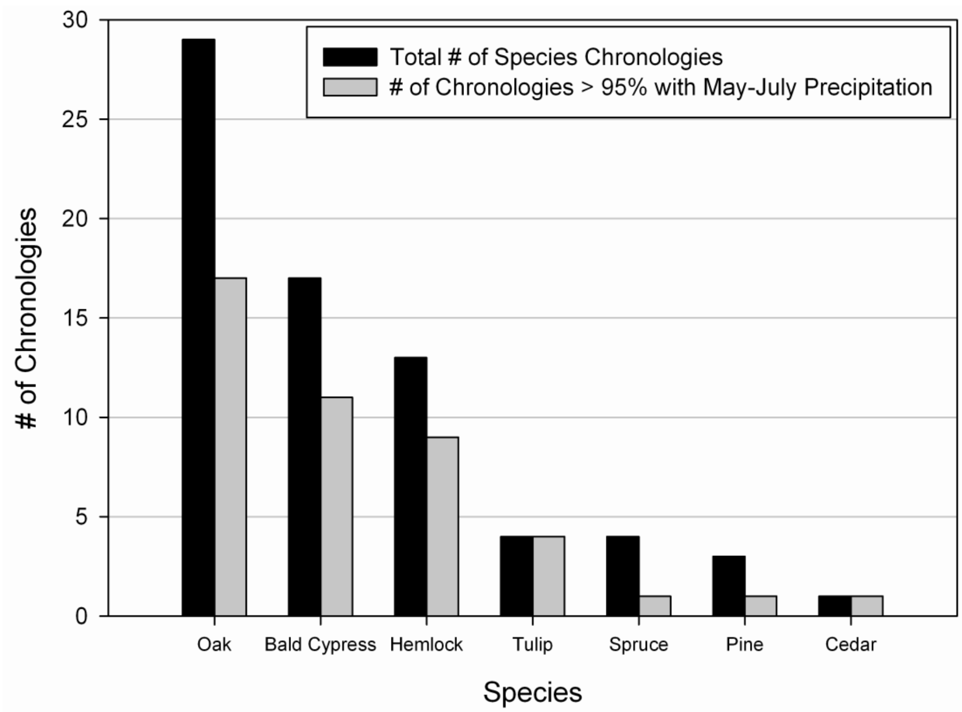

FIGURE 3: Tree-Ring Chronology Species Distribution in the Southeastern U.S. The black bar represents the total number of tree-ring chronologies collected and analyzed in our study. The gray bar represents the number of tree-ring chronologies that are correlated at 95% significance with May–July precipitation.

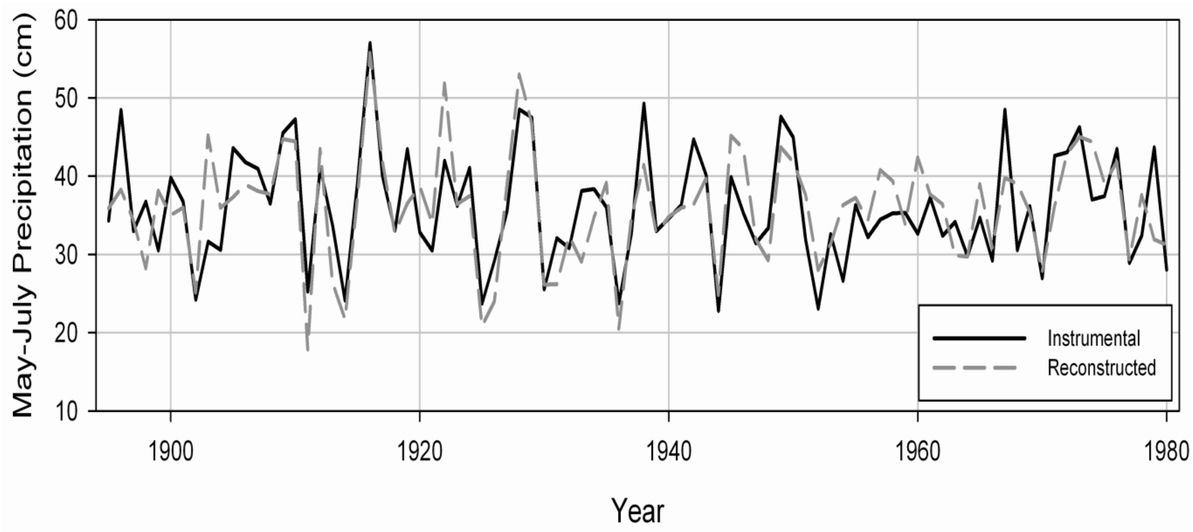

FIGURE 4. Tennessee Valley Calibration Model. The regression model explains 56% of the variance in spring-summer precipitation.

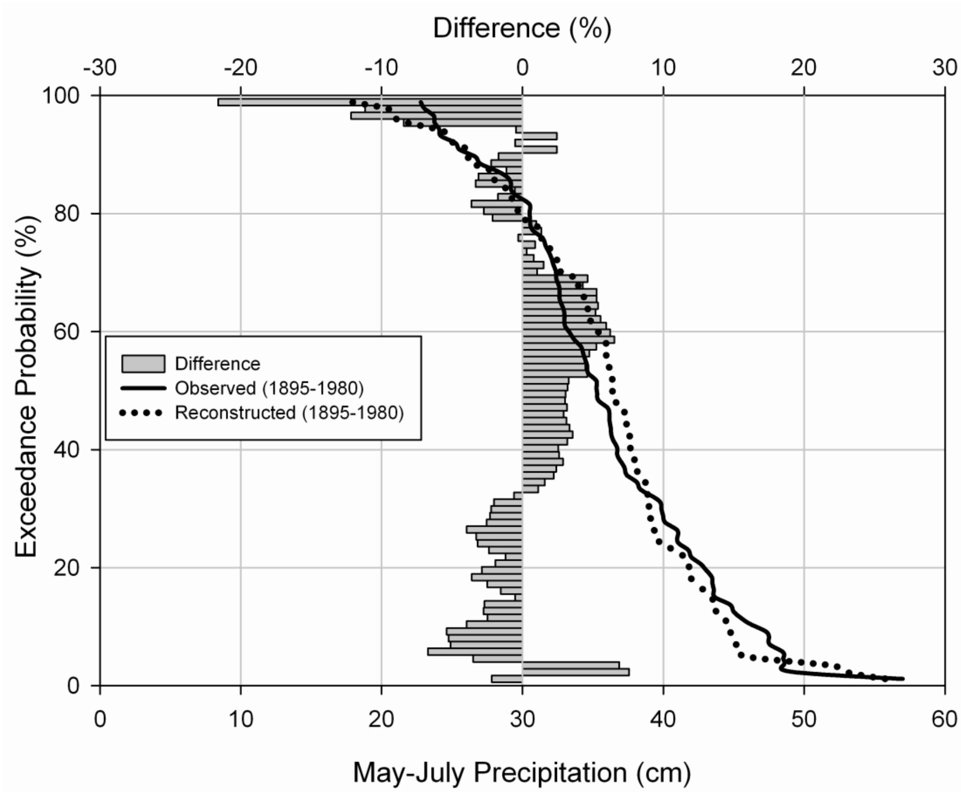

FIGURE 5. Tennessee Valley Weibull Distribution for May–July Precipitation. The reconstruction model generally underestimates extreme (high and low) precipitation and overestimates average precipitation.

