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 Analysis

Portland/ North Central Tennessee

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

Date: October 12, 2009
Re: Critical Regional Drought Evaluation – Portland/ North Central TN

WATER RESOURCES REGIONAL PLANNING PILOT STUDY
FOR
PORTLAND/ NORTH CENTRAL TENNESSEE

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

October 12th, 2009

US Army Corps of Engineers
Nashville District

GKY & Associates, inc.

TETRA TECH

Table of Contents

1. Introduction **1**
1.1. Scope 1
1.2. Study Area 1
1.3. Effects of the 2007-2008 Drought 2
2. Summary of Local Drought Planning **3**
2.1. Gallatin Public Utilities 3
2.1.1. General Principles 3
2.1.2. Authority 4
2.1.3. Drought Levels 4
2.1.4. Emergency Actions 4
2.1.5. Emergency Sources and Water Sharing 4
2.2. Hartsville Water Department 4
2.2.1. General Principles 4
2.2.2. Authority 5
2.2.3. Drought Levels 5
2.2.4. Emergency Actions 5
2.2.5. Emergency Sources and Water Sharing 5
2.3. Portland Water Department 6
2.3.1. General Principles 6
2.3.2. Authority 6
2.3.3. Drought Levels 6
2.3.4. Emergency Actions 6
2.3.5. Emergency Sources and Water Sharing 7
2.4. Westmoreland Water Department 7
2.4.1. General Principles 7
2.4.2. Authority 8
2.4.3. Drought Levels 8
2.4.4. Emergency Actions 8
2.4.5. Emergency Source and Water Sharing 8
2.5. Castalian Springs/ Bethpage U.D. 8
2.6. Lafayette Utility District 8
2.7. White House Utility District 8
3. Drought Evaluation **9**
3.1. Drought Index Selection 9
3.2. SPI Computation in the Study Area 11
4. Results **13**
4.1. SPI Analysis Results 15
4.1.1. Portland Group 16
4.1.2. Lebanon Group 17
5. Conclusion and Continuation **18**
6. References **19**

Table of Figures

Figure 1 - Portland/North Central Tennessee Study Area (Image credit TDEC) 2
Figure 2 - U.S. Drought Monitor Map for Tennessee showing the study area during the most severe portion of the 2007 drought 3
Figure 3 - Map of the Portland and Lebanon precipitation stations...12
Figure 4 - SPI values over time for three analysis durations 14
Figure 5 – Rotated SPI series with duration axis..14
Figure 6 - Surface plot of 9, 12, 15 month SPI value series over time 15

Table of Tables

Table 1 - SPI values and associated descriptions 10
Table 2 – Precipitation Stations in the Portland group (daily stations only) 11
Table 3 – Precipitation Stations in the Lebanon group (daily and monthly stations) 12
Table 4 - Summary Statistics for the precipitation records 13
Table 5 - Critical 3 to 60 months duration SPI values for droughts at Portland, TN 16
Table 6 - Critical 3 to 60 months duration SPI values for droughts at Lebanon 17

1. Introduction

The drought of 2007-2008 severely tested the water supplies of the North Central Tennessee study area. The impact of the recent drought rivaled that of the droughts of the 1930s and 1940s. 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 on mandatory and voluntary conservation measures to reduce demand and on neighboring water districts to help provide additional supply.

The impact of the recent drought acted as a catalyst to perform a comprehensive water resources planning study 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 Portland/ North Central Tennessee 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 Portland/ North Central Tennessee. 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 historical 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 North Central Tennessee Study Area covers a five-county geographical region. Portions of Robertson, Sumner, Macon, Trousdale and Wilson counties, which include the towns of Portland, Gallatin, Hartsville, Castalian Springs/Bethpage, White House, Lafayette, and Westmoreland, are included in the study. The study area is indicated in Figure 1.

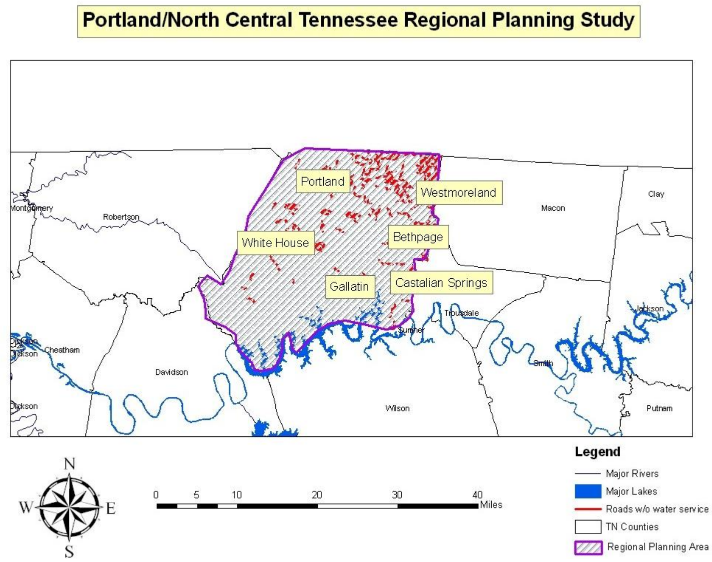

Figure 1 - Portland/North Central Tennessee Study Area (Image credit TDEC)

Climatically, the study area is fairly warm and humid with average rainfall of around 50 inches per year and a 60 degree average temperature. The northern part of the study area is drained by the Barren River which is part of the Ohio River's drainage area. The rest of the study area falls within the Old Hickory Lake and Red River Basins, which drain to the Cumberland River. The drainage divide is aligned along the northernmost portion of the Highland Rim, which reaches an elevation of over 900 feet. South of the Highland Rim is the Central Basin which includes Old Hickory Lake, and eventually, Nashville. The Central Basin is characterized geologically by Ordovician Carbonates, while the Highland Rim and areas north are characterized by Mississippi Carbonates and have a greater occurrence of karst formations.

