4229 Lafayette Center Drive, Suite 1850
Chantilly, Virginia 20151
(703) 870-7000 • FAX (703) 870-7039
http://www.gky.com

Memorandum

Phase II – Task 3a (Final)

Critical Regional Drought Evaluation

Southern Cumberland Plateau

To: Benjamin Rohrbach, Nashville District Corps of Engineers
From: Stuart Stein and Lars Hanson, GKY & Associates

Date: September 22, 2009
Re: Critical Regional Drought Evaluation – Southern Cumberland Plateau

---

Please find enclosed the final version of the critical regional drought evaluation for the Southern Cumberland Plateau study area.

WATER RESOURCES REGIONAL PLANNING PILOT STUDY
FOR
THE SOUTHERN CUMBERLAND PLATEAU

PHASE II

CRITICAL REGIONAL DROUGHT EVALUATION
Final Report

Prepared by

GKY & Associates
Chantilly, VA

in cooperation with
U.S. Army Engineers District, Nashville
Corps of Engineers
Nashville, TN

and

TetraTech, Inc.
Seattle, WA

September 22nd, 2009

US Army Corps of Engineers
Nashville District

GKY &Associates,inc.

TETRA TECH

Table of Contents

Tables

Figures

1. Background and Scope

Between the years of 2007 and 2009, Tennessee's Southern Cumberland Plateau experienced one of the worst recorded droughts in the region's history. The impact of the recent drought rivaled that of the droughts of the 1930's and 1940's. During this recent drought period, Tennessee's Emergency Management Agency managed many critical water supply situations across the state. Many of the water supply systems neared failure by the end of the drought, relying heavily on neighboring water districts to help with the essential water demand of their customers.

The impact of the recent drought acted as a catalyst to perform a comprehensive water resources planning studies for North Central Tennessee and the Southern Cumberland Plateau, which will provide insight into existing and potential water supply issues in these two regions.

The U.S. Army Corps of Engineers (USACE), Nashville District, the Tennessee Department of Environment and Conservation (TDEC), and a steering committee composed of representatives from TDEC's Water Resources Technical Advisory Committee (WRTAC) are conducting a comprehensive water resources study for the Southern Cumberland Plateau Region. This project serves as a pilot study for regional water resources planning by TDEC.

This study is being conducted under the Planning Assistance to States (Section 22) Authority, of the Water Resources Dev. Act of 1974, as amended. This authority allows USACE to provide technical assistance to support state preparation of comprehensive water resource development plans and to conduct individual studies supporting the state plan. TDEC is contributing fifty percent of the cost of this study. This study has been split into two phases. This report presents results of the drought evaluation exercise for Phase II of this study.

1.1. Scope

This task is titled Critical Regional Drought Evaluation and is part of the Water Resources Regional Planning Pilot Study for the Southern Cumberland Plateau. The scope of the drought evaluation study presented in this report is to summarize drought emergency and contingency plans within the study area, and to perform an analysis of the meteorology of the region to identify and analyze the severity of historical droughts. This analysis will help focus the hydrologic analyses in the other Phase II tasks including the "Existing Water Source Yield Analysis" and "Alternative Water Source Identification and Yield Analysis."

1.2. Study Area

The Southern Cumberland Plateau Region covers a four-county geographical region. Parts of Franklin, Grundy, Marion, and Sequatchie Counties, which include the towns of Tracy City, Sewanee, Altamont, and Monteagle, are included in the study. This geographical region includes parts of the Upper Elk River Basin, Collins River Basin, Sequatchie River Basin, and Guntersville Lake Basin. The utility districts of Big Creek, Tracy City, Monteagle, and Sewanee, and the geographic areas which they serve, are recommended for further investigation during Phase II of this regional planning pilot. Figure 1 shows the study area.

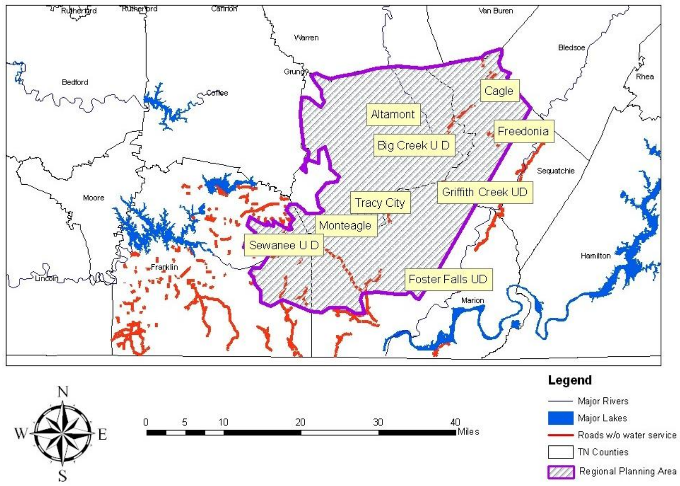

Figure 1 - Southern Cumberland Plateau study area (Image Courtesy of TDEC)

Geographically, the study area is located in Southeastern Tennessee, near the point where both Alabama and Georgia meet Tennessee. The study area sits on the Southern Cumberland Plateau, which runs northeast to southwest, at an elevation of 1800 to 1900 feet. To the East is the Sequatchie River valley, and further to the South and East is the Tennessee River. To the West are the low hills of the Elk River Watershed, and further is the far southern end of the Highland Rim. Though the study area is close to several rivers, no major rivers pass through it, as it is primarily a headwater area. The Southern Cumberland Plateau does receive abundant rainfall in most years, often in excess of 55 or 60 inches per year.

1.3. Effects of the 2007 Drought

The Southern Cumberland Plateau region experienced a severe drought in 2007 and 2008 that had dire effects on local water supply sources and serious consequences for social and economic activity and on everyday life. There is little doubt that the drought was one of the most severe in recent memory.

Since 1999, the U.S. Drought Monitor has been keeping track of drought conditions across the country. A collaboration between the U.S. Department of Agriculture, the National Weather Service's Climate Prediction Center, National Climatic Data Center, and the National Drought Mitigation Center produces the weekly maps which can be viewed at http://drought.unl.edu/dm/monitor.html. The U.S. Drought Monitor classifies drought based on a blend of five or more indicators which track changes in conditions of rainfall, soil moisture, streamflow, and some composite indices such as the Palmer Drought index. The Drought Monitor's most severe drought classification is the D4 – Exceptional Drought.

Figure 2 displays selected archived U.S. Drought Monitor maps for Tennessee from the 2007-2008 drought. A week-by-week analysis of the archives found that some portion of the study area was in the D4 – Exceptional Drought classification from June 12, 2007 to March, 18 2008. The drought appeared to have the broadest effect on Tennessee during the week of October 16, 2007. The long period of time in the exceptional drought classification strained water supplies in the study area.