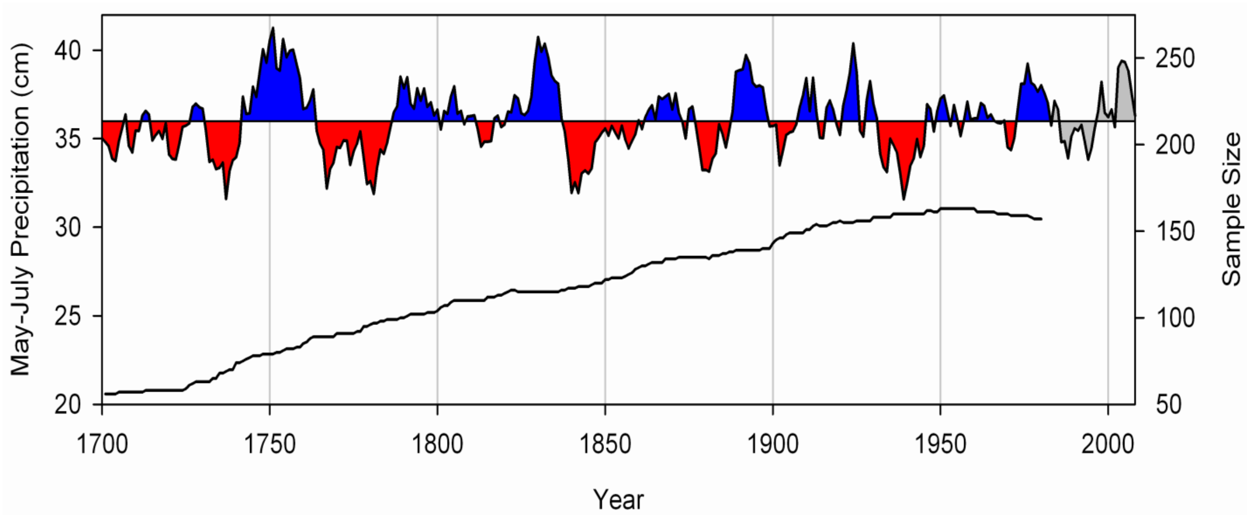

FIGURE 6. May-June-July Tennessee Valley Precipitation Reconstruction (Smoothed with a Five-Year Filter). Values are plotted against the long-term (full reconstruction) mean, with periods of below-average precipitation shown in red and periods of above-average precipitation shown in blue. Recent instrumental May–July (1981–2008) precipitation is shown in gray. The change in total number of samples in the five chronologies used in the reconstruction is shown by the line at the bottom (right hand y-axis).

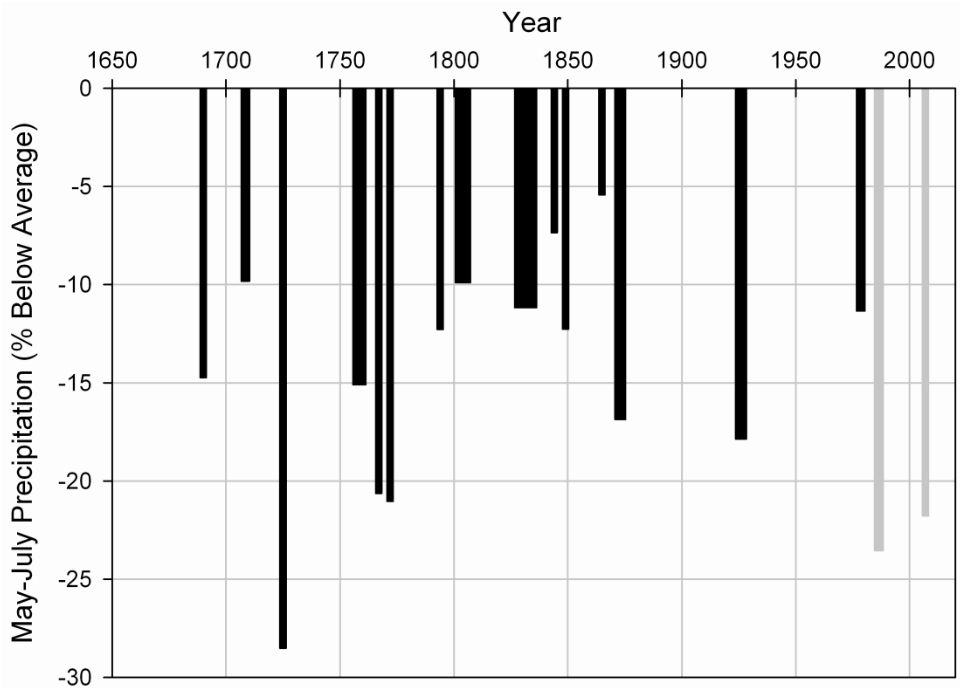

FIGURE 7. Tennessee Valley Spring-Summer Droughts in the Past Three Centuries. The length of each bar represents drought severity while the width represents drought longevity. The most severe drought occurred from 1724 to 1726 and the longest drought occurred from 1827 to 1836. Black bars represent droughts found using the reconstruction. Droughts occurring from 1981 to 2008 are shown in gray and are based on observed data.

TABLE 1. Tree-Ring Chronologies used for the Tennessee Valley Precipitation Reconstruction. Listed chronologies are found to be correlated at 95% with spring-summer precipitation in the region and have an adequate period of record to create the reconstruction.

Chronology	State	Span	Species
Scotts Gap	TN	1686-1980	*Liriodendron tulipfera L.*
Lassiter Swamp	NC	1527-1984	*Taxodium distichum L.*
Mt. Collins	TN	1658-1986	*Picea rubens S.*
Land Between The Lakes	KY	1692-2005	*Quercus stellata W.*
Black River	NC	367-1985	*Taxodium distichum L.*

TABLE 2. Calibration and Verification Statistics for the Precipitation Reconstruction.

	Calibration Model
Calibration Period	1895-1980
r	0.75
R^2	0.56
R^2 (predicted)	0.49
RE	+ 0.50
RMSE (cm)	5.03
Durbin-Watson	2.15

TABLE 3. Extreme Spring-Summer Precipitation Periods in the Tennessee Valley. The wettest and driest 5, 10, and 25-year periods are shown for the instrumental record and the reconstruction. In all cases, the reconstruction reveals that more variability in spring-summer precipitation has occurred compared to what has been observed in recent instrumental records. Values are in percentage of May–July normal.

	Instrumental (1895-2008)		Reconstruction (1692-1894)	
# of Years	Dry	Wet	Dry	Wet
5	-16.5	18.0	-25.8	23.9
10	-11.1	9.7	-12.3	14.5
25	-5.4	6.5	-6.4	7.7

TREE-RING RECONSTRUCTIONS OF STREAMFLOW FOR THE TENNESSEE VALLEY

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ABSTRACT

This study used USGS streamflow data from 11 gages within the Tennessee Valley and regional tree-ring chronologies to analyze the dendroclimatic potential of the region and create seasonal flow reconstructions. Prescreening methods included correlation, chronology end date, and temporal stability analysis of predictors to ensure practical and reliable reconstructions. Seasonal correlation analysis revealed that large numbers of regional tree-ring chronologies were significantly correlated ($p \leq 0.05$) with May-June-July streamflow. Stepwise linear regression was used to create the May-June-July streamflow reconstructions. Nine of the 11 streamflow reconstructions were considered statistically skillful ($R^2 \geq 0.40$). Skillful reconstructions ranged from 208 to 301 years in length and were statistically validated using leave-one-out cross validation, the sign test, and comparison of the distribution of low flow years. The long-term streamflow variability was analyzed for the Nolichucky, Nantahala, Emory, and SF Holston stations. The reconstructions revealed that while most of the western U.S. was experiencing some of its highest flow years during the early 1900s, the Tennessee Valley region was experiencing very low flow. Results reveal the potential benefit of using tree-ring chronologies to reconstruct hydrologic variables in the southeastern U.S. by demonstrating the ability of proxy-based reconstructions to provide useful data beyond the instrumental record.

Keywords: Tennessee Valley, tree-ring, reconstruction, streamflow, dendroclimatology

INTRODUCTION

Water planners and managers can make more accurate decisions based on information provided by expanding hydrologic records. Tree rings have been widely used as a proxy to reconstruct hydrologic variables in the western U.S. (Woodhouse 2003; Meko *et al*. 2007; Watson *et al*. 2009; Barnett *et al*. 2010). Relatively little dendroclimatological research has been conducted within the southeastern U.S. during the past 20 years when compared to the number of studies conducted in the southwestern, northwestern, and Rocky Mountain regions of the U.S. Many misconceptions still linger among scientists that tree-ring research simply is not possible in the southeastern U.S. because of high decomposition and decay rates, a lack of trees that are long-lived, and the absence of climatically sensitive patterns of tree rings to facilitate crossdating (Grissino-Mayer 2009). Furthermore, a lower priority is put on hydrologic reconstructions in the southeastern U.S. due to abundant water supplies.

The limited number of streamflow reconstructions for the southeastern U.S can be explained by a number of factors. Tennessee Valley Authority (TVA) dam construction has limited the number of undisturbed streams in the region. The region's natural topography divides the area into many small catch basins and obstructs rainfall pathways within watersheds. The effects of the topography may explain why the proximity of a tree-ring chronology to a streamflow gage is not always indicative of a statistically significant streamflow-tree-growth relationship. In addition, the southeastern U.S. receives more precipitation than most parts of the country, especially when compared to the western U.S., providing less motivation for water quantity studies. Furthermore, the lack of streamflow gage and tree-ring datasets spanning cooperative lengths contributes to the difficulty of obtaining long calibration windows.