1.3. Effects of the 2007-2008 Drought

The drought of 2007-2008 was one of the most severe droughts on record in Tennessee, and in the study area. According to the U.S. Drought Monitor archives, the majority of the study area reached a level D4, or Exceptional Drought, which is the most severe drought intensity on the U.S. Drought Monitor's scoring system. The U.S. Drought Monitor is a multi-indicator representation of drought conditions published weekly by 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. Figure 2 shows a U.S. drought monitor map of the study area in Tennessee during the most severe portion of the 2007-2008 drought.

The majority of the study area is in the dark red D4 region, and the rest of the area is classified as in a D3 drought. An analysis of the weekly U.S. Drought Monitor archives (available at http://drought.unl.edu/dm/archive.html) found that some portion of the study areas was at least in D1 or Moderate drought from mid-April 2007 until early March, 2008.

Regardless of the drought level recorded under the U.S. Drought Monitor or any other drought metric, it is more important to investigate the effects of the drought on water supplies, public water utilities and the communities they serve.

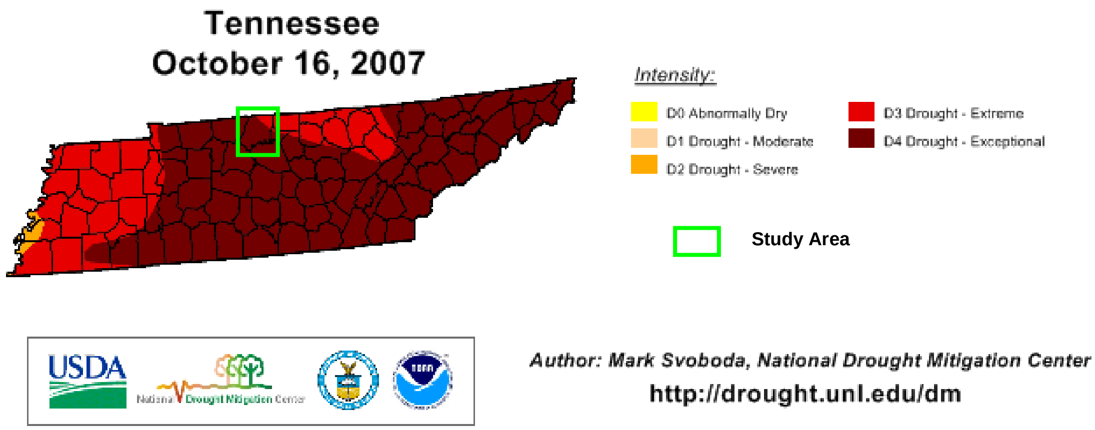

Figure 2 - U.S. Drought Monitor Map for Tennessee showing the study area during the most severe portion of the 2007 drought

2. Summary of Local Drought Planning

Due to the variety of types of water sources used by the utility districts in the study area, the impacts of the 2007-2008 drought varied widely. Utility districts getting water from Old Hickory Lake and the Cumberland River suffered far fewer consequences than those with small impoundments, springs, or smaller rivers for sources. Regardless of type of water source, utilities are required to have some type of 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 requires 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."

The following sections of this chapter describe the current state of drought emergency planning by the various towns and water suppliers in the study area.

2.1. Gallatin Public Utilities

Gallatin Water Department withdraws all of its water from Cumberland River at Old Hickory Lake. As part of an emergency operations plan, there is a recommended priority to furnishing water during shortage. A drought plan was not available at the time of this writing.

2.1.1. General Principles

Gallatin establishes a classified priority for water use during drought conditions in an emergency plan document. 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 include water for ornamental purposes, outdoor non-commercial watering, washing motor vehicles, and air conditioning.

2.1.2. Authority

At the time of this writing, this information was unavailable.

2.1.3. Drought Levels

At the time of this writing, no information on drought levels or triggers for drought emergency status was available.

2.1.4. Emergency Actions

The emergency operations plan contains a list of critical water customers. The list includes primarily medical care facilities, notably, the Sumner Regional Medical Center. In addition, doctors' offices, surgery centers, and nursing homes are included.

2.1.5. Emergency Sources and Water Sharing

Gallatin withdraws water from Old Hickory Lake, treats it, and sells water to Castalian Springs (maximum capacity 1.5 MGD) and Westmoreland (maximum capacity 0.75 MGD) during normal operations. Gallatin can sell up to 1 MGD to White House Utility District during emergencies.

2.2. Hartsville Water Department

The Town of Hartsville has an emergency plan which establishes a four-level recommended priority for establishing water during an emergency, establishes a two category system of non-essential use restrictions during water shortage emergency, and outlines non-compliance penalties and procedures.

2.2.1. General Principles

The Hartsville Water District establishes a classified priority for water use during drought conditions in an emergency plan document. 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 4 uses are "Non-essential Uses of Water," which include water for ornamental purposes, outdoor non-commercial watering, washing motor vehicles, and air conditioning.

2.2.2. Authority

The Town of Hartsville has the authority to declare a water shortage emergency. The Town must notify the local media.

The Town of Hartsville has the right to adjust allowances during periods of restrictions to better protect community welfare, and more equally share the burden among customers.