During the drought, all of the major utility districts in the study area including Monteagle Public Utility Board, Sewanee Utility District, Tracy City Public Utilities, and Big Creek

Utility District implemented some form of conservation measures as a way to preserve their limited water supplies.

Monteagle faced the greatest test in water management. According to the Tennessee Emergency Management Agency archives of the Drought 2007 Task Force's Situation Reports, Monteagle implemented voluntary conservation measures during the third of fourth week of August, 2007. In mid-September, Monteagle began buying 50,000 gallons per day (gpd) from Tracy City UD. At the end of September, Monteagle's source, Laurel Lake was down to three days of supply, and Monteagle closed two rest areas on Interstate 24 due to lack of water. By early October, Monteagle had begun purchasing 150,000 gpd from Sewanee UD, and increased purchases to 100,000 gpd from Tracy City, whose own lake source was six feet below normal.

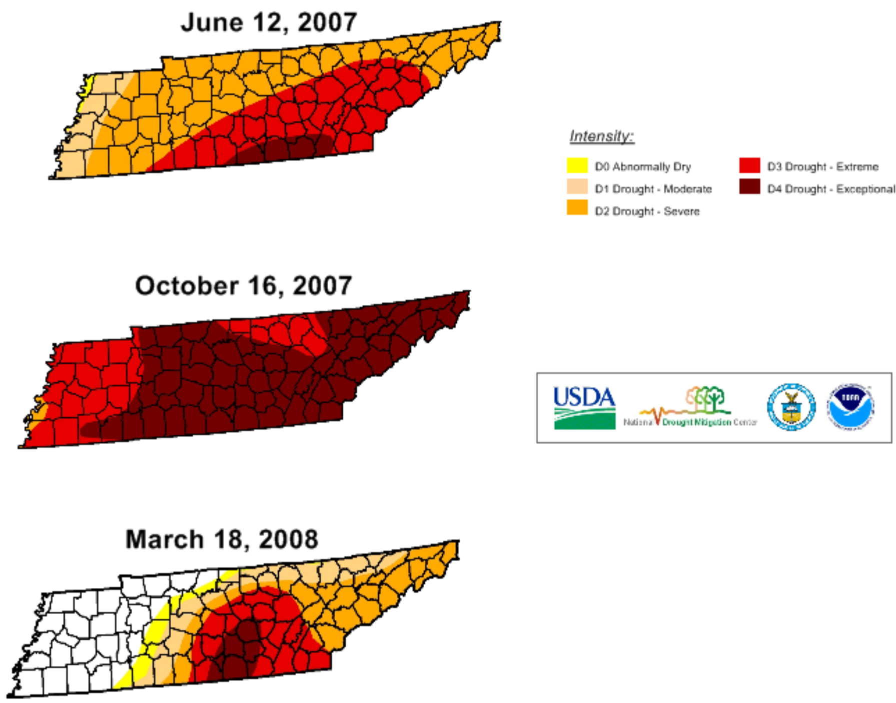

Figure 2 – U.S. Drought Monitor maps for Tennessee for the 2007-2008 drought

By the 18th of October, both Tracy City and Monteagle implemented mandatory conservation measures, while Sewanee and Big Creek Utility Districts implemented voluntary conservation. During the third week or October, Monteagle began plans to install a filtration unit to use Lake Louisa as an emergency water source. By the end of October, Monteagle was also purchasing 100,000 gpd from Big Creek UD. By early November, Monteagle stopped using Laurel Lake and relied on purchases from other utility districts. Monteagle continued work to operate Lake Louisa as a source and also to pump water from a local sand mine into Laurel Lake. By the end of November, Monteagle was awaiting approval to pump water from the sand mine to Laurel Lake, and was waiting for equipment to make Lake Louisa an operational source. The other utilities announced they would have to suspend water sales to Monteagle in mid-December due to their own supply situations.

According to the Chattanooga Times Free Press on January 11th, Laurel Lake was back to normal levels, and Monteagle was only buying 62,000 gpd from Tracy City. The connection to the sand mine was operating. Ultimately, rains returned, and the study area moved out of severe drought by the middle of 2008. Still, rights to use Lake Louisa as an emergency source were secured on March 24, 2008 in the event of future droughts.

The failure of Monteagle's source, and the severe restrictions throughout the study area helped prompt the regional planning study to re-examine the water resources, infrastructure, emergency plans, and water usage in the region. Though the 2007-2008 drought was severe, there is no guarantee it represents the worst conditions for water supplies that the region has experienced or will experience in the future. This report examines in more detail the historical drought conditions going back to at least the late 1920s to identify other severe droughts in the study areas history.

In addition, the next chapter examines the current state of drought planning by the utility districts in the study area.

2. Summary of Local Drought Planning

By authority under Chapter 1200-5-1-.17 of Tennessee's Safe Drinking Water Rules, the Tennessee Department of Environment and Conservation requires all community water systems to have an emergency operations plan. Either as part of this operations plan or a stand-alone, TDEC is requiring that systems with a history of drought susceptibility have a drought management plan. According to TDEC's February 2009, *Drought Management Plan*, "one of the most significant components of a community water system's plan is the designation of trigger points – the points at which certain drought response actions are required as determined by that community water system – with identified corresponding actions."

This chapter summarizes the drought management plans for utility districts in the study area. The summaries include a description of the plan, the relevant authorities, trigger points, and actions.

2.1. Sewanee Utility District of Franklin and Marion Counties

The Sewanee Utility District (SUD) passed a Water Conservation Resolution on August 12, 2009 to establish guidelines for declaring a water shortage emergency and related actions.

2.1.1. General Principles and Focus

The Water Conservation Resolution is focused on reducing demand from non-essential uses in order to protect community welfare. Prioritized water uses include public health, fire protection, and domestic use. Any actions restricting non-essential uses should be enacted fairly and quickly.

2.1.2. Authority

Authority for declaring and managing the Water Emergency is balanced between the General Manager of SUD and the Board of Commissioners.

The General Manager has the ability to declare a change in the Water Shortage Emergency Status and initially select non-essential uses which are prohibited. The General Manager may also recommend changes to prohibited uses to the Board of Commissioners. The General Manager is required to inform the local media of declaration of emergencies. The General Manager also has power to investigate non-compliance with use prohibitions by water customers, and request immediate compliance or discontinue water service.

The Board of Commissioners has the sole power to declare the end of a water emergency. In addition, the Board of Commissioners may declare a water shortage emergency even if the conditions of Water Shortage Emergency Status are not met. The Board also has power to make adjustments to prohibited uses. Finally, the Board of Commissioners has to approve reinstatement of water service to disconnected water users.

2.1.3. Drought Levels – Trigger Points

There are two levels of water emergency in Sewanee Utility District, called Water Shortage Emergency Status 1 and 2.

Water Shortage Emergency Status 1 may be declared by the General manager when the water level in a major distribution system reservoir can't be brought above two-thirds full level in a 48 hour period.

Water Shortage Emergency Status 2 is at the discretion of the manager.