Although misconceptions still exist regarding the applicability of dendroclimatology in the Southeast, tree rings in the region have been used to investigate the relationships between climate and tree-growth. Blasing *et al*. (1981) found that tree-rings were a good predictor of May-June precipitation for East Tennessee. Phipps (1983) reconstructed Occoquan River monthly summer streamflow in Virginia, finding June streamflow to be the strongest predictand. Stahle and Cleaveland (1992) created a 1,000-year spring-summer precipitation reconstruction within North Carolina, South Carolina, and Georgia that was found to replicate most of the multidecadal variability apparent in the available instrumental rainfall data. More recent studies have found strong climate signals in tree-ring patterns from Texas to Florida to Virginia and sites further inland (Henderson and Grissino-Mayer 2009; Speer *et al*. 2009; DeWeese *et al*. 2010; Harley *et al*. 2011), confirming the potential ability to develop a more extensive network of sites for spatial reconstructions of past climate.

The first objective of this research was to analyze the dendroclimatic potential of a critical flood control and hydropower region in the southeastern U.S. (Tennessee Valley) using streamflow and regional tree-ring chronology datasets. Based on previous studies, we hypothesized that regional tree-growth would be significantly correlated with spring-summer streamflow. Our second objective was to create statistically skillful (based on overall variance explained and model stability) streamflow reconstructions for 11 gages within the Tennessee Valley. Our final objective was to examine the long-term hydrologic variability of Tennessee Valley streamflow on a timescale exceeding the instrumental record. Doing so may provide valuable water availability information to Tennessee Valley water resource planners and managers.

DATA AND METHODS

Streamflow (USGS)

Unimpaired streamflow data for 11 gages within the Tennessee Valley were obtained from the United States Geological Survey (USGS) website via the National Water Information System (NWIS 2009). One of the most important components in a streamflow reconstruction is the accuracy and length of existing streamflow gage records. Although the USGS streamflow-gaging program began collecting streamflow data as early as 1887, not all of the USGS gage stations have the same period of record. Some USGS gage stations have missing data due to technical, mechanical, or otherwise unknown reasons. The USGS gage stations that were used in this study contained no missing data and most of the stations had at least 40 years of data to compare with regional tree-ring chronologies. Although these rivers are located in close proximity (Figure 1), the elevation and drainage area of each station is unique (Table 1). Cumulative flow in million cubic meters (MCM) was used.

Tree-Ring Chronologies (ITRDB)

Tree-ring chronology datasets within and around the southeastern U.S. were retrieved from the International Tree-Ring Data Bank (ITRDB) (Grissino-Mayer and Fritts 1997), which is maintained by the National Oceanic and Atmospheric Administration (NOAA) Paleoclimatology Program. All ring width series were uniformly processed and standardized using the AutoRegressive STANdardization (ARSTAN) program (Cook 1985). Conservative detrending methods (negative exponential/straight line fit or a cubic spline two thirds the length of the series) were used to combine all series into a single site chronology (Cook *et al*. 1990). Low-order autocorrelation in the chronologies that may in part be attributed to biological factors (Fritts 1976) was removed by autoregressive modeling, and the resulting residual chronologies were used for analysis. The residual chronology type has been found appropriate (rather than the standard chronology type which retains autocorrelation) when modeling hydrologic variables in the western U.S. (Woodhouse 2003; Meko *et al*. 2007; Watson *et al*. 2009; Barnett *et al*. 2010) and the southeastern U.S. (Crockett *et al*. 2010). We initially examined 102 chronologies across 12 states (Figure 1) for the strength of their responses to Tennessee Valley streamflow.

Predictor Prescreening Methods

Three prescreening methods were used to identify the most suitable tree-ring chronologies to use as predictors for the reconstruction models. First, a date screen was used. Many of the tree-ring samples within the southeastern U.S. were last collected during the early 1980s. We used the year 1980 as the cutoff date for initial predictor pool tree-ring chronologies, and removed any chronologies cored before 1980 from analysis.

Next, we inspected correlation coefficients between various streamflow seasons and residual tree-ring chronologies (in and adjacent to the Tennessee Valley) to identify the streamflow season most influential to tree growth and therefore most suitable for reconstruction. One of the most important aspects of the seasonal correlation analysis was to determine a consistent streamflow season to reconstruct for all 11 of the streamflow gages. Based on similar studies in surrounding regions, we hypothesized that a strong relationship would be found between tree growth and spring-summer (April–August) streamflow (Blasing *et al*. 1981; Phipps 1983; Stahle and Cleaveland 1992). However, numerous streamflow seasons of various lengths were analyzed for completeness. We considered the relationship between tree growth and ten different streamflow seasons of various durations. Three-month seasonal precipitation periods investigated included January–March, April–June, May–July, July–September, and October–December. Six-month seasonal precipitation periods include January–June, April–September, and July–December. May-June and annual precipitation were also considered. We retained significant ($p \leq 0.05$), positive r-values for analysis.

The last pre-screening method involved temporal stability analysis. Temporal stability analysis consisted of performing a 30-year moving correlation window, similar to Biondi *et al*. (2004), between the various streamflow seasons and residual tree-ring widths. Chronologies containing negative 30-year correlation values with seasonal flow were considered unstable and removed from analysis. Stability analysis ensured that reliable and practical streamflow reconstructions were generated.

Reconstruction Methodology

Model calibration windows were controlled by the date that streamflow was first collected at each gage station. While all calibration windows ended at 1980, the beginning dates of the calibration windows ranged from 1919 to 1949 (Table 1). The ability of the statistically significant and stable moisture sensitive tree-ring chronologies to predict precipitation was tested using a forward and backward (standard) stepwise regression model. Standard stepwise regression adds and removes predictors as needed for each step. The model stops when all variables not in the model have p-values that are greater than the specified alpha-to-enter value and when all variables in the model have p-values that are less than or equal to the specified alpha-to-remove value. Following the procedure of Woodhouse *et al*. (2006), the alpha-level for a predictor chronology had to have a maximum p-value of 0.05 for entry and 0.10 for retention in our stepwise regression model.

Numerous statistical measures were used to establish the statistical skill of each streamflow reconstruction. R^2 explained the amount of variance being explained by each model. R^2-predicted was calculated from the Predicted REsidual Sums of Squares (PRESS) statistic. The PRESS statistic is based upon a leave-one-out cross-validation in which a single year or observation is removed when fitting the model. As a result, the prediction errors are independent of the predicted value at the removed observation (Garen 1992). The Variation Inflation Factor (VIF) indicates the extent to which multicollinearity is present in a regression analysis. Generally, a VIF value close to 1.0 indicates low correlation between predictors and is ideal for a regression model (O'brien 2007). The Durbin-Watson (D-W) statistic was used to analyze the autocorrelation structure of model residuals. The sign test, a nonparametric procedure to count the number of agreements and disagreements between instrumental and reconstructed flow, was used for additional model validation.

RESULTS

After the date screen, 72 of the 102 chronologies were retained and used for seasonal correlation analysis. Similarly to Blasing *et al*. (1981), the two-month period May-June contained the largest number of significant tree-ring chronologies for the majority of the 11 gages. Furthermore, the winter months never yielded a large number of highly correlated tree-ring chronologies. While the number of significant tree-ring chronologies was similar for the seasons of April–June and May–July, tree-growth contained a stronger moisture signal (higher correlation) with May–July streamflow when compared to April–June streamfow. Rather than reconstructing May–June streamflow as performed in Blasing *et al*. (1981), we reconstructed May–July streamflow because reconstructing a three-month season provides more information on temporal characteristics of climate variability over a longer season. The number of chronologies with positive, significant ($p \leq 0.05$) r-values after seasonal (May-June-July) correlation varied for each streamflow station and ranged from three (Watauga gage) to 35

(NF Holston, Nolichucky, and Valley gages). Stability analysis removed the highest number (nine) of predictor pool tree-ring chronologies from the Valley gage, and the final number of chronologies that entered as initial predictors in the calibration models ranged from three (Watauga gage) to 34 (NF Holston gage).

For all of the streamflow gages, the most feasible calibration models and reconstructions were chosen (Table 2). We based feasibility on the length of the reconstruction, the overall variance explained of the model, and the predictability of the model. Nine of the 11 calibration models were considered statistically skillful ($R^2 \geq 0.40$). The D-W test for autocorrelation in the residuals from regression showed that the autocorrelation was not significant for most of the models, indicating that the residuals are random and the models were appropriate (Draper and Smith 1981). However, the D-W value for the Nolichucky calibration suggested that the model had serial correlation, but results were not conclusive. VIF values for all models were within acceptable ranges and sign test results were significant ($p \leq 0.01$) for 10 of the 11 calibration models.