The Town of Hartsville will investigate complaints of non-compliance with restrictions made by a citizen to any official from the Town of Hartsville. The Town of Hartsville may discontinue service to non-complying violators after a request to comply has not been followed. The customer has the right to appeal the disconnection, and can have service reconnected after paying a reconnection charge and meeting requirements and conditions imposed by the Town of Hartsville representatives.

2.2.3. Drought Levels

The Town of Hartsville has established two categories of water use restrictions. No specific criteria are listed as triggers to implement the categories of restrictions, but Category 1 restrictions are to be considered in the event of severe drought conditions, while Category 2 restrictions are considered in the event of extreme drought conditions.

2.2.4. Emergency Actions

Hartsville has two successive categories of restrictions on non-essential uses.

The Category 1 restrictions include:

- Non-residential use exceeding 70% of prior year use for same billing period
- Washing exterior paved areas
- Filling or refilling a swimming pool
- Non-commercial washing of privately-owned vehicles
- Watering lawns, flower gardens, and sports fields
- Watering any part of a golf course
- Use of water for construction (dust control and compaction)

The Category 2 restrictions include all Category 1 restrictions, and additionally:

- Watering of trees and shrubs in excess of 50% of prior year use by commercial consumer, with the exception of commercial vehicles
- Use by a commercial vehicle washing facility
- Water reserved at restaurants, except by customer's request
- Non-residential use exceeding 50% of prior year use for same billing period

2.2.5. Emergency Sources and Water Sharing

As described in the Water Resources Regional Planning Pilot for North Central Tennessee Phase I report, Hartsville/Trousdale Utility District withdraws all of their water from the Cumberland River. They sell water to Castalian Springs/Bethpage U.D., South Side U.D., and Cordell Hull U.D. in normal times, and to Lafayette during emergencies. The maximum transfer capacity to Lafayette has been estimated at roughly 20,000 gallons per day.

2.3. Portland Water Department

Resolution Number 2103, which went into effect on March 6, 1989, authorizes and sets forth guidelines for the declaration of a water shortage emergency.

2.3.1. General Principles

Portland's emergency operations plan and Resolution Number 2103 outline several actions and authorities during drought emergencies. As a general principle, no water is to be wasted during drought emergencies. The importance of monitoring sources is established. In general, the resolution establishes a two-tiered water use restriction regime for non-essential uses. Additionally, a prioritized list of emergency sources is provided.

2.3.2. Authority

The authority to declare a water shortage emergency is granted to the Mayor (or a designee), who also makes the determination based on conditions of water supplies whether an emergency should be designated as Status 1 or 2. The Mayor is required to notify local media of a decision to declare a water emergency.

The Board of Aldermen has authority to modify the water use restrictions, and has sole authority to terminate the emergency. The Board of Aldermen may also declare a water emergency even if the conditions triggering a particular water emergency status are not met.

The Mayor or his designees are charged with investigating non-compliance with restrictions, and have the right to discontinue water service to non-complying customers. The Board of Aldermen hears appeals for reinstatement of service, and may impose terms and conditions for reinstatement of service.

2.3.3. Drought Levels

The City of Portland has two levels of drought restrictions, which are called Water Shortage Emergency Status 1 and 2. The trigger for the declaration of Water Shortage Emergency Status is the level of distribution system reservoirs.

Water Shortage Emergency Status 1 exists when the water level in a major distribution system reservoir cannot be brought above the two-thirds full level in a forty-eight hour period.

Water Shortage Emergency Status 2 exists when the water level in a major distribution system reservoir cannot be brought above the one-quarter full level in a forty-eight hour period.

2.3.4. Emergency Actions

The Portland Emergency Operations plan outlines several potential actions for responding to drought. The first action is to increase monitoring of reservoir levels and flow levels in Drakes Creek. Then, non-essential use restrictions are considered. Under more serious droughts, assistance can be asked for from neighboring counties and utility districts. Finally, the drought plan considers constructing a small dam on Drakes Creek to protect the intakes by increasing the flow depth.

The non-essential use restrictions are enacted in accordance with the Water Shortage Emergency Status.

For Water Shortage Emergency Level 1, the following non-essential use restrictions, termed Category 1, can be implemented:

- Non-residential use exceeding 70% of prior year use for same billing period
- Washing exterior paved areas
- Filling or refilling a swimming pool
- Non-commercial washing of privately-owned vehicles
- Watering lawns, flower gardens, and sports fields
- Watering any part of a golf course
- Use of water for construction (dust control and compaction)

For Water Shortage Emergency Level 2, the following non-essential use restrictions, termed Category 2, can be implemented in addition to Category 1 restrictions:

- Watering of trees and shrubs in excess of 50% of prior year use by commercial consumer, with the exception of commercial vehicles
- Use by a commercial vehicle washing facility
- Water reserved at restaurants, except by customer's request
- Non-residential use exceeding 50% of prior year use for same billing period

Other emergency actions are described in the following subsection.

2.3.5. Emergency Sources and Water Sharing

Portland has a few options for securing emergency water supplies. Portland withdraws most of its water supply from West Fork Drakes Creek. Portland uses Portland City Lake as a source when the flow on the creek gets too low. Portland City Lake is frequently used in the summer months, so it is not a true emergency source.

As a true emergency back-up, Portland has connections to Westmoreland and to White House Utility District. Additionally, Portland may have to ask Franklin, Kentucky and Simpson County, Kentucky for assistance.

Finally, Portland has considered building a small dam during drought emergencies on West Fork Drakes Creek to keep their intakes submerged and provide some additional supply.