2.1.4. Emergency Actions

In any water emergency, waste of water is prohibited. Waste of water includes permitting water to escape down a surface drain, failure to repair an uncontrolled leak, or failure to put water to a beneficial use.

The Emergency Status determines category of non-essential water use that are prohibited. For emergency status 1, Category 1 uses may be prohibited. For emergency status 2, Category 2 uses may be prohibited.

Category 1 uses include:

- Non-residential use exceeding 70% of prior year's use for same billing period
- Washing exterior paved areas
- Filling and re-filling swimming pools
- Non-commercial washing of vehicles
- Watering of lawns, flower gardens, ball fields, and golf courses
- Dust control during construction or construction compaction

Category 2 uses include all Category 1 uses, and:

- Watering trees, shrubs, and plants, except by commercial nurseries
- Commercial vehicle washing
- Non-residential use exceeding 50% of prior year's use for same billing period
- Water served at restaurants unless requested by customer

2.1.5. Emergency Sources and Water Sharing

Sewanee uses Lake O'Donnell as its primary source, and uses Lake Jackson as an auxiliary source to fill Lake O'Donnell. By contract, Sewanee can use the top two feet of Lake Dimmick for water supply in an emergency.

In 2007, Sewanee sold water to Monteagle through a connection between the two utility districts.

2.2. Town of Monteagle

The *Town of Monteagle, TN Master Drought Management Plan* was adopted by a Town Council vote on March, 3 2008.

2.2.1. General Principles and Focus

As a result of Monteagle's experience with drought in 2007, they have developed an extensive drought management plan with several key principles and a variety of drought management actions considered.

The Drought Managements Plan highlights a need for planning to help mitigate future droughts. Monteagle is modifying its building codes to require more efficient fixtures, and investigating pricing policies to discourage wasteful use.

During drought, public communication and information sharing is adopted as a key prinicipal for effective drought management. Education is seen as a key element to spur voluntary conservation and increase effectiveness of other conservation measures. Additionally, actions that undermine an effective message, such as wasteful use by the Town, are discouraged. The communication message is targeted to influence consumers' five predictable attitudes toward drought: perceived seriousness of drought, social/moral commitment, perceived efficacy of conservation, perceived inconvenience and cost, and perceived equity.

The drought plan outlines several potential demand management options and related positions on whether to use them.

Options including public education, technical assistance to business and industry, leak detection and repair, and checking meter accuracy are embraced as common sense conservation measures.

Residential plumbing retrofit programs and alternative pricing policies during drought are under consideration. Outdoor water use reductions are recognized as necessary.

Physical rationing and mandatory reductions are discouraged, but may in some cases be necessary. Specific use bans are advanced as an alternative. In dire situations, a moratorium on new connections can be considered. Valve restrictions and pressure reductions are discouraged, but not ruled out.

Mandatory shutdown of large users is not recommended.

2.2.2. Authority

The Town of Monteagle has the authority to pass drought plans, and establish building and plumbing codes for the town of Monteagle. The drought conditions and trigger points are monitored by the Public Works Department in cooperation with the Mayor and Town Council. Only the Public Works Director may declare a drought and response actions. The Public Works director must notify the Mayor and Town Council before a declaration.

2.2.3. Drought Levels – Trigger Points

The Mayor and Town Council have adopted drought stages based on trigger points, which are based on the level of Laurel Lake. These drought stages and levels are described in Table 1.

Table 1 - Drought stages and triggers for Monteagle

Drought Stage	Level	Laurel Lake Conditions
Stage 1- Minimal	Level 1	Full pool
	Level 2	Lake level has fallen one foot
Stage 2 - Moderate	Level 3	Lake level has fallen two feet
Stage 3 – Severe	Level 4	Lake level has fallen three feet
Stage 4 - Critical	Level 5	Lake level has fallen four feet
	Level 6	Lake level has fallen five feet

2.2.4. Emergency Actions

Documentation describing specified drought response actions at different drought stages was not available at the time of this writing.

2.2.5. Emergency Sources and Water Sharing

Monteagle was forced to take several different emergency actions in 2007 to continue operating. Monteagle has connections with and can buy water directly from Sewanee and Tracy City. The contract with Tracy City is for up to 21,000 million gallons per year. Monteagle can also buy water from Big Creek Utility District after it has passed through Tracy City. Monteagle now has an agreement and water treatment facilities in place so that it can use Lake Louisa as an emergency source. In 2007, Monteagle used a sand mine owned by Sequatchee Silica as an emergency source. Monteagle is working to secure Clifftops Lake as an emergency source, and is investigating running a line to South Pittsburg (which uses the Tennessee River) for additional supplies.

2.3. Big Creek Utility District

As part of its Emergency Plan, the Big Creek Utility District has adopted a *Shortage and Emergency Policy* and enacted a *Shortage and Emergency Resolution.*

2.3.1. General Principles and Focus

The Big Creek Utility establishes a two stage non-essential use restriction policy that is triggered by reservoir level. The Emergency Plan also identifies general policies for conserving water such as repairing leaks as soon as they are discovered. Like many other Tennessee water suppliers, Big Creek Utility District does not provide service guarantees, and treats every customer fairly but in a way that other customers' interests will not be compromised.

As an appendix, the emergency plan document adopts a recommended priority for furnishing water in an emergency. Priority 1 uses are "Essential Water Uses," which include domestic use necessary to maintain health and sanitation, health care facilities, public use, and flushing of sewers and hydrants. Priority 2 uses are "Economically Important Uses of Water," which include publicly supplied agricultural water, industrial use, commercial use, office and industrial air conditioning, and motel and hotel use. Priority 3 uses are "Socially Important Uses of Water," which include school showers, filling and operation of swimming pools, and some domestic uses including kitchen use, laundry use, and landscape watering. Priority 3 uses are " Non-essential Uses of Water," which included water for ornamental purposes, outdoor non-commercial watering, washing motor vehicles, and air conditioning.

2.3.2. Authority

The Big Creek Utility District governing board is authorized to declare water emergencies, upon which they must notify local media of reasons for restricted usage, actions required of customers, and estimated duration of restrictions. The governing board is able to extend or modify provisions of a water shortage emergency, and is also the only party allowed to terminate a water shortage emergency. Utility district personnel are charged with investigations of non-compliance with restrictions, and may shut off water service to these customers. Only the governing board may reinstate service, and the board may also make terms and conditions for the customer to meet before reinstating service.

2.3.3. Drought Levels – Trigger Points

Big Creek Utility District has two categories of shortage based on the conditions at Big Creek Lake (also known as Ranger Lake).

Category 1 is triggered when the lake level falls to 4 feet below the spillway.

Category 2 is triggered when the lake level falls to 6 feet below the spillway.

2.3.4. Emergency Actions

Service restrictions are instituted in accordance with drought level.