Tree-ring chronologies, that were retained by at least one of the stepwise regression models, varied by location (Figure 1) and species (Table 3). The Knob Job chronology (

Eastern red cedar) was retained by the highest number of calibration models (five). More oak chronologies are available on the ITRDB in the southeastern U.S. than any other species, and at least one oak chronology was retained in eight of the 11 models. While the Hampton Hills chronology (white oak) contained a strong moisture signal and was retained in four of the models, it only dated back to 1772, which limited the reconstruction length of those gages. Furthermore, many of the baldcypress tree-ring chronologies on the Atlantic coast previously found to contain a high moisture signal (Stahle and Cleveland 1992) were retained in many of our models.

We chose four streamflow stations (Nolichucky, Nantahala, Emory, and SF Holston) that had sufficient calibration windows (≥ 40 years) and covered a large spatial region of the Tennessee Valley (Figure 1) for analysis. These four calibration models (Figure 2) explained 42–52% of the variance in May-June-July streamflow records. The models generally captured the year-to-year trend and peaks of regional streamflow (Figure 2).

May-June-July streamflow reconstructions, smoothed with 5-year end year filters, were created for the Nolichucky, Nantahala, Emory, and SF Holston gages (Figure 3). Flow at the Nolichucky gages was reconstructed back to 1686, Nantahala (1679), and flow at the Emory and SF Holston gages was reconstructed back to 1772. The reconstructions revealed numerous wet and dry periods that varied slightly at each gage. The distribution of flow years in the lowest 10th percentile from 1772 to 1980 was analyzed for visual validation of the streamflow reconstructions (Figure 4). The distribution of low flow years across the four stations were fairly consistent from 1772 to 1910. The period from 1910 to 1940 revealed numerous dry years that matched favorably across the four stations. Stahle and Cleaveland (1992, 1994) also found relative dry periods in their reconstructions of North Carolina, South Carolina, and Georgia in spring-summer precipitation during this period. In the western U.S., specifically the Upper Colorado River Basin, the highest sustained flows in the last 500 years occurred in the early decades of the 20th century (Woodhouse *et al*. 2006). This period coincided with allocation of Colorado River flows. Our results show reveal that while most of the western U.S. was experiencing some of its highest flow years during the early 1900s, the Tennessee Valley region was experiencing very low spring-summer conditions.

Although our reconstructions were not as robust (in terms of length and explained variance) as those found in the western U.S., they can provide regional water managers with a visual tool to analyze current and future spring-summer streamflow patterns and extremes within the Tennessee Valley.

Climatic persistence from year to year and biological persistence in tree growth in the southeastern U.S. makes it challenging to create statistically skillful hydrologic reconstructions because tree growth is likely driven by a number of environmental variables. Value would be found in the collection of more recent samples from tree species found to contain a significant response to precipitation in our research. Many of the chronologies in the region available on the ITRDB were last cored in the 1980s, making it difficult to compare recent changes in climate with climate of past centuries.

ACKNOWLEDGEMENTS

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LITERATURE CITED

Barnett, F., T. Watson, S. Gray, and G. Tootle, 2010. Upper Green River Basin streamflow reconstructions. *Journal of Hydrologic Engineering* 15(7):567–579.

Blasing, T.J., D.N. Duvick, and D.C. West, 1981. Dendroclimatic calibration and verification using regionally averaged and single station precipitation data. *Tree-Ring Bulletin* 41:37–43.

Cook, E.R. 1985. *A Time Series Analysis Approach to Tree-Ring Standardization*. Ph.D. dissertation. University of Arizona, Tucson.

Cook, E.R., K. Briffa, S. Shiyatov, and V. Mazepa, 1990. Tree-ring standardization and growth-trend estimation. In: *Methods of Dendrochronology: Applications in the Environmental Sciences*, E.R. Cook and L.A. Kairiukstis. (Editors). Springer, New York. 104–123 pp.

Crockett, K., J.B. Martin, H.D. Grissino-Mayer, E.R. Larson, and T. Mirti, 2010. Assessment of tree rings as a hydrologic record in a humid subtropical environment. *Journal of the American Water Resources Association* 46(5), 919–931, doi:10.1111/j.1752-1688.2010.00464.x.

DeWeese, G.G., H.D. Grissino-Mayer, C.W. Lafon, and S.R. Aldrich, 2010. Evaluating the dendrochronological potential of central Appalachian Table Mountain pine (*Pinus pungens* Lamb.). *Dendrochronologia* 28:173–186.

Draper, N.R., and H. Smith, 1981. *Applied Regression Analysis* (2nd ed.). John Wiley, New York. 736 pp.

Fritts, H.C., 1976. *Tree Rings and Climate*. Academic Press, New York. 567 pp.

Garen, D.C., 1992. Improved techniques in regression-based streamflow volume forecasting. *Journal of Water Resources Planning and Management*, 118(6):654–670.

Grissino-Mayer, H.D., 2009. An Introduction to Dendroarchaeology in the Southeastern United States. *Tree-Ring Research* 65(1):5–10.

Grissino-Mayer, H.D., and H.C. Fritts, 1997. The international tree-ring data bank: an enhanced global database serving the global scientific community. *The Holocene*, 7(2), 235–238.

Harley, G.L., H.D. Grissino-Mayer, and S.P. Horn, 2011. The dendrochronology of *Pinus elliottii* in the Lower Florida Keys: chronology development and climate response. *Tree-Ring Research* 67(1):39–50.

Henderson, J.P. and H.D. Grissino-Mayer, 2009. Climate-tree growth relationships of longleaf pine (*Pinus palustris Mill*.) in the Southeastern Coastal Plain, USA. *Dendrochronologia* 27(1):31–43.

Meko, D.M., C.A. Woodhouse, C.A. Baisan, T. Knight, J.J. Lukas, M.K. Hughes, and M.W. Salzer, 2007. Medieval drought in the Upper Colorado River Basin. *Geophysical Research Letters* 34(10), L10705, doi:10.1029/2007GL029988.

National Weather Information System (NWIS), 2009. USGS surface-water data for the nation, http://waterdata.usgs.gov/nwis/sw. Accessed 16 November 2009.

O'brien, R.M., 2007. A caution regarding rules of thumb for variance inflation factors. *Quality and Quantity* 41(5):673–690, doi: 10.1007/s11135-006-9018-6.

Phipps, R.L., 1983. Streamflow of the Occoquan River in Virginia as reconstructed from tree-ring series. *Water Resources Bulletin* 19:735–743.

Speer, J.H., H.D. Grissino-Mayer, K.H. Orvis, and C.H. Greenberg, 2009. Climate response of five oak species in the Eastern Deciduous Forest of the Southern Appalachian Mountains. *Canadian Journal of Forest Research* 39(3):507–518.

Stahle, D.W., and M.K. Cleaveland, 1992. Reconstruction and analysis of spring rainfall over the Southeastern United-States for the past 1000 years. *Bulletin of the American Meteorological Society* 73(12):1947–1961.

Stahle, D.W., and M.K. Cleaveland, 1994. Tree-ring reconstructed rainfall over the Southeastern USA during the Medieval Warm Period and Little Ice Age. *Climatic Change* 26(2-3):199–212.

Watson, T., F.A. Barnett, S. Gray, and G. Tootle, 2009. Reconstructed streamflows for the headwaters of the Wind River, Wyoming, United States. *Journal of the American Water Resources Association* 45(1):1–13, doi:10.1111/j.1752-1688.2008.00274.x.

Woodhouse, C.A., 2003. A 431-Yr reconstruction of Western Colorado snowpack from tree rings. *Journal of Climate* 16(10):1551–1561.

Woodhouse, C.A., S.T. Gray, and D.M. Meko, 2006. Updated streamflow reconstructions for the Upper Colorado River Basin. *Water Resources Research* 42(5), WO5415, doi:10.1029/2005WR004455.

Table 1. Descriptions of the 11 USGS streamflow stations used for analysis.

Station	Description	State	Drainage Area (km^2)	Elevation (m)	Start Date
03528000	Clinch River above Tazewell	TN	3818	323	1920
03524000	Clinch River at Cleveland	VA	1380	457	1921
03540500	Emory River at Oakdale	TN	1979	232	1928
03500000	Little Tennessee River near Prentiss	NC	363	612	1945
03504000	Nantahala River near Rainbow Springs	NC	134	937	1941
03488000	NF Holston River near Saltville	VA	572	519	1921
03465500	Nolichucky River at Embreeville	TN	2085	463	1921
03512000	Oconaluftee River at Birdtown	NC	477	562	1949
03473000	SF Holston near Damascus	VA	785	546	1932
03550000	Valley River at Tomotla	NC	269	474	1919
03479000	Watauga River near Sugar Grove	NC	239	795	1941

Table 2. May-June-July streamflow reconstruction statistics and Tree-Ring Chronologies (TRCs) used for each model.