2.4. Westmoreland Water Department

As a wholesaler of water, Westmoreland buys its entire supply from Gallatin Utility District, which withdraws its water from Cumberland River at Old Hickory Lake. Westmoreland then resells water to other utility districts both during normal operations and during emergencies. Westmoreland has general principles for providing water during times of shortages. In general, the lack of its own water source to manage means that Westmoreland cannot formulate a drought plan that prescribes actions based on the condition of its water supply.

2.4.1. General Principles

The Westmoreland Water Department establishes a classified priority for water use during drought conditions in an emergency plan document. 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 4 uses are "Non-essential Uses of

Water," which include water for ornamental purposes, outdoor non-commercial watering, washing motor vehicles, and air conditioning.

2.4.2. Authority

No information on authority during a drought emergency was available at the time of this writing.

2.4.3. Drought Levels

No information on drought levels or triggers during a drought emergency was available at the time of this writing.

2.4.4. Emergency Actions

No information on specific restrictions or actions during a drought emergency was available at the time of this writing.

2.4.5. Emergency Source and Water Sharing

Westmoreland does not have any water sources of its own. Instead, they buy all of their water from Gallatin. They sell water to Castalian Springs during normal operations. They can sell water to Portland during emergencies. They can buy water from or sell water to Lafayette Utility District in emergencies, depending on the situation.

2.5. Castalian Springs/ Bethpage U.D.

Castalian Springs/ Bethpage Utility District purchases all of their water supply. Gallatin is the most important seller, but Westmoreland and Hartsville sell to Castalian Springs/Bethpage in emergencies.

No information on local drought planning in Castalian Springs/Bethpage was available at the time of this writing.

2.6. Lafayette Utility District

No information on drought planning in Lafayette was available at the time of this writing.

Lafayette U.D. relies primarily on two springs (White's and Adams), but can use an intake on the Barren River as an emergency source. Lafayette U.D. also has connections to Hartsville, Westmoreland, and Red Boiling Springs. Water is purchased from Hartsville during emergencies. Water can be sold to or bought from Westmoreland, and water is sold to Red Boiling Springs in emergencies.

2.7. White House Utility District

No information on drought planning in White House was available at the time of this writing.

White House Utility District uses Old Hickory Lake as the primary supply source, and also purchases water from Gallatin and Springfield in quantities of up to 1 and 0.25 MGD, respectively, during the summer.

3. Drought Evaluation

The purpose of this drought evaluation is to examine the historical meteorological 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 simulating the conditions of the 2007 drought, it is perhaps better to reexamine the firm yields of the water sources in the study area for as long a period of record as possible. 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. If a reservoir of fixed capacity is operating at its firm yield, the critical drought sequence results in the reservoir just emptying its available storage (before beginning to refill).

Even in a small study area, reservoirs of different sizes may not have the same critical drought sequence because they may respond to droughts of different durations. Spring sources and streamflow sources may be depleted or become unusable in response to still other drought durations.

As a result, to capture the appropriate conditions for all sources this regional drought evaluation must look at droughts over a long period of record and investigate the relative severity of drought conditions at several durations. That is, look for the driest three month periods, one year periods, two year periods, etc. Since streamflow gage records longer than approximately 40 years are not available in the study area, the starting point for the regional critical drought analysis must be from meteorological data.

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 the study area's location, climate, and water sources make some drought indices more applicable than others. The study area is in a rural, hilly region of North Central Tennessee, and has a variety of types of water sources including stream withdrawals, springs, small reservoirs, and a large multi-purpose reservoir (Old Hickory Lake). Despite the size of Old Hickory Lake, drought indices that rely on large scale surface water conditions such as the Surface Water Supply Index and Reclamation Drought Index are better suited to larger basins in the Western states. Though there is certainly agriculture in the study area, the general indices that track soil moisture conditions such as the Crop Moisture Index and various Palmer drought indices (PDSI, modified PDSI, PHDI) are not particularly well suited to small regions with varied terrain, and are somewhat cumbersome to analyze on multiple time scales. Furthermore, this study is concerned with the study area's water supplies, and not directly with agricultural production.

Thus, considering the type of water sources and local hydrology, a flexible precipitation based index would be the most straightforward method for identifying historical drought conditions. Perhaps the best known method is to calculate the departure from normal precipitation. The problem with this method is that it is difficult to compare the relative severity of short and long term droughts, since the magnitude of the deficit varies by so much. Instead, the more flexible Standardized Precipitation Index can be used.

The Standardized Precipitation Index (SPI) method is selected for drought identification in this study. The Standardized Precipitation Index (SPI) is a flexible, multi-timescale approach for drought identification based exclusively on precipitation conditions. 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 computed 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. In the following month, the SPI for April would total the precipitation for February, March, and April.

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 of one). The index value is roughly analogous to the number of standard deviations the rainfall total falls from the median. 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 1 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 1 - 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

According to McKee et al. (1993), a drought can be identified by a stretch of at least two months 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. 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.

3.2. SPI Computation in the Study Area

It is not known at which duration the critical drought for the study area occurs, as it likely varies depending on the water source. Therefore, the SPI will be computed at multiple durations to identify the most severe drought persistence at several different durations. For the purposes of this analysis, the SPI is computed for the 1, 3, 6, 9, 12, 15, 18, 24, 30, 36, 42, 48, 54 and 60 month durations. Especially when computing the SPI at long durations, it is important to have a long, complete monthly precipitation record.