Category 1 Service Restrictions include the following non-essential uses:

- Non-residential use exceeding 70% of prior year's use for same billing period
- Washing exterior paved areas
- Filling and re-filling swimming pools
- Non-commercial washing of vehicles
- Watering of lawns, flower gardens, ball fields, and golf courses
- Dust control during construction or construction compaction

Category 2 Service Restrictions include the Category 1 uses and the following non-essential uses:

- Watering trees, shrubs, and plants, except by commercial nurseries
- Commercial vehicle washing
- Non-residential use exceeding 50% of prior year's use for same billing period
- Water served at restaurants unless requested by customer

2.3.5. Emergency Sources and Water Sharing

Big Creek Utility District has a connection to Tracy City, which was used in 2007 to sell water to Tracy City, and use Tracy City as a conduit to sell water to Monteagle. Big Creek Utility District is investigating a connection from Ramsey Lake.

Big Creek also provides water (even in normal conditions) to Cagle/Fredonia and Griffith Creek.

2.4. Tracy City Public Utilities

The Tracy City Public Utilities established *Water Shortage/Drought Management Plan* with the objective: "To establish the policies, rules, duties, penalties, and plans for the Tracy City Public Utilities Water System that will be implemented during declared droughts or water shortage."

2.4.1. General Principles and Focus

Tracy City's drought plan is a staged demand reduction plan that starts with voluntary conservation, and has two stages of mandatory restrictions. Tracy City strives to provide reliable service, but does not guarantee it. The utility operates for the benefit of present and future customers, and customers are treated fairly, and such that no customer's treatment comprises other customers' interests.

2.4.2. Authority

The Board of Public Utilities and Manager of Tracy City Public Utilities can implement and enforce restrictions on non-essential uses. The utility has discretion to discontinue service to customers failing to abide by restrictions.

2.4.3. Drought Levels – Trigger Points

Tracy City defines three Stages of Alert for its drought management plan. The triggers for the Stages of alert are not defined by conditions of the water supplies, but instead by the current value of the Palmer Drought Severity Index (PDSI). The current Palmer Drought Severity Index map for Tennessee can be found at http://drought.unl.edu/dm/DM_state.htm?TN,S.

Stage 1 is triggered when Tracy City falls under a Moderate (D1) Drought according to the PDSI.

Stage 2 is triggered when Tracy City falls under a Severe (D2) Drought according to the PDSI.

Stage 3 is triggered when Tracy City falls under an Extreme (D3 or higher) Drought according to the PDSI.

2.4.4. Emergency Actions

Actions vary by drought stage.

Stage 1. Voluntary reductions of essential use by 10% and non-essential by 15%.

Stage 2. Mandatory restrictions include:

- Outdoor watering restricted to 5 -10 AM, three days per week.
- Golf course and athletic field watering restricted to 12:01 AM – 5AM
- Fire hydrant testing reduced 50%

Stage 2. Prohibited uses include

- Washing hard outdoor surfaces
- Non-commercial washing of vehicles
- Filling or re-filling swimming pools
- Dust control during construction
- Fire-fighting training

Stage 3. Mandatory restrictions include
- Minimum usage at commercial nurseries to keep plants alive
- Watering at golf courses (tees and greens) and athletic fields restricted to 3 days per week
- Water at restaurants by request only

Stage 3. Prohibited uses include
- Residential watering
- Watering golf course fairways
- Non-state mandated line flushing

2.4.5. Emergency Sources and Water Sharing

Tracy City has connections to Big Creek Utility District and Monteagle's utility district. In general, Tracy City sells water to Monteagle in emergencies. Tracy City can receive water from Big Creek Utility District, either for its own use or to sell to Monteagle. Tracy City supplies Foster Falls even during normal conditions.

3. Drought Evaluation

The purpose of this drought evaluation is to examine the historical hydrologic record in order to identify and evaluate the relative severity of the 2007 drought and other major droughts. The drought evaluation also serves to better inform the investigation of yield and reliability of existing and potential future sources by identifying droughts which could be critical.

Instead of determining the chance of reservoir failure for the 2007 drought, it is perhaps better to reexamine the firm yields of the reservoirs that currently serve as water supply sources for the utility district in the study area. The first step in re-evaluating the yield is to determine the critical drought period over which the firm yield of the reservoir will be computed. The critical drought is the sequence of hydrologic conditions (rainfall, evaporation, other losses) affecting reservoir inflow that results in the maximum storage deficit at a particular reservoir with defined storage and watershed conditions. Given a constant reservoir capacity, the critical drought sequence results in a condition in which the reservoir experiences maximum drawdown.

Since extremely long streamflow gage records are not available in the Southern Cumberland Plateau or at the existing reservoirs, the starting point for critical drought analysis must be from other hydrologic data, specifically meteorological data including rainfall. There are several widely used indices of drought severity that may be appropriate for conducting a drought evaluation. They are discussed, and one is selected for analysis in section 3.1.

3.1. Drought Index Selection

The characteristics of a study area's location, climate, and water sources make some drought indices more applicable than others. The Southern Cumberland Plateau study area is in a rural, mountainous region of Southeastern Tennessee, and much of its water is provided by a system of small reservoirs. As a headwater region, there are no very large lakes or reservoirs, so drought indices that rely on large scale surface water conditions such as the Surface Water Supply Index and Reclamation Drought Index can't even be calculated in the study area.

The various Palmer Indices and their derivatives (including Palmer Drought Severity Index, Palmer Hydrological Drought Index, and Crop Moisture Moisture Index, among others) use a combination of precipitation, temperature (used to estimate evapotranspiration), and the available water content (AWC) of soils. (NCDC, 1994) The PDSI has some drawbacks including that the index values quantifying the intensity and beginning and end of droughts are somewhat arbitrary and were developed for central Iowa and western Kansas. (Hayes, 2006) Furthermore, this study is concerned with the study area's water supplies, and not directly with agricultural production. The Palmer Drought Severity Index has been calculated for all four NOAA climate divisions in Tennessee dating back to 1895. The climate divisions, however, cover several hundred square miles, and this study is concerned with a more well-defined study area. The Palmer Indices are more difficult to calculate in small study areas because of the data requirements (precipitation, temperature, and soil moisture data) and the difficulty in creating continuous climate records for all three data types.

To both focus the geographical scope of the study, and to simplify and make more robust calculations, it makes sense to limit the analyses to a drought evaluation method based on precipitation. Since the study area is located on a high plateau, the rainfall pattern within the study area has an especially important role in determining the viability of water supplies.

The Standardized Precipitation Index (SPI) is a flexible, multi-timescale approach for drought identification based exclusively on precipitation conditions. Though the general methodology can be applied to precipitation data computed at any time-step, the SPI is usually computed with monthly data for identifying droughts.