Station	Reconstruction Date	R^2	R^2(p)	D-W	VIF	Sign Test (Hit/Miss)	TRCs Retained
Clinch TN	1752	0.45	0.34	1.87	1.1	49/12*	LH, LCT, KJ, FBS
Clinch VA	1752	0.36	0.27	2.05	1.2	46/14*	KJ, LCT, LH
Emory[a]	1772	0.42	0.33	2.06	1.1	38/15*	HH, LBL, LS
Little TN	1679	0.42	0.31	2.06	1.0	28/8*	KT, PR
Nantahala[a]	1679	0.48	0.36	2.25	1.1	31/9*	KT, PC, PR
NF Holston	1797	0.50	0.42	2.11	1.3	48/12*	SG, KJ, HH, HWFB
Nolichucky[a]	1686	0.52	0.43	1.55	1.1	45/15*	SG, LS, GM, KJ
Oconaluftee	1679	0.48	0.39	2.08	1.0	24/8*	PC, KT
SF Holston[a]	1772	0.56	0.45	1.88	1.2	37/12*	KJ, PC, PW, HH
Valley	1772	0.47	0.33	1.89	1.1	44/18*	BRSC, SG, RDR, HH
Watauga	1797	0.12	0.03	1.39	1.0	23/17	HWFB

[a]Calibration and reconstruction figures shown

*$p \leq 0.01$

Table 3. Tree-ring chronologies retained in the stepwise regression models and used for the reconstructions.

Code	Chronology	State	Species[a]	Elevation (m)	Period
BRSC	Black River South Carolina	SC	TADI	1	551–1993
FBS	Francis Beidler Swamp	SC	QULY	12	1643–1992
GM	Grandfather Mountain	NC	PCRU	1800	1563–1983
HH	Hampton Hills	NC	QUAL	108	1772–1992
HWFB	Hen Wallow Falls B	TN	TSCA	218	1797–1995
KJ	Knob Job	WV	JUVI	500	1477–1982
KT	Kelsey Tract	NC	TSCR	1000	1679–1983
LBL	Land Between The Lakes	KY	QUST	175	1692–2005
LCT	Lilley Cornet Tract	KY	QUAL	500	1666–1982
LH	Lynn Hollow	TN	QUPR	700	1752–1997
LS	Lassiter Swamp	NC	TADI	2	1527–1984
PCPW	Piney Creek Pocket Wilderness	TN	QUAL	300	1652–1982
PR	Pearl River	MS	TADI	116	1549–1983
PW	Pulaski Woods	IN	QUAL	250	1694–1985
RDR	Ramseys Draft Recollection	VA	TSCA	1000	1598–1982
SG	Scotts Gap	TN	LITU	520	1686–1981

[a]TADI = *Taxodium distichum*, QULY = *Quercus lyrata*, PCRU = *Picea rubens*, QUAL = *Quercus alba*, TSCA = *Tsuga Canadensis*, JUVI = *Juniperus virginiana*, TSCR = *Tsuga caroliniana*, QUST = *Quercus stellata*, QUPR = *Quercus Montana*, LITU = *Liriodendron tulipifera*.

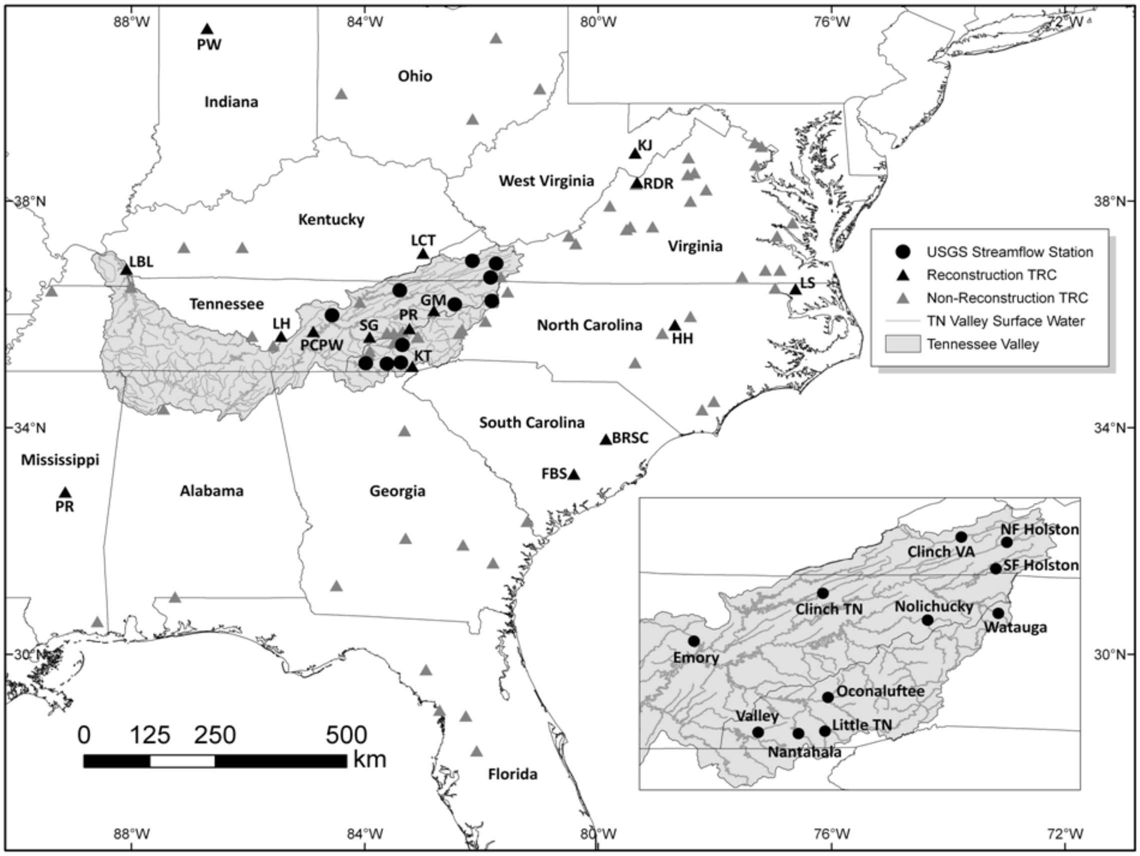

Figure 1. Location map showing the 11 USGS streamflow stations analyzed and all ITRDB tree-ring chronologies ((TRCs) in the southeastern U.S.