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 severity at two locations within the study area. 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 or two stations serving as the primary station(s) and the others used as auxiliary stations for filling in the records. The primary stations should make up at least 95% of the record length, with the auxiliary stations only used to fill in months when none of the primary stations have data. Ideally, auxiliary stations should be located within about 20 miles of the primary stations, but this range may have to be extended for time periods at the beginning of the record.

Two station groups were identified for this study area, one centered near Portland and the other near Lebanon. The stations in the Portland group are identified in Table 2 by their name, Cooperative Station Identification number (COOP ID), and county. Additionally, each station's location, approximate period of record, function in the group, elevation, and distance from the primary station is identified. The period of record used for SPI analysis in Portland was from 1928 to 2009. All stations in Portland Group have daily precipitation records that were totaled to create the monthly time series needed for SPI analysis.

Table 2 – Precipitation Stations in the Portland group (daily stations only)

Station	COOP ID	County	Lat/Long	Period of Record	Function	Elevation	Dist. From Primary
Entire Portland Group				*1928-2009*	*All*	-	*0*
Portland Sewage Plt	407359	Sumner	36.35N/ 86.32W	1952-2009	Primary	794	0
Portland	407358	Sumner	36.35N/ 86.31W	1943-1952	Extension/ Auxiliary	922	0.93
Franklin 1 E(KY)	153036	Simpson (KY)	36.41N/ 86.30W	1928-2009	Extension/ Auxiliary	680	7.15
Bowling Green Warren Co Aiport	150909	Warren (KY)	36.58N/ 86.25W	1932-2009	Auxiliary	528	27.26
Franklin Sewage Plt (TN)	403280	Williamson	35.57N/ 86.52W	1928-2009	Auxiliary	655	47.53

Table 3 shows the stations in the Lebanon group in a similar format. The overall record length for the Lebanon composite station is 1928 – 2009. The Lebanon group has two primary stations located in very close proximity, whose main difference is period of record and data type. The Lebanon 7 N station is the station used for the majority of the record. The Lock 5 Cumberland Rvr station is considered as an early extension of the Lebanon 7 N station by the National Climatic Data Center, and so it is listed as a primary station. Its data was only available as monthly data prior to 1948.   The Carthage station is also a monthly record station used to extend the record back to 1931 and fill in missing months prior to 1948. The Murfreesboro 5 N station is another monthly record station (prior to 1948) and was used to extend the record back to 1928 in order to match the length of the Portland record.

Table 3 – Precipitation Stations in the Lebanon group (daily and monthly stations)

Station	COOP ID	County	Lat/Long	Period of Record	Function	Elevation (ft)	Dist. From Primary
Entire Lebanon Group				*1928-2000*	*All*	-	*0*
Lebanon 7 N	405118	Wilson	36.28N/ 86.25W	1948-2009	Primary	510	0
Lock 5 Cumberland Rvr	405353	Wilson	36.30N/ 85.27W	1934-1948	Primary	510	0
Lebanon	405108	Wilson	36.14N/ 86.19W	1948-2009	Auxiliary	525	5.4
Lock 6 Cumberland Rvr	405355	Trousdale	36.21N/ 86.09W	1948-1956	Auxiliary	489	7.4
Hartsville	403938	Trousdale	36.38N/ 86.18W	1998-2009	Auxiliary	511	7.4
Carthage	401480	Smith	36.25N/ 85.95W	1931-1948	Auxiliary/ Extension	515	18.0
Murfreesboro 5 N	406371	Rutherford	35.92N/ 86.38W	1928-1948	Auxiliary/ Extension	535	27.3

Both station groups are highlighted in the map in Figure 3. The Portland group appears in the upper middle of the map, and the Lebanon group at the lower right. For the Portland Group, the Bowling Green and Franklin (TN) stations are not shown, but the three stations in the Portland box make up 95 percent of the period of record. The majority of stations in the Lebanon group are shown in Figure 3. The stations in the green box at the lower right make up the majority of the record. The Carthage station is at bottom corner in the far right, and the Murfreesboro 5 N station is off the map to the South.