Given a long monthly rainfall record, the SPI calculates a normalized index reflecting probability of occurrence for rainfall totals of the selected duration (e.g 1, 3, 12, 48 months, etc.). The ***duration*** for the SPI analysis is reflective of the number of months of precipitation that are summed together. The index value indicates where that sum falls compared to all the other precipitation sums of the same duration in the record, which also start in the same month. For a 3-month duration SPI in March, the index value is reflective of the probability of occurrence of the total precipitation for January, February, and March compared with all other January-March totals in the record.

The SPI index value reflects the probability of certain rainfall totals occurring for the given analysis duration. Instead of reporting this probability as a percentile, the SPI index uses a standard normal variate (or Z-score). The rainfall totals, though originally fitted to a gamma distribution, are transformed to a normal distribution (with a median of zero and standard deviation on one). The index value is roughly analogous to the number of standard deviations the rainfall total falls from the median (i.e. a Z-score). Below average precipitation, therefore, has a negative index value. The SPI has practical limits of -4 to 4, limits beyond which the probability of occurrence is too low to detect within standard periods of record.

Table 2 presents a range of SPI values and the degree of wetness or dryness to which they correspond. The table is adapted from a white paper on drought indices by Hayes (2006).

Table 2 - SPI values and associated descriptions

SPI Values	
2.0+	extremely wet
1.5 to 1.99	very wet
1.0 to 1.49	moderately wet
-.99 to .99	near normal
-1.0 to -1.49	moderately dry
-1.5 to -1.99	severely dry
-2 and less	extremely dry

The *drought length* is the total number of months the SPI value remained negative. *Drought length is not to be confused with duration (i.e. analysis duration).* ***Duration*** is simply the number months (x) that are totaled to compute the SPI value. Drought length is the number of consecutive months for which the totals of the previous 'x' months had below average precipitation (and therefore, a negative SPI value). For the remainder of this report, duration refers only to the analysis duration. According to McKee et al. (1993), a drought can be identified by a stretch of at least two months (i.e. drought length of two or greater regardless of duration) for which the SPI value is continuously negative and reaches a value of -1 or less at some point in that period. The drought concludes when the SPI value becomes positive once again.

3.2. Computing the SPI in the study area

In order to use the SPI to investigate drought, it is important to have long, complete monthly precipitation records.

If possible, the precipitation records should be from stations located within or in very close proximity to the study area. Monthly precipitation records from the National Climatic Data Center were used to evaluate the historical drought records at two locations. In order to maximize the record length and account for any gaps in records, each location was represented by a group of stations, with one station serving as the primary station and the others used as auxiliary stations for filling in the records. Two stations were identified for this study area, one at Monteagle and the other at Tullahoma. Monteagle is in the center of the high plateau that makes up the study area. Tullahoma presents another long record station that is roughly 20 miles away, but is much lower in elevation. The locations of the Monteagle and Tullahoma stations, and others within the study area, are presented in Figure 3.

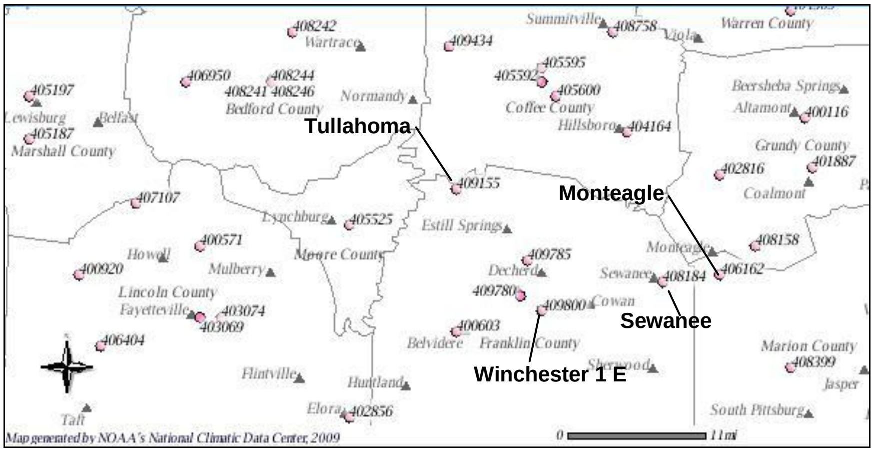

Figure 3 - Map of Precipitation Stations in the study area

Table 3 presents the station information for the Monteagle group of stations. Monteagle's precipitation gaging station serves as the primary station, and the nearby Sewanee station was used to extend the record back to 1927, and fill in the few gaps in Monteagle's record. The rest of the stations in the table were used to fill in other small gaps in Monteagle's record in the priority they are presented in the table. Coalmont, though slightly farther away than Winchester 1 E has a higher priority because it is on the plateau, and Winchester 1 E is not. Tullahoma was used to fill gaps not covered by the other stations. Together, the Monteagle and Sewanee stations make up over 97% of the record length.

Table 3 – Precipitation Stations in the Monteagle group

Station	COOP ID	County	Lat/Long	Period of Record	Function	Elevation (feet)	Dist. From Primary
Monteagle Group				*1928-2009*	*All*	*~1850*	*0*
Monteagle	406162	Marion	35.21N/ 85.85W	1938-2009	Primary	1850	0
Sewanee	408184	Franklin	35.20N/ 85.92W	1927-1962, 1999-2009	Auxiliary/ Extension	1900	3.93
Coalmont	401887	Grundy	35.37N/ 85.70W	1999-2009	Auxiliary	1856	13.38
Winchester 1 E	409800	Franklin	35.18N/ 86.10 W	1985-2009	Auxiliary	940	13.27
Tullahoma	409155	Coffee	35.35N/ 86.22W	1928-2009	Auxiliary	1022	22.64

Table 4 shows the stations in the Tullahoma group in a similar format. The overall record length for the Tullahoma group of stations is 1928 - 2009. The Sewanee station' record length only lists 1927 - 1962 because the station was only used to fill in gaps in the early part of the period of record because the Winchester 1 E station is closer to Tullahoma and covers the end of the record. The Lewisburg Exp Stn station was only used to verify rainfall values in the earliest years of the record.

Table 4 – Precipitation Stations in the Tullahoma group

Station	COOP ID	County	Lat/Long	Period of Record	Function	Elevation (feet)	Dist. From Primary
Tullahoma Group				*1928-2009*	*All*	*~1022*	*0*
Tullahoma	409155	Coffee	35.35N/ 86.22W	1928-2009	Primary	1022	0
Winchester 1 E	409800	Franklin	35.18N/ 86.10 W	1985-2009	Auxiliary	940	13.27
Sewanee	408184	Franklin	35.20N/ 85.92W	1927-1962	Auxiliary	1900	19.85
Monteagle	406162	Marion	35.21N/ 85.85W	1938-2009	Auxiliary	1850	22.64
LewisburgExpStn	405187	Marshall	35.4N/ 86.8W	1928-2009	Auxiliary	787	34.11

Table 5 contains summary statistics for the two stations used in the analysis. At both stations, March is the month with the highest average precipitation, while October has the lowest average.