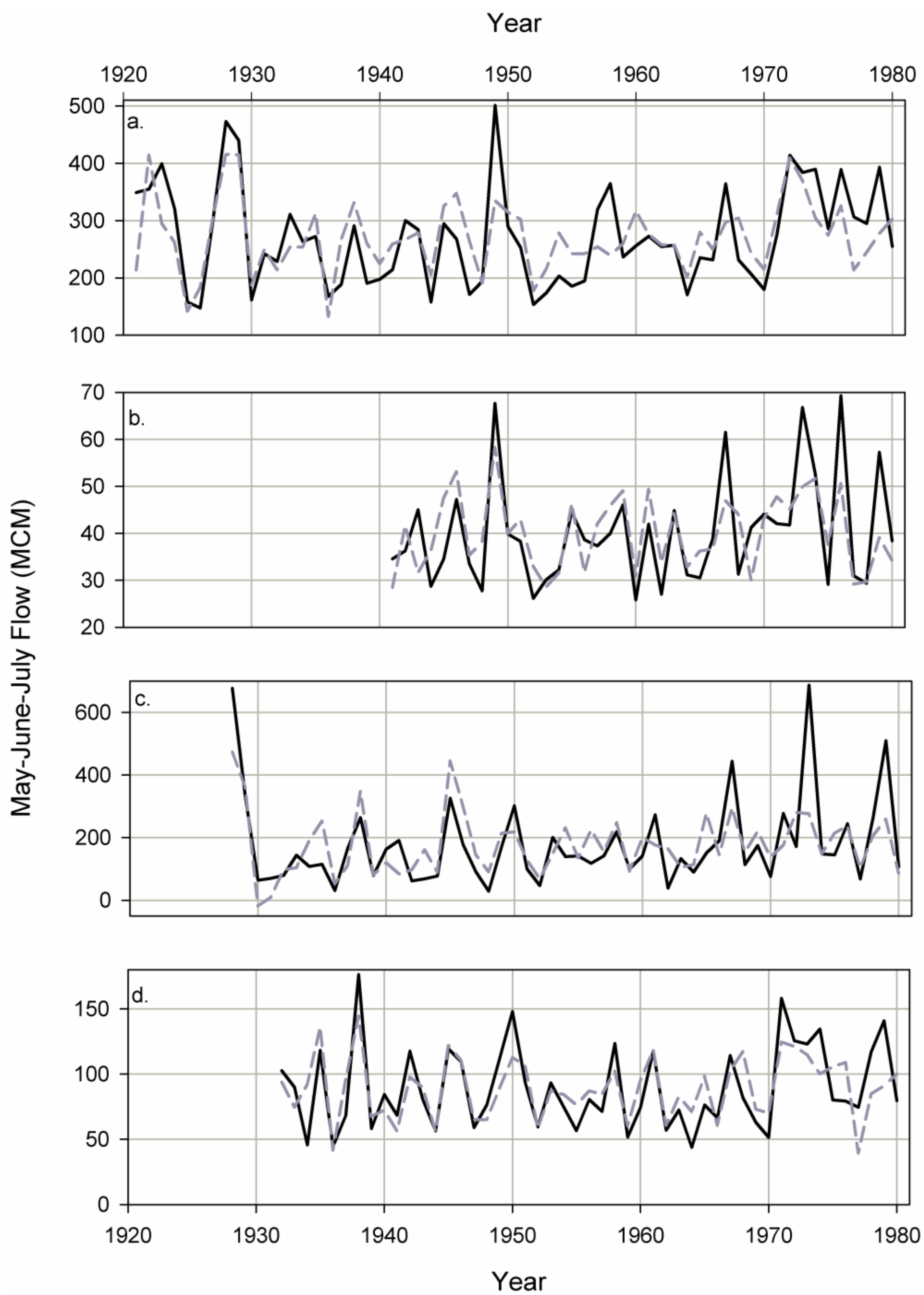

Figure 2. May-June-July streamflow calibration models for (a) Nolichucky River (1921–1980), (b) Nantahala River (1941–1980), (c) Emory River (1928–1980), and (d) SF Holston (1932–1980). Observed (dark line), reconstructed (gray line).

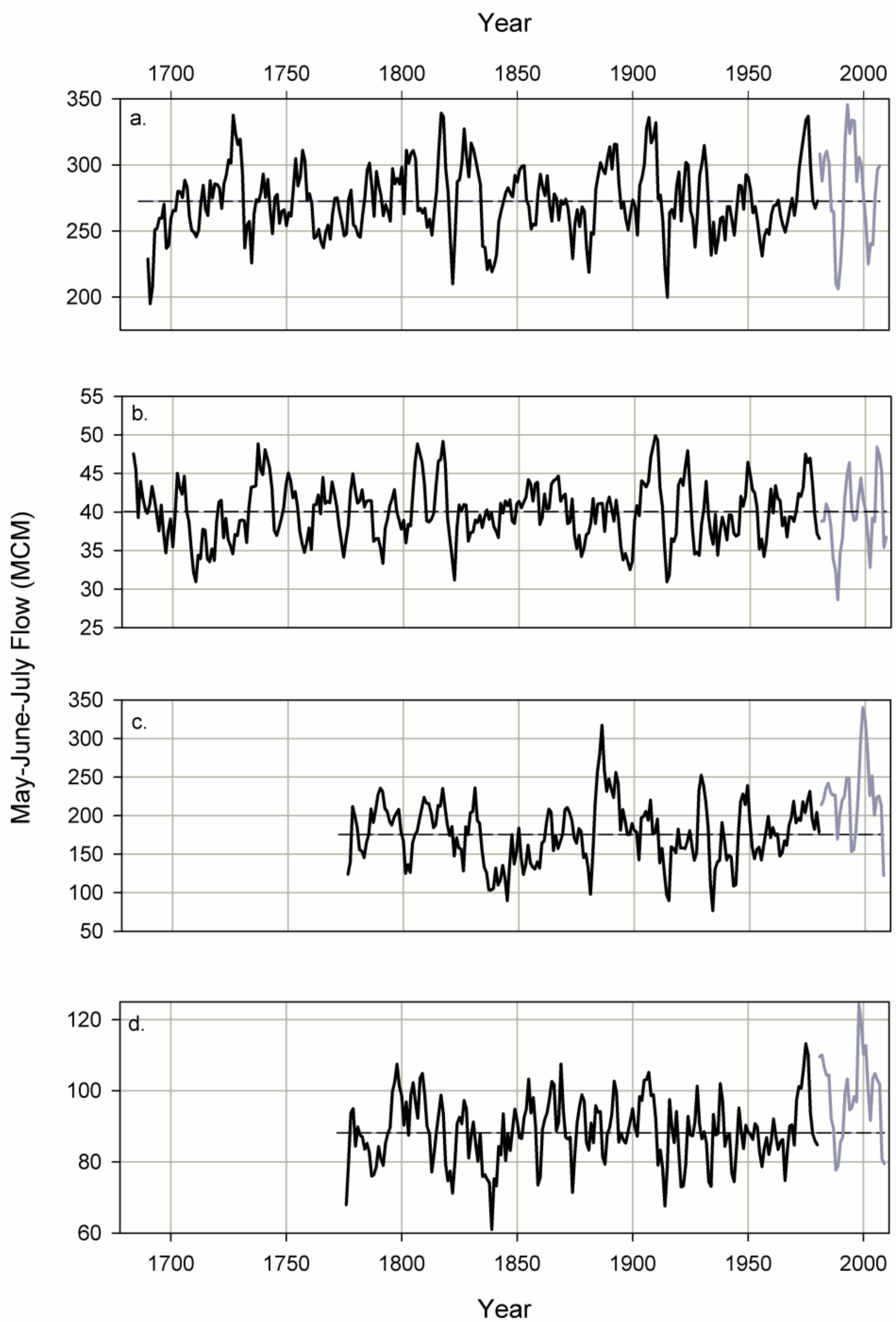

Figure 3. May-June-July streamflow reconstructions for (a) Nolichucky River (1686–1980), (b) Nantahala River (1679–1980), (c) Emory River (1772–1980), and (d) SF Holston (1772–1980). Values have been smoothed with a 5-year end year filter. May-June-July instrumental streamflow values after 1980 are shown in gray. Also shown is the long-term mean for each record (dotted line).

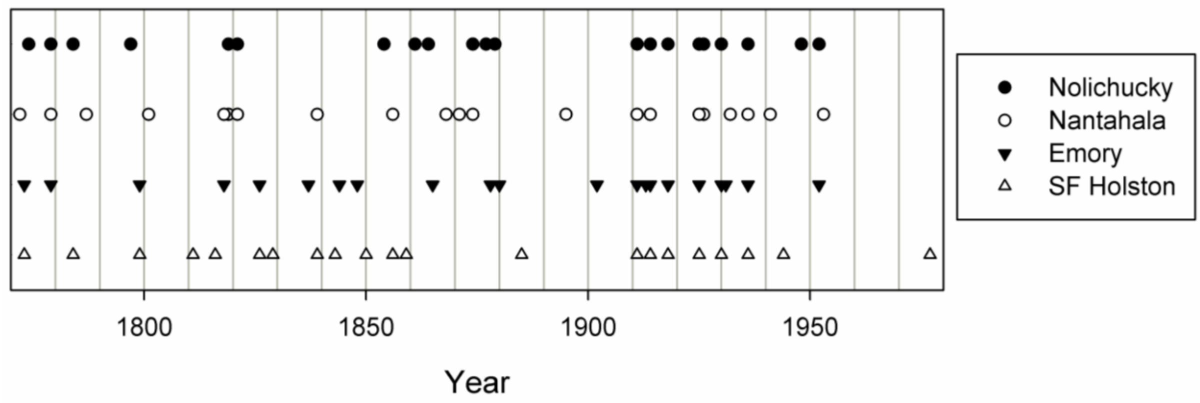

Figure 4. Distribution of May-June-July flows in the lowest 10th percentile for the streamflow reconstructions from 1772 to 1980.

Information Transfer Program Introduction

The major emphasis of the information transfer program during the FY 2010 grant period focused on technical publication support, conference planning/development, and improvement in the information transfer network. The primary purpose of the program was to support the objectives of the technical research performed under the FY 2010 Water Resources Research Institute Program.

The primary objectives, as in previous years, of the Information Transfer Activities are:

To provide technical and structural support to water researchers performing research under the WRRIP.

To deliver timely water-resources related information to water researchers, agency administrators, government officials, students and the general public.

To coordinate with various federal, state, and local agencies and other academic institutions on program objectives and research opportunities.

To increase the general public's awareness and appreciation of the water resources problems in the state.

To promote and develop conferences, seminars and workshops for local and state officials and the general public which address a wide range of issues relating to the protection and management of the state's water resources.

During the FY 2010 grant period, a major focus of the information transfer activities was on the participation of the Center staff in the planning and implementation of several statewide conferences and training workshops.