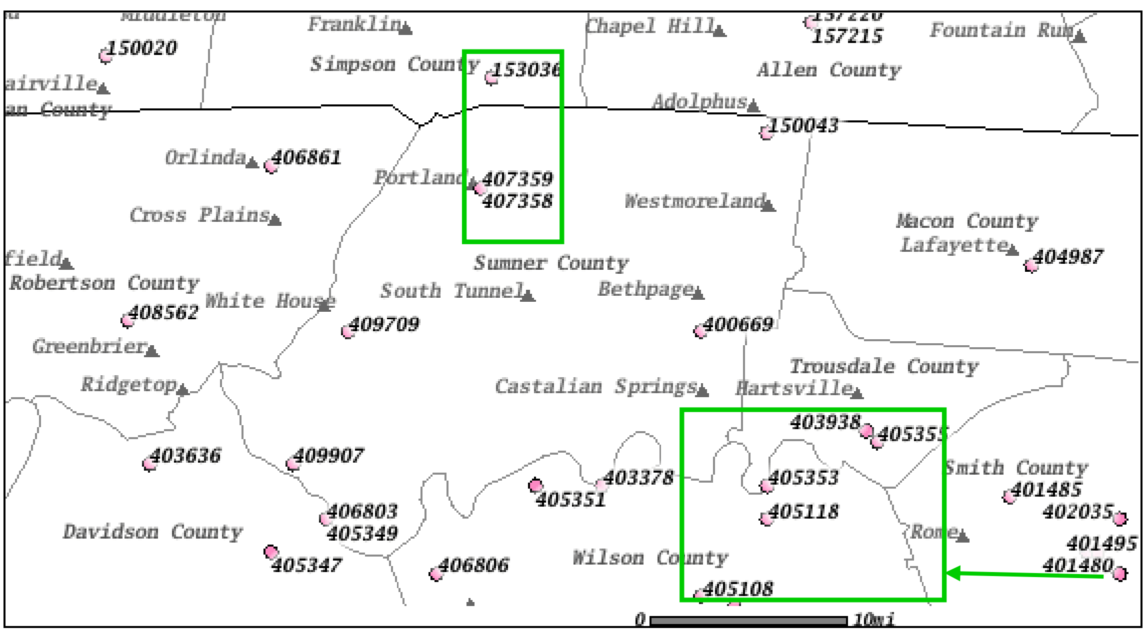

Figure 3 - Map of the Portland and Lebanon precipitation stations.

Table 4 contains summary statistics for the two station groups used in the analysis. At both locations, March is the month with the highest average precipitation, while October has the lowest average. Unless otherwise noted, all units are monthly and in inches.

Table 4 - Summary Statistics for the precipitation records

Station Group:	Portland	Lebanon
Yearly Average (in)	49.8	51.9
Mean	4.16	4.33
Median	3.71	4.30
Standard Deviation	2.43	2.29
Minimum	0.00	0.00
Maximum	20.70	14.56
March Mean	4.97	5.18
October Mean	2.98	3.09
Record Length (mo.)	979	730

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. 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 SPI reports its value as a normalized Z-score, the dry periods can be easily identified. The results for the Portland Group of stations are shown first, followed by the Lebanon stations for comparison.

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.

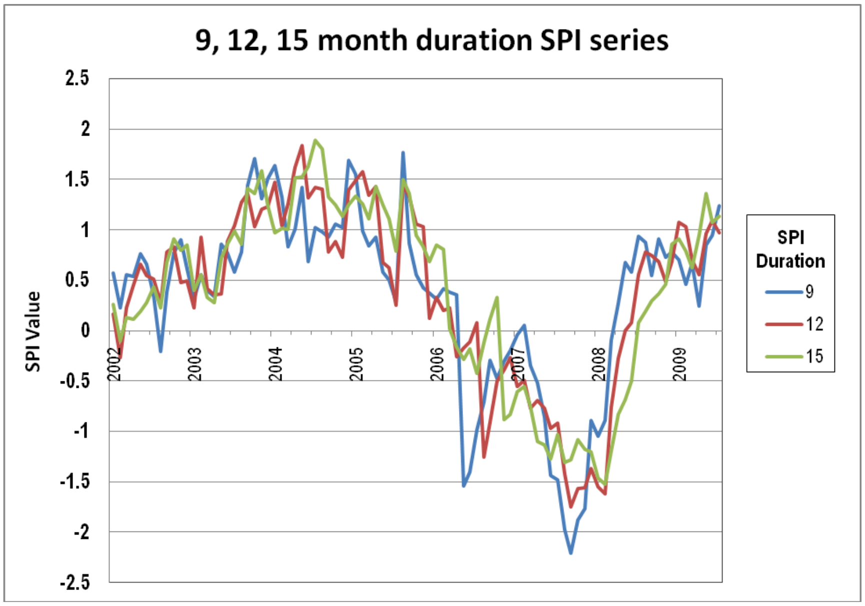

Figure 4 - SPI values over time for three analysis durations

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.

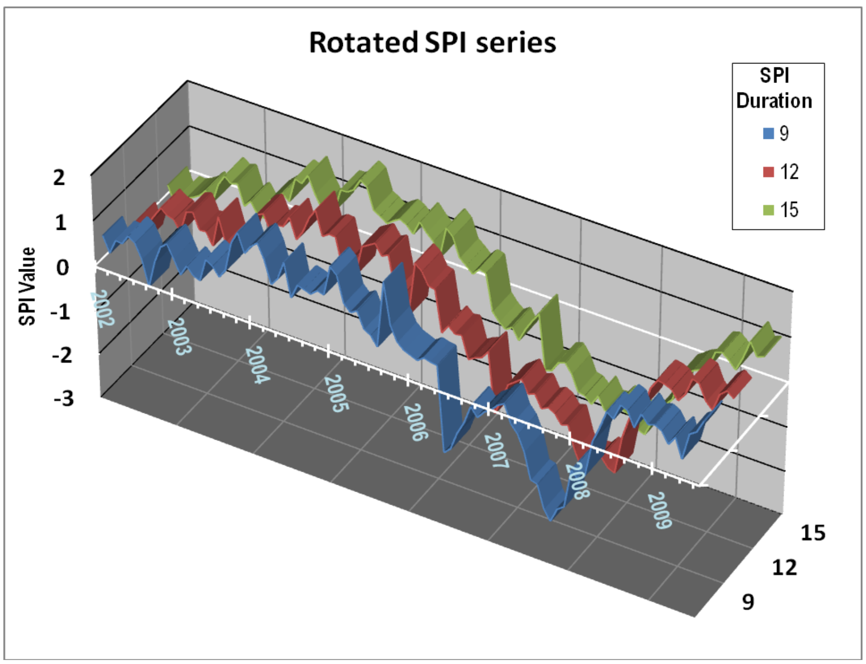

Figure 5 – Rotated SPI series with duration axis

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. 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 horizontal 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 are displayed as continuous along only the time axis, Figure 6 interpolates across the data series on the duration axis to make a two dimensional projection of a three dimensional surface plot. It is an important caveat to note that the plot is most accurate 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 three months for short duration drought analysis, and six 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.