Table 5 - Summary Statistics for Precipitation Stations (Monthly, in inches unless otherwise noted)

Station:	Monteagle	Tullahoma
Yearly Average (in)	61.45	56.38
Mean	5.12	4.70
Median	4.66	4.29
Standard Deviation	2.72	2.70
Minimum	0.00	0.00
Maximum	18.32	20.77
March Mean	6.54	6.09
October Mean	3.64	3.37
Record Length (mo.)	985	979

It is not known at which duration the critical drought for each supply source in the study area occurs. For reservoirs, the timing of the critical drought will depend on the relationship between the size of the watershed, the demand for water, and the available storage capacity of the reservoir. Changes in the relationship between any of these factors can change which drought produces the necessary conditions for a critical drought to occur. Different reservoirs will have different ratios of storage capacity to the area of their contributing watershed. It's possible that two reservoirs within a very close proximity of each other will have critical droughts of different duration because one may have enough storage to survive short intense droughts, while the other may not. Since it is not known at which duration a reservoir will experience critical drought conditions, a broad range of durations should be tested.

Therefore, the SPI was computed at multiple durations. For the purposes of this analysis, the SPI was computed for the 1, 3, 6, 9, 12, 15, 18, 24, 30, 36, 42, 48, 54 and 60 month durations. This range should allow a complete understanding of short, medium, and long term droughts.

The *SPI_SL_6* program, made available by the National Drought Mitigation Center (NDMC) was used for calculation of the SPI at all the desired drought durations. The program download and documentation are available at the NDMC website : http://drought.unl.edu/monitor/spi/program/spi_program.htm.

4. Standardized Precipitation Index Analysis Results

The SPI analysis effectively identifies dry periods and wet periods based on the historical probability of rainfall totals of the given duration. Because the index reports drought periods as a normalized Z-score, the dry periods can be easily identified by their negative values. More severe droughts result in more negative SPI values. The results for the Monteagle station are presented first, followed by the Tullahoma station.

This study uses a composite, multi-duration SPI plot to give a complete picture of drought severity over the whole period of record. It is necessary to briefly introduce this type of plot before displaying it for the station groups.

For each SPI analysis duration, the *SPI_SL_6* program outputs a monthly time series of SPI index values. It is easy enough to plot this series over time to see how drought conditions change for a given analysis duration, for instance 12 months. Figure 4 shows a sample of how the 12 month duration SPI series changes over the 2002-2009 time period. The horizontal axis displays time and the vertical axis shows the SPI value at that time. The 9 and 15 month durations' series are also shown for comparison. The drought periods are immediately evident as the periods when the SPI value of the series drop below zero. The three series mostly move together, but even with only three series, there is considerable variability. With even more series, a line plot such as Figure 4 would become unreadable.

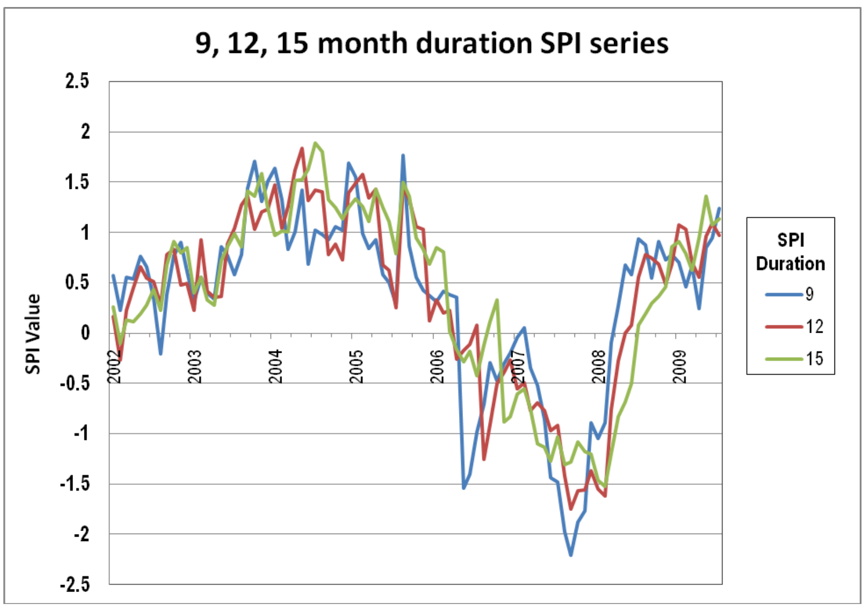

Figure 4 - SPI values over time for three analysis durations

In order to improve the visualization of multiple series, the series could be spread out in a third dimension onto an analysis duration axis. Figure 5 shows the same three series of SPI values as in Figure 4, but the series are now separated on an SPI duration axis, and the whole chart is rotated for perspective.

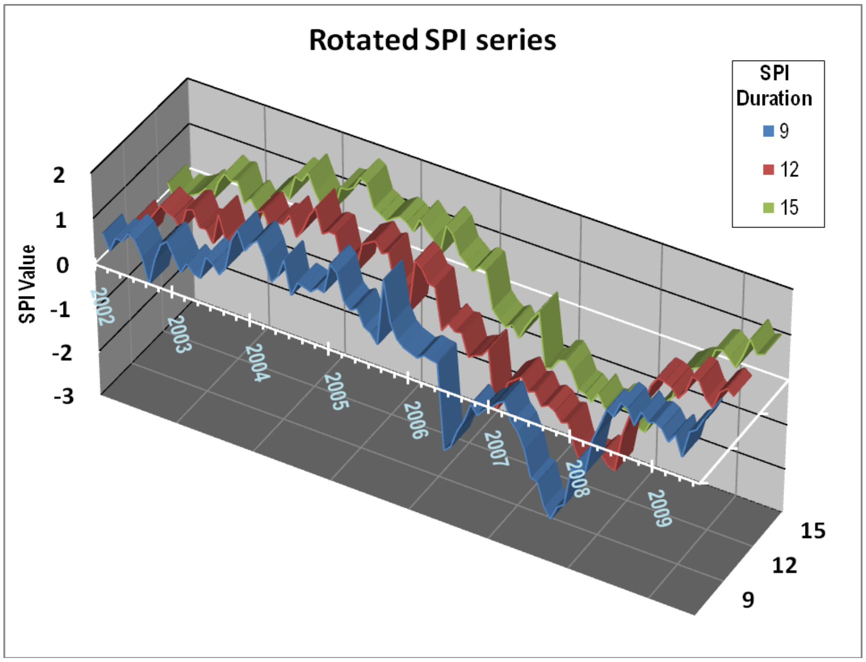

Figure 5 – Rotated SPI series with duration axis

While it is somewhat easier to distinguish the series, it is difficult to read the time and SPI value at a given point on any of the series in Figure 5 due to the perspective. A logical alternative would be to view the plot in plan view (from above) with axes of time and analysis duration, and a different way to display the SPI value (height). One way to display the SPI values is as color contours on a surface plot.