As co-sponsor, the Center was involved in the planning and implementation of the Twentieth Tennessee Water Resources Symposium, which was held on April 13-15, 2010 at Montgomery Bell State Park in Burns, Tennessee. The goals of the symposium are: (1) to provide a forum for practitioners, regulators, educators and researchers in water resources to exchange ideas and provide technology transfer activities, and (2) to encourage cooperation among the diverse range of water professionals in the state. As with previous symposia, the sixteenth symposium was very successful with over 315 attendees and approximately 61 papers and 14 posters being presented in the two-day period. The event received a good deal of publicity across the state.

The Center also participated in several meetings and workshops across the state that were held to address water related problems and issues such as stormwater management, water quality monitoring, non-point source pollution, water supply planning, TMDL development, watershed management and restoration, multiobjective river basin management and lake management issues and environmental education in Tennessee.

The following is a brief listing of formal meetings, seminars and workshops that the Center actively hosted, supported and participated in during FY 2010:

-East Tennessee MS4 Stormwater Management Working Group, March 18, 2010, June 10, 2010, and October 8, 2010, January 27, 2011 at Ijams Nature Center, Knoxville, TN. TNWRRC and the Tennessee Department of Environment and Conservation sponsored a quarterly meeting of local government officials responsible of implementing local stormwater programs under the MS4 Phase II permit. These meeting are designed to provide local officials with information that will add them in development of their local stormwater management programs.

-Tennessee Department of Agriculture, Nonpoint Source 319 Program Workshop, Ellington Agriculture Center, Nashville, TN. March 25, 2010.

-Tennessee Wetlands Technical Advisory Task Force meeting, April 26-27, 2010, Nashville, Tennessee. Meeting of government agency staff and technical experts to advise to the State on issues related to the Tennessee Wetlands Management Plan.

-WaterFest, May 7, 2010, Knoxville, TN. An annual community-wide event sponsored by the Water Quality Forum that highlights the importance of our water resources and the activities of the WQF partners to protect and manage those resources. Over 1,200 elementary school age students from the Knox County school systems and schools from the surrounding region attended.

- Fundamentals of Erosion Prevention and Sediment Control Level I Training workshops, sponsored by the Tennessee Department of Environment and Conservation and the Tennessee Water Resources Research Center. A one day course for developers, contractors, road builders and others involved with construction activities across the State. The course was offered on the following dates in FY 2010: February 10, 2010, Nashville, TN.; March 5, 2010, Knoxville, TN.; April 20, 2010, Jackson, TN.; April 29, 2010,Chattanooga, TN.; May 5, 2010, Nashville, TN.; May 11, 2010, Johnson City, TN.; June 3, 2010, Associated Builders & Contractors, Memphis, TN.; September 1, 2010, Nashville, TN.; December 8, 2010, Nashville, TN.; December 15, 2010, Knoxville, TN.; February 10, 2011, Nashville, TN.

- Design Principles for Erosion Prevention and Sediment Controls for Construction Sites Level II workshops sponsored by the Tennessee Department of Environment and Conservation and the Tennessee Water Resources Research Center. A two day training workshops for engineers and other design professionals responsible for the development of Storm Water Pollution Prevention Plans for construction activities. The course was offered on the following dates: May 18-19, 2010, Nashville, TN.; October 28-29, 2010, Nashville, TN; December 4-5, 2010, Knoxville, TN.

- Construction Site Inspection as Required by Tennessee s Construction Stormwater General Permit Level I Recertification course sponsored by the Tennessee Department of Environment and Conservation and the Tennessee Water Resources Research Center. This is a half day course which focuses on inspection requirement under the current TNCGP. This course is required for all inspectors of construction sites that have coverage under the TNCGP and serves as a recertification course for those that have completed the Level I Fundamentals course. The course was offered on the following dates: September 9, 2010, Nashville, TN.; September 15, 2010, Knoxville, TN.; September 23, 2010, Jackson, TN.; October, 12, 2010, Memphis, TN.; October 13, 2010, Chattanooga, TN.; October 20, 2010, Ft. Campbell, TN.; October 28, 2010, Nashville, TN.; November 3, 2010, Johnson City, TN.; November 4, 2010, TDOT Region 2, Nashville, TN.; November 10, 2010, Cookeville, TN.; November 16, 2010, Chattanooga, TN.; November 18, 2010, Knoxville, TN.; November 23, 2010, Sevierville, TN.; November 30, 2010, Nashville, TN.; December 2, 2010, TDOT, Nashville, TN.; December 7, 2010, Dyersburg, TN.; December 14, 010, Memphis, TN.; December 16, 2010, Knoxville, TN.

- North Carolina State University, Residential Rain Garden Certification workshop, Banner Elk, NC. March 22-23, 2010. TNWRRC staff attended the 2 day certification course for design and installation of rain gardens in residential areas. TNWRRC will be developing a similar training course as part of the new Tennessee Yards and Neighborhoods program.

- Nature-Art-Science Education: Bringing it all together in the Outdoor Classroom workshop, May 1, 2010, Knoxville, TN. This workshop was conducted for Knox County School system Science and Arts teacher at the hall High School Outdoor Classroom. The purpose of the workshop was to introduce the concept of the outdoor classroom and to encourage teachers to create one at their school. A highlight of the workshop was a presentation and demonstration by Mr. Dan Ladd, a renowned botanical artist, that has been grafting living trees and plants into architectural and geometric sculptures for over 30 years. Mr. Ladd's presentation and demonstration showcased the interdisciplinary aspects of the sciences and arts and how they can be intertwined within an OC venue.

- Adopt-A-Watershed teacher training workshop, June 14-17 2010, Knoxville, TN. This four day workshop sponsored by TNWRRC and partners of the Water Quality Forum trains middle and high school science teachers on how to work with their students to conduct watershed investigations and develop watershed improvement service projects and part of their classroom curriculum. Eight new teachers completed the training course in 2010.

- EPA Region 4 Basic Inspector Training Course, June 22-24, 2010, Knoxville, TN.; TNWRRC , EPA Region4, TN. Department of Environment & Conservation and the TN Stormwater Association co-sponsored this 3 day training for state and local government staff. This is an introductory course designed for new federal, state, local and tribal environmental inspectors and meets the training requiremenst under EPA order 3500.1. The course provides an overview of all aspects of inspection preparation, conduct and follow-up. The course also introduces various federal environmental laws and regulations. Over 80 state and local government inspectors attended the course.

- Bioretention Summit: Ask the Researcher, June 29-30, 2010 Raleigh, NC.; Cosponsored by The Center for Watershed Protection, the Low Impact Development Center, USEPA-Chesapeake Bay Program, NIFA-Southeast Regional Water Program. The purpose of the 2 day training course is to deliver the most up-to-date research-based information that will lead to dramatic improvements in how bioretention cells are credited by regulators, designed by engineers and landscape architects and built and maintained by contractors and maintenance personnel.

- Tennessee Stormwater Association Conference, October 2-27, 2010, Nashville, GA. TNWRRC is a charter member of TNSA and assisted with conducting an tour of Low Impact Development stormwater management practices in downtown Nashville for conference attendees.

- Knoxville Water Quality Forum, Quarterly meetings, May, July and October 2010 and January 2011. Meeting of government agencies and other organizations to share information and discuss water quality issues in the Tennessee River and it's tributaries in Knox County. - Little River , French Broad River, Bull Run Creek, Beaver Creek Stock Creek and Emory River Watershed Associations, monthly meetings. Agency staff and community leaders working towards protection of the Little River, Lower French Broad, the Emory/Obed and smaller tributaries watersheds. - Joint UT-TVA-ORNL Water resources Consortium Seminar Series on timely water resources topics, issues and projects of common interest to the three organizations.

Other principal information transfer activities which were carried out during the FY 2010 grant period focused on the dissemination of technical reports and other water resources related reports published by the Center as well as other types of information concerning water resources issues and problems. A majority of the requests for reports and information have come from federal and state government agencies, university faculty and students, and private citizens within the state. The Center also responded to numerous requests from across the nation and around the world.

Development of GIS Data Management System for Water Resources and Climate Research in Tennessee

Basic Information

Title:	Development of GIS Data Management System for Water Resources and Climate Research in Tennessee
Project Number:	2010TN71B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	Second
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Climatological Processes, Models
Descriptors:	
Principal Investigators:	Shesh Raj Koirala, Randall Wilson Gentry

Publications

There are no publications.