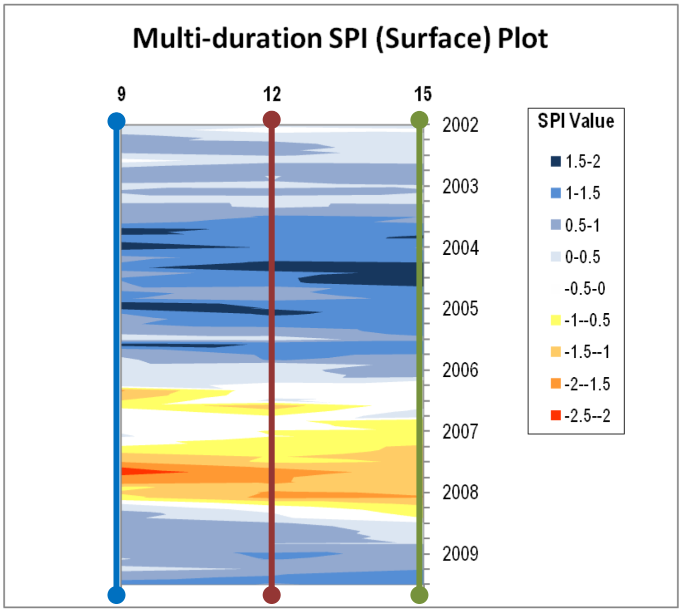

Figure 6 - Surface plot of 9, 12, 15 month SPI value series over time

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. SPI Analysis Results

Using the multi-duration SPI plots, the precipitation sequences for the Lebanon and Portland stations were analyzed to identify severe historical droughts.

4.1.1. Portland Group

As a preliminary tool for rapid evaluation of the most severe droughts, a plot of the SPI over time at all durations in the analysis was created. Figure A.1 of the Appendix shows the multi-duration SPI plot for the Portland group of stations.

Figure A.1 clearly identifies the dry periods in the redder colors, making the droughts relatively easy to identify. As expected, the drought severity varies according to the analysis duration of interest. Some droughts are short and intense, while others remain severe even at longer durations.

Using the multiple duration SPI chart, six potentially critical drought periods can be identified. Table 5 displays the most severe 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 critical (i.e. most negative) within each drought period.

The most negative SPI value for each duration is highlighted in bold red text, and the most severe duration for each individual drought (i.e. each row) is underlined and has an orange background. Cells are marked with “--" when the SPI values fall out of approximately the 10% of most severe droughts for the duration. (Or in the case of 1930-1934 drought, the longer durations are left blank because the record did not start early enough to meaningfully include these long durations.)

Table 5 - Critical 3 to 60 months duration SPI values for droughts at Portland, TN

Drought	3	6	9	12	15	18	24	30	36	42	48	54	60
1930-1934	-3.15	-3.14	**-3.07**	**-3.62**	**-3.17**	**-3.06**	-2.22	-1.48	-1.61	- -	- -	- -	- -
1941-1946	-2.69	-3.09	-2.71	-2.19	-2.28	-2.23	**-2.61**	-2.28	-2.41	**-2.56**	-2.46	**-2.53**	-2.38
1953-1958	**-3.64**	**-3.39**	-2.44	-2.4	-2.33	-2.4	-2.5	**-2.39**	**-2.60**	-2.47	**-2.7**	-2.44	**-2.49**
1963-1966	-2.4	-2.53	-1.99	-1.78	-2.10	-1.84	-1.76	-1.72	-1.52	-1.53	-1.65	-1.54	-1.51
1986-1988	-2.77	-2.36	-2.15	-1.95	-2.21	-1.95	-1.59	-1.45	-1.50	-1.99	-1.55	-1.17	-0.87
2007-2008	-1.89	-2.49	-2.21	-1.75	-1.52	-1.54	-1.79	-1.66	-0.99	- -	- -	- -	- -

Table 5 indicates that for the Lebanon area, the droughts of the early 1930s, early 1940s, and mid 1950s are the most severe in the period of record for the majority of durations. In general, it appears the region’s droughts reach their most severe SPI values at shorter durations of 3-6 months. SPI values, however, are not entirely comparable across durations because the sample size for a 3-month SPI is greater than a 9-month SPI (by six), so more severe droughts at longer periods may not show SPI values of the same magnitude as shorter duration droughts.

The 1930s drought appears to be the most severe for the 9 to 18 month durations, which are likely to be important for small reservoirs in relatively wet climate zones such as the study area. Unfortunately, the longer duration drought results were not very representative for the early 1930s drought since the period of record began in 1928. Even without the record extending back before 1928, the 9-18 month duration results establish the early 1930s drought as a strong candidate for most severe drought.

The other drought with potential to be most severe at short durations is the drought of the mid 1950s. This drought is the most severe drought at the 3 and 6 month durations, and again at some of the longer durations (i.e. 30+ months). The 1940s drought is the most severe relative to the other droughts at several of the longer durations, though its most severe SPI value of -3.09 occurs at the 6-month duration.

Notably, the drought of 2007-2008, though indeed severe, is not the most severe drought at any duration as measured by SPI value. Of course, the longer duration SPI values could become more severe again if the remainder of 2009 and future years are dry. The rain in 2008 and 2009 seems to have mostly abated the drought at longer durations, though.