Figure 6 displays such a plot, with the rotation from Figure 4 to Figure 5 continued such that the duration axis is now the horizontal axis and the time axis is displayed vertically. Instead, of distinct data series for each duration, a surface is shown. Thus, whereas the data in Figure 4 and Figure 5 is displayed as continuous along only the time axis, Figure 6 interpolates across the data series on the duration axis to make a two dimensional plot. It is an important caveat to note that the plot is most accurate only on the vertical lines descending from the marked 9, 12, and 15 points on the duration axis. (Vertical lines with the same color scheme as in Figure 4 and Figure 5 have been added as a guide.) As long as the series for the analysis duration are plotted in the correct order, there is enough continuity across the duration axis to make a readable plot. To increase the effective resolution of the plot, the SPI values could be computed for the 10, 11, 13, and 14 month durations. Spacing the series by 3 months for short duration drought analysis, and 6 months for longer duration analysis should give enough detail to decipher the major characteristics of individual droughts across durations.

The third dimension of the plot is the SPI value, and is shown by color contours. The scale at the right side of the plot shows the SPI value colors for various contours. Droughts on the plot are indicated by the colors yellow, orange, and red, with red being the most severe. Blue colors indicate wetter than normal conditions, with darker blues indicating severely wet periods.

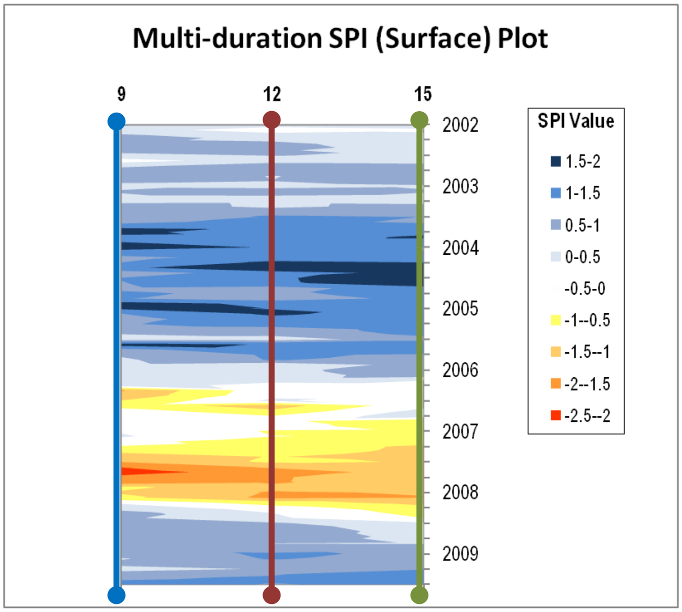

Figure 6 - Surface plot of 9, 12, 15 month SPI value series over time

Multi-duration SPI plots such as the one shown in Figure 6 are used to investigate the occurrence and severity of droughts in the historical precipitation record for each station group.

4.1. Monteagle Station

As a preliminary tool for rapid identification of the most severe droughts, a plot of the SPI over time at all durations in the analysis was created. Figure A.1 (in Appendix A) displays a surface plot with time (months) along the vertical axis, the duration of analysis on the horizontal axis and the SPI value indicated by colors on the plot. The legend shows the corresponding SPI values. For this plot, comparing individual drought periods is best done by picking a duration on the horizontal axis, and moving down the time axis on a vertical line. Alternatively, the evolution of a single drought can be accomplished by picking a time on the vertical axis and tracing a horizontal line across the durations presented.

In Figure A.1, the dry periods are indicated by yellow, orange, and red colors. The redder the color, the more severe the drought is. The most severe droughts are relatively easy to identify, but have different characteristics in terms of their speed of onset, persistence, and durations of greatest severity. Some droughts are short and severe but quickly abate, while others vary in severity over many durations. For instance, the drought of 1963 was short and intense, but was very quickly ameliorated by higher rainfall, whereas a series of short droughts in the mid to late 1980s were severe separate droughts at shorter durations, but combined to form a longer duration drought.

Using the multiple duration SPI chart, seven of the most severe drought periods can be identified. Table 6 displays the most critical SPI values at various durations for the seven droughts. The approximate time periods of the most severe droughts are in the left column, while the duration of the SPI calculation is in the first row. The SPI values reported in the table are the most severe (i.e. most negative) within each drought period. The most negative SPI value for each duration is highlighted in bold and red, and the most severe duration for each individual drought (i.e. each row) is underlined and the cell is colored orange.

At the longest durations, the 1939-1942 drought and the 1944-1945 drought overlap, so their cells are merged in the table. Cells are marked with "--" when a the SPI value for a drought at a given duration falls outside of the top 10% of most severe droughts at that duration, and the drought does not become more severe again at longer durations.

Table 6 - Critical 3 to 60 months duration SPI values for droughts at Monteagle Stn

Drought	3	6	9	12	15	18	24	30	36	42	48	54	60
1930-1934	-2.50	-3.02	-3.20	-3.27	-3.02	-3.08	-2.92	-2.52	-1.96	-1.92	-2.09	-1.91	-1.92
1939-1942	-2.65	-2.81	-2.51	-2.04	-2.06	-1.97	-2.41	-2.38	-2.53	-2.33	-2.13	-2.32	-2.22
1944-1945	-3.98	-2.78	-2.00	-1.95	-1.39	-1.54	-1.56	-1.26	-1.32	-1.42	-1.81		
1960-1961	-2.56	-2.50	-2.04	-1.88	-1.55	-1.45	--	--	--	--	--	--	--
1963-1964	-3.22	-1.79	-1.21	--	--	--	--	--	--	--	--	--	--
1986-1988	-2.14	-2.65	-2.46	-2.29	-2.65	-2.49	-1.93	-1.95	-1.92	-2.01	-1.96	-2.06	-1.78
2007-2009	-2.97	-2.84	-3.31	-3.07	-3.24	-2.80	-2.91	-2.76	-2.63	-2.25	-2.02	-1.89	-1.19

Table 6 indicates the difficulty in identifying the most severe drought. By SPI value alone, the 1944-1945 drought at the three month duration appears to be the most severe drought with an SPI value of -3.98. SPI values, however, are not entirely comparable across durations because the sample size for a 3 month SPI is greater than a nine month SPI. (The sample size is greater by six since the nine month duration cannot be calculated for the first time until nine months into the record, while the three month duration can be computed after just three months.) So, it is predictable that all of the droughts would reach their most critical SPI value at a shorter duration. Additionally, longer durations of analysis tend to lead to some balancing of wetter and drier than normal months. Thus, severe droughts at longer durations may not show as impressive SPI values as shorter duration droughts.