11. Title: **DEVELOPMENT OF GIS DATA MANAGEMENT SYSTEM FOR WATER RESOURCES AND CLIMATE RESEARCH IN TENNESSEE**

12. Statement of Critical Regional or State Water Problems:

Scientists believe that water resources are vulnerable and have the potential to be strongly impacted by climate variability and change. This has a wide range of consequences for human societies and ecosystems. According to Intergovernmental Panel on Climate Change (IPCC) fourth assessment report (AR4), observed global warming has been linked to changes in the large-scale hydrological cycles such as: changes in precipitation patterns, intensities and extremes; increase in atmospheric water vapor content; reduced snow cover and wide spread melting of ice; and changes in soil moisture and runoff. However, our ability to interpret changes in impact-relevant variables (e.g. changes in circulation, precipitation and extremes) remains limited. So IPCC AR4 recommended more research to improve the ability of models related to circulation and precipitation patterns, extremes, El-Nino and seasonal variability, hydrological cycle both in a short and long terms. It also recommended to increase the focus on regional-scale climate study. For long-term water resources planning and management, the impact of climate change on water resources should be understood in a broad range of scales from global to watershed scale. The capability of GIS to work across different spatial scales is particularly useful in this regard. Climate data in GIS format for spatial analysis by researchers is important from both an application and research perspective.

The State of Tennessee (and the southeastern United States region) has many water resources and climate researchers, who participate in a very active and robust research program. The need exists to offer a better platform where the researchers could utilize the GIS data related to climate and water resources and launch the research in a coordinated manner.

13: Nature, Scope and Objectives of Research:

The nature of this project was to develop better information transfer to the state and regional stakeholders in the area of water resource planning and management. The goal of this project was to develop a database center for water resources and climate research. The specific objectives of this project were as follows:

1. Explore the development of water resources and climate change information within GIS domain;
2. Develop database by performing geospatial processing of earth system grid data applicable to water resources utilizing different climate change scenario mainly focusing on Tennessee-Cumberland basin scale.

14: Methods, Procedures, and Facilities:

Climate and water resources data from different sources mainly from federal sources were obtained. They were processed in a GIS to be accessible for planning and simulation purposes. During this first phase, a computer (server) was purchased to store and develop databases. The data were processed using ESRI ARC GIS software and stored in the server. The regional focus of datasets included the Tennessee and Cumberland River Systems. These systems are the most sensitive large-scale hydrologic reservoirs to climate variability in Tennessee.

A survey was conducted at the University of Tennessee regarding the datasets the researchers would like to have included in the management system and how they would use the system to support their research.

15. Statement of Results or Benefits to Date:

Survey: A detail survey was conducted by meeting/interview with eight of the water resources, natural resources, and engineering researchers whose research are focused on water and natural resources, climate change, and GIS. The meetings were focused on identifying the data needs in teaching and research. Discussion also included on how the data could be best utilized by contributing, storing and sharing. The researchers pointed out the difficulties in updating, sharing and the extent of the type of data. Some researchers lean toward application directly – for example: map rendering across different water data variables; eg different watershed models – run the model in real time and utilize in various types of modeling, etc. The focus should be not only gathering data but develop some model to identity the problems. (Based on such recommendation, a sample model was developed and explained below).

Data processes and modeling: The project supported climate change and water resources research by developing the data for a variety of audiences associated with climate and water resources study. Researchers in Tennessee can utilize their expertise using available data in a GIS domain to address some of the climate change problems related to water resources in Tennessee and the southeastern United States.

The data included digital elevation models, soil, land use/landcover data for the entire Tennessee, Cumberland watersheds. In addition, as a sample model development, Soil and Water Assessment Tool (SWAT) model was also developed for Clinch River watershed. The specific objectives were to evaluate the climate change impact on the future water yield at the outlet of Clinch River Watershed upstream of Norris Lake in Tennessee and see how the frequency of extreme water yield (e.g. flood) changes compared to present condition.

It is expected that the hydrologic models should provide a link between climate changes and water yields through simulation of hydrologic processes within watersheds. However, most hydrologic models are unable to incorporate the climate change effect for simulation. The SWAT model is one widely used model which has the capability of incorporating the climate change effect for simulation. In SWAT, it is possible to incorporate the general circulation model (GCM) projections of carbon dioxide concentration, precipitation and temperature changes. Hence SWAT was used in this sample study. In the future, we recommend to extend this modeling approach to the entire Tennessee and Cumberland watershed to estimate the water yield due to climate change in this region. The Clinch River is one of the tributaries of the Tennessee River. The Clinch River watershed in Tennessee was selected for study because this watershed in the Tennessee River Basin was one of the basins which has not regulated and this may represent the natural watershed response. The watershed is a 3,818 square kilometer forested watershed. Deciduous forest covers about 76 percent of the basin and rest of the landcover includes hay and range grasses.

Climate data required by the model are daily precipitation, minimum and maximum daily air temperature, solar radiation, wind speed and relative humidity. These daily climatic inputs can be entered from historical records, and/ or generated internally in the model using monthly climate

statistics that are based on long-term weather records and are available internally in the SWAT database for US. In this study, daily total rainfall, daily maximum and minimum temperature are obtained from four National Climatic Data Center (NCDC) coop weather stations within and near the watershed from 1970 to 2009. Monthly average discharge for calibration and validation was also used from 1970 to 2009 from United State Geological Survey (USGS) gauge station 03528000 at the outlet of the watershed upstream of the Norris Lake. Rest of the climate data required were generated internally in SWAT.
Elevation data were obtained from USGS 30 m digital elevation model (DEM). Landuse data were obtained from 1:24,000 NLCD database. Soil data were obtained from the State Soil Geographic (STATSGO) database.

The results indicate that significant changes in monthly water yield occur under the potential climate change scenario adopted. Maximum reduction of 13% in May and a maximum increase of 200% in September represent the most extreme conditions by the end of this century. Clinch River basin can be represented as a typical hydrological and meteorological system in the Upper Tennessee River Basin. Frequency analysis indicated the clustering of extreme hydrological events in the study area which may cause frequent flooding in the downstream. It is important to know how monthly water yield patterns could change in the Clinch Basin, so that negative effects on water resources and the economy can be anticipated and mitigated. The forested hilly terrain and karstic geology of Clinch basin is similar to many other basins in the Upper Tennessee and Cumberland. These basins including Clinch basin have significant contribution to the annual discharge in the Tennessee and Cumberland Rivers. Therefore, if the climate change scenario adopted for this study were to occur in the future, significant changes in the Tennessee and Cumberland Rivers could occur. The analysis simply illustrates the relative changes in the direction and magnitude of water yield in the basins similar to Clinch River basin, related to possible changes in carbon dioxide, precipitation and temperature. Additional analyses are needed that extend this work with utilizing refined climate change models, different scenarios, and hydrological models.

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	2	0	0	0	2
Masters	6	0	0	0	6
Ph.D.	2	0	0	0	2
Post-Doc.	1	0	0	0	1
Total	11	0	0	0	11

Notable Awards and Achievements

Publications from Prior Years

1. 2003TN7B ("Evaluation of Pathogen Occurrence and Causation withing the Stock Creek Watershed (Knox County) as a Model for Watershed Restoration") - Conference Proceedings - Layton, Alice, D. Willams, L. McKay and J. Farmer.2010. Identiying and Detecting Waterborne Pathogens in Tennessee,"in" Proceedings of the Twentieth Tennessee Water Resources Symposium, Tennessee Section of the American Water Resources Association, Nashville,TN. 2A-4.
2. 2005TN17B ("Impacts of watershed urbanization on longitudinal fragmentation of stream habitat quality and fish habitat use") - Conference Proceedings - Neff, Keil, A. Dodson and M. Hamrick,2010, A Modeling Approach to Restoring Pool-Riffle Structure in an Incised, Straightened Channel of an Urban Steam,"in" Proceedings of the Twentieth Tennessee Water Resources Symposium, Tennessee Section of the American Water Resources Association, Nashville, TN. 2b-1.
3. 2005TN17B ("Impacts of watershed urbanization on longitudinal fragmentation of stream habitat quality and fish habitat use") - Conference Proceedings - Barry, William, J. Schwartz, B. Wood and P. McMahon,2010, BAGS Application for Channel Design,"in" Proceedings of the Twentieth Tennessee Water Resources Symposium, Tennessee Section of the American Water Resources Association, Nashville, TN. 2B-13.
4. 2008TN53B ("A Survey of Bank Erosion in Beaver Creek, Knox County, Tennessee: Correlations of Channel Stability with Force and Resistance Variables") - Conference Proceedings - Chen, Si,2010, Export of Carbon, Nutrients and Microbiological Indicators in Beaver Creek Watershed, Tennessee,"in" Proceedins of the Twentieth Tennessee Water Resources Symposium, Tennessee Section of the American Water Resources Association, Nashville, TN. 2C-8.