Thus, by this analysis, while the drought of 2007-2008 was a severe drought, it is clear the region has experienced considerably more severe droughts in the past, notably in the 1930s , 1940s and 1950s. Water sources that did not fail during the recent drought may still be vulnerable if a drought more similar to the most severe droughts in the record occurs.

Accordingly, it is imperative that conditions as severe as those in the 1930s, 1940s, and 1950s be incorporated into analyses of yield for the various water sources.

4.1.2. Lebanon Group

The Lebanon group of stations is located at the southeastern edge of the study area, and is closer to the intakes on Old Hickory Lake. While the precipitation record extends back to 1928, all data before 1948 is monthly data only. Figure A.2 in the Appendix displays the multiple duration SPI chart for the Lebanon group of stations.

In general, the dry and wet periods seem to match quite well with the Portland Group, but there are some differences in severity among the droughts. Notably, the droughts of the 1980s are slightly more severe and have sharper distinctions between short-term wet and dry periods. Table 6 displays eight of the most severe droughts in the period of record at the Lebanon stations. The SPI values reported in the table are the most critical (i.e. most negative) within each drought period. The most negative SPI value for each duration is highlighted in bold red text, and the most severe duration for each individual drought (i.e. each row) is underlined and has an orange background.

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

Drought	3	6	9	12	15	18	24	30	36	42	48	54	60
1930-1934	-1.97	-2.13	-2.36	-2.45	**-2.64**	-2.26	-2.35	-1.87	-1.24	-1.43	- -	- -	- -
1936-1939	-3.1	-1.88	-2.05	-1.77	-1.71	-1.58	-1.43	-1.55	-1.53	- -	- -	- -	- -
1941-1945	-3.1	**-3.15**	**-3.25**	**-3.05**	-2.49	**-2.55**	**-2.78**	**-2.33**	**-2.47**	-2.18	-2.23	**-2.06**	**-2.13**
1947-1950	-2.6	-2.98	-1.74	-1.65	-1.54	-1.62	- -	- -	- -	- -	- -	- -	- -
1953-1956	-3.27	-2.69	-1.89	-2.09	-2.18	-2.22	-1.75	-2.1	-1.99	- -	- -	- -	- -
1986-1988	-3.11	-2.75	-3.13	-2.37	-1.82	-2.01	-1.37	-1.79	-1.47	-1.77	- -	- -	- -
1998-2000	**-3.29**	-1.65	-1.64	-1.51	-1.57	- -	- -	- -	- -	- -	- -	- -	- -
2007-2009	-2.63	-2.35	-2.47	-2.21	-2.14	-2.1	-2.28	-2.33	-2.28	**-2.38**	**-2.36**	-2.02	-1.9

The most severe droughts in Lebanon fall into generally two categories. The first category is characterized by short, but very intense droughts, which reach their greatest severity at 3 or 6 months, but then rapidly taper off. The droughts of 1998-2000, the late 1940s, the late 1930s, and to a lesser extent the late 1980s fall into this category. The other droughts are the more sustained severe droughts whose intensity varies over durations, and don't drop as rapidly in severity at longer durations.

To some extent, the mid 1950s and early 1930s droughts fall into this category. The early 1930s drought is the most severe drought at the 15 month duration. The 2007-2008 and early 1940s drought have even more sustained severity. The 1940s is an excellent candidate for the most severe overall drought for Lebanon since it has the most severe SPI values at 9 of the 13 durations tested.

One major difference between the Lebanon and Portland Stations is that the 2007-2009 is comparatively more severe in Lebanon. It is possible that the 2007-2008 drought was indeed slightly more severe in Lebanon. It is equally likely, however, that the historical droughts were also experienced differently in Lebanon than in Portland. Notably, the 1940s and 1950s droughts do not show the persistence at long durations that they do in Portland. This comparative difference may also contribute to the severe SPI values at long durations for the 2007-2008 drought at Lebanon because the other droughts were less severe at these durations.

The reasons for the differences between the Lebanon and Portland station groups are not clear, and may be a result of random variations. It is also quite possibly that geography, and the associated localized differences in climate may play a role as well. Lebanon is located in the middle of the northern portion of the basin surrounded by the Highland Rim. Portland is located north of the Highland Rim and has less mountainous land extending to the North and East. Though only roughly 25 miles apart, the differences in the geography (and topology) of the stations may have an effect on storm tracks and rainfall patterns that is significant enough to alter the relative severity of individual droughts.

5. Conclusion and Continuation

The North Central region of Tennessee, though generally wet compared to the nation as a whole, has experienced severe drought conditions several times over the past 100 years, and most recently in 2007.

The regional drought analysis using the Standardized Precipitation Index showed that drought severity varies according to the analysis duration, and that it is not possible to identify any single drought as the most severe at all durations. The SPI analysis did identify several droughts that are likely to be the critical drought for a variety of water sources.

Notably, the droughts of the early 1930s, mid 1950s, 2007-2008, and especially the mid 1940s appear to have the greatest potential to be critical droughts for various types of water sources. For reservoirs, the best way to determine the actual critical drought is to run a sequent peak analysis of the reservoir's inflows for the entire period of record. Based on this drought evaluation, it is important that the period of record at least stretch back to before 1930. Since records of reservoir operations are unlikely to cover this entire period, hydrologic models will need to be created to generate estimates of inflow to reservoirs based on precipitation.

Additionally, it appears that the comparative severity of droughts may vary somewhat by location, so when building hydrologic models, it is important to select precipitation gages that best represent the particular area being studied.

6. References

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.

TDEC, 2009. *Drought Management Plan.* Tennessee Department of Environment and Conservation. February, 2009.