It is more interesting perhaps, to investigate which drought is the most severe for the various durations. The most evident pattern is that the early 1930s and recent drought starting in 2007 are the dominant droughts from the 6 month duration to 36 month duration. It is especially striking that there is no particular duration that marks the transition between the two for most severe drought, but rather an alternating pattern, especially between the 6 and 18 month durations. With this information, it is nearly impossible to determine which drought is more severe. Rather, it is clear that month-to-month changes in precipitation can affect which drought has a higher SPI value for a given duration. Presumably, computing SPI values at other intermediate durations (4, 5, 7, 8, 10, etc) would result in even more alternation between the two.

To put these droughts in context, an SPI value of -3.0 corresponds to a cumulative probability of 0.0014, which means it is exceeding unlikely. The fact that two droughts in the last 90 years exceed -3.0 for multiple time scales is remarkable. Both of these droughts must be included in any analysis of firm yield for water sources.

As a final note, the droughts of the early and mid 1940s are the most critical droughts at the longer analysis durations. At the two longest durations, both droughts are captured, so they are combined in the table.

4.2. Tullahoma

As a comparison to the Monteagle station, the Tullahoma station is investigated because long records were available, and it represents a slightly different climate zone even though it is only a bit more than 20 miles away, as it has a different elevation than Monteagle. Even so, as expected, the SPI analysis yields similar results.

Figure A.2 in the Appendix shows the multi-duration SPI plot for Tullahoma. In general, the SPI analysis identifies similar drought periods as for Monteagle. Table 7 shows seven droughts selected from the plot and their most severe SPI values for each duration. The selection of droughts varied slightly from the Monteagle results table. In many cases, minor droughts were left off of the tables. For instance, in Monteagle, the early 1960s drought had more severe SPI values than many other droughts, but in Tullahoma, the mid 1960s drought was slightly more severe, and was picked instead. Additionally, the 1999-2000 drought was very short and severe, and is completely abated by the 12 month duration (marked as '--' in the table). The years listed for the identified drought periods are rough bounds only.

As in Monteagle, the two most severe droughts were the early 1930s drought and the recent drought that started in 2007. In Tullahoma, the 1930s drought was the most severe at a greater number of durations, especially in the important 6-24 month range of durations. Surprisingly, the recent drought reaches its greatest severity at longer durations. This could indicate lingering vulnerability in water supply sources that respond to longer range precipitation trends. The 1939-1945 drought is also notable as it has the most severe SPI values at the 30, 36, 54, and 60 month durations.

The second tier of droughts showed different behavior in Tullahoma as compared to Monteagle. The mid 1930s and early 1940s droughts showed less overall severity at the shorter durations, but greater persistence than at Monteagle. This is visible by comparing the two SPI plots and viewing the larger areas of orange in Tullahoma. The other main difference is that the droughts of the late 1980s are much less severe in Tullahoma.

Table 7 - Critical 3 to 60 months duration SPI values for droughts at Tullahoma Stn

Drought	3	6	9	12	15	18	24	30	36	42	48	54	60
1930-1934	-2.61	**-2.57**	**-2.63**	**-2.65**	**-2.73**	**-2.96**	**-2.58**	-2.36	-1.90	-1.60	-1.48	-1.33	-1.45
1936-1937	-2.51	-1.85	-2.06	-2.46	-2.01	-1.82	-1.69	--	--	--	--	--	--
1939-1945	-2.43	-2.30	-2.34	-2.38	-2.49	-2.58	-2.55	**-2.65**	**-2.59**	-2.47	-2.52	**-2.53**	**-2.25**
1963-1964	**-2.97**	-2.10	-1.23	--	--	--	--	--	--	--	--	--	--
1980-1983	-2.07	-2.19	-2.42	-2.37	-2.24	-1.84	-1.46	--	--	--	--	--	--
1999-2000	-2.94	-2.46	-1.82	--	--	--	--	--	--	--	--	--	--
2007-2009	-2.06	-1.99	-2.37	-2.58	-2.48	-2.31	-2.44	-2.33	-2.56	**-2.69**	**-2.64**	-2.50	-1.94

As a final note, the most severe SPI values in Tullahoma, are of lower magnitude on average than in Monteagle, except at the longer durations. It is unclear what effect this might have on firm yield analyses, but it may mean that short and medium length severe droughts are slightly more likely to be broken up by occasional rainfall in Tullahoma.

5. Summary and Upcoming Tasks

The South Cumberland Plateau in Tennessee, though generally wet compared to the nation as a whole, has experienced severe drought conditions several times over the past 80+ years, and most recently in 2007-2008. The study area's location on the top of a plateau makes its water supply vulnerable during periods of lower than normal precipitation. In cases of drought, several of the local utility districts have plans and arrangements to mitigate the effects, which have been summarized in this report.

The Standardized Precipitation Index was used to identify the particularly dry periods in the Southern Cumberland Plateau's rainfall record. The Monteagle and Tullahoma precipitation stations were selected for analysis. The SPI was calculated at durations ranging from 3 to 60 months.

By using the SPI, seven potentially critical droughts have been identified. The drought that is most severe varies according to the duration at which the SPI is calculated. Based on the size of the water sources and their catchments, it is hypothesized that the critical drought duration is between 9 and 15 months. Overall, the droughts of 1930 – 1934, and 2007 - 2009 appear the most likely to be the critical drought. No single drought however, appears to be the most critical at all of these durations based on the SPI analysis alone.

In the Existing Sources Yield Analysis task of Phase II, the firm yield of the reservoirs will be reanalyzed, taking into account both the recent drought and the early 1930s drought. To identify the critical drought sequence for each water supply reservoir, a sequent peak analysis will be performed based on streamflow for the entire period of record. The sequent peak analysis uses streamflow to determine the maximum cumulative storage deficit for a given water demand (yield). The critical drought is the period when the maximum storage deficit occurs. Where possible, existing streamflow and reservoir operations records will be used to evaluate the firm yield at existing water sources. If the records are not available or not long enough to cover both of the most severe droughts identified in this study, a hydrologic model will be developed to create a synthetic flow record. In future work, the synthetic streamflow will be generated in HEC-HMS using the Tullahoma and Monteagle precipitation gages' daily rainfall record as the hydrologic input.

6. References

Benton, Ben. "Monteagle reservoir situation improves, but fears persist." *Chattanooga Times Free Press.* 11 Jan 2008. <http://www.timesfreepress.com/news/2008/jan/11/Monteagle-reservoir-situation-improves-but/>

Hayes, Michael J., 2006. "What is Drought?: Drought Indices." National Drought Mitigation Center. (Online). <http://drought.unl.edu/whatis/indices.htm>, 2006.

McKee, T.B.; N.J. Doesken; and J. Kleist. 1993. The relationship of drought frequency and duration to time scales. Preprints, 8th Conference on Applied Climatology, pp. 179–184. January 17–22, Anaheim, California.

NCDC, 1994, Time Bias Corrected Divisional Temperature-Precipitation-Drought Index. Documentation for dataset TD-9640. Available from DBMB, NCDC, NOAA, Federal Building, 37 Battery Park Ave. Asheville, NC 28801-2733. 12pp.