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GKY & Associates, Inc.

Cumberland County Regional Water Supply Study

Drought Identification and

Existing Sources Yield Analysis

Final Report

CUMBERLAND COUNTY REGIONAL WATER SUPPLY STUDY

Drought Identification and
Existing Sources Yield Analysis

FINAL REPORT

Prepared by
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Chantilly, VA

in cooperation with

U.S. Army Engineers District, Nashville
Corps of Engineers
Nashville, TN

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**US Army Corps
of Engineers.**
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Cumberland County Regional Water Supply Study

Drought Identification and Existing Source Yield Analysis

Introduction

This report presents an analysis of Cumberland County's existing water supplies in two parts. First, the meteorological records of Cumberland County are examined to determine the drought of record and the relative severity of the 2007-2008 drought. Second, the existing yields of Cumberland County's three primary reservoirs (Lake Holiday, Meadow Park Lake, and Otter Creek Lake) are investigated. Cumberland County, located on a high plateau, depends on these three sources for the large majority of its publicly supplied water. Other sources used in the County include water purchased from other counties and ground water wells. The scope of this study is limited to the three reservoirs indicated in Figure 1.

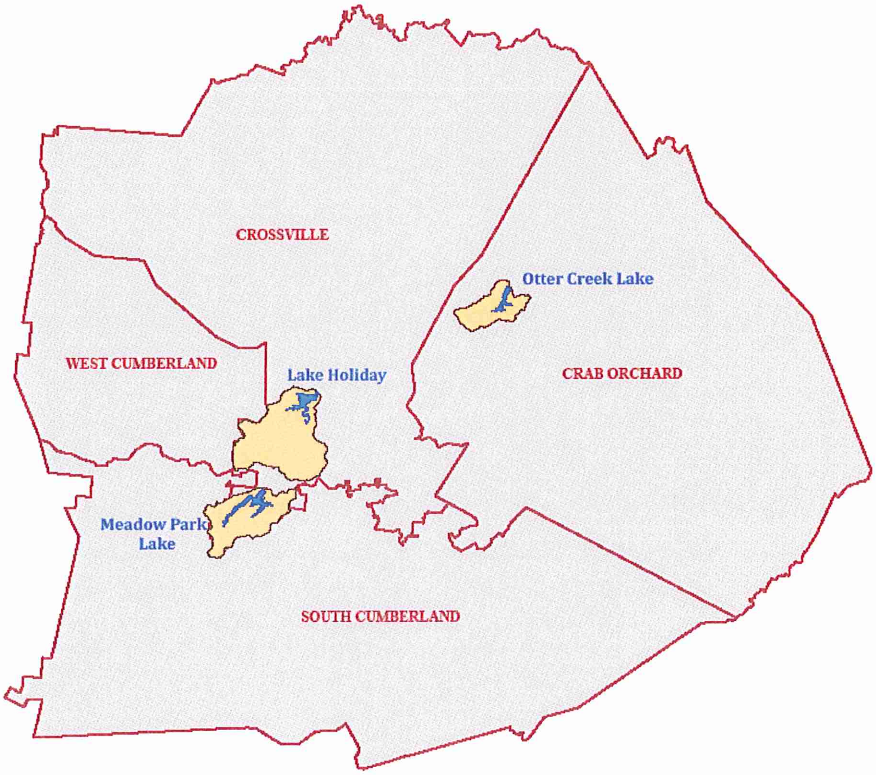


Figure 1 - Three primary reservoirs in Cumberland County, their watersheds, and utility district boundaries

Figure 1 presents the three reservoirs with their surface area indicated in blue and contributing watershed area in tan. The utility district boundaries are shown in red. Lake Holiday and Meadow Park Lake are operated by the City of Crossville Utility District, which sells water to the South Cumberland Utility District, and has contracts to sell to West Cumberland and other utility districts when needed. Crab Orchard Utility District operates the Otter Creek Lake source.

Drought Identification

1. Drought Identification in Cumberland County

As Cumberland County continues to grow, it approaches to a situation where existing water supplies may be exhausted in dry years. In 2007, Cumberland County endured a particularly harsh drought, severe enough to force the utility districts to enact a broad range of water use restrictions. The extremely low reservoir levels in the County were likely a result of both increased water demand and one of the lowest rainfall periods on record. While the severe drought tested the water supplies of Cumberland County, it did not result in reservoir failure. It has not been determined; however, just how severe this drought was in comparison to previous ones.

Instead of determining the chance of failure for the 2007 case, it is perhaps better to reexamine the firm yields of the reservoirs. The first step in re-evaluating the yield is to determine the critical drought period that causes the conditions that control the firm yield. 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, and just barely empties, but does not fail.

Since streamflow gage records are not available at the Cumberland County reservoirs, the starting point for critical drought analysis must be from other meteorological conditions. There are several widely used indices of drought severity, notably the Palmer Drought Severity Index, Crop Moisture Index, Standardized Precipitation Index and Decile Method, among others.

The characteristics of Cumberland County's location, climate, and water sources make some drought indices more applicable than others. Cumberland County sits on a high plateau in East Central Tennessee, and as result, the great majority of its water comes directly from rainfall within the county. As a headwater region, there are no very large lakes or reservoirs, no major rivers, and rarely any snowpack, 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 Cumberland County. Though there is certainly agriculture in the County, 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 mountainous regions, and are difficult to analyze on multiple time scales. Furthermore, this study is concerned with Cumberland County's water supplies, and not with agricultural production. Thus, considering Cumberland County's hydrology, a flexible precipitation based metric such as the Standardized Precipitation Index is best suited for identifying meteorological drought conditions.

The Standardized Precipitation Index (SPI) method is selected for drought identification in this study. The following sections describe the SPI methodology, application of the SPI to precipitation data for Cumberland County and the SPI results for Cumberland County.

2. Standardized Precipitation Index

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 any rainfall data collection frequency, 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 (for the same duration) in the record. For a 3-month duration SPI, the index value for each month in the time series is reflective of the probability of occurrence of the total precipitation for the current month and the two previous months compared against every other three month precipitation sum in the historical record. For the remainder of this drought identification section, duration refers to the analysis duration.

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 are fitted to a normal distribution, and the score 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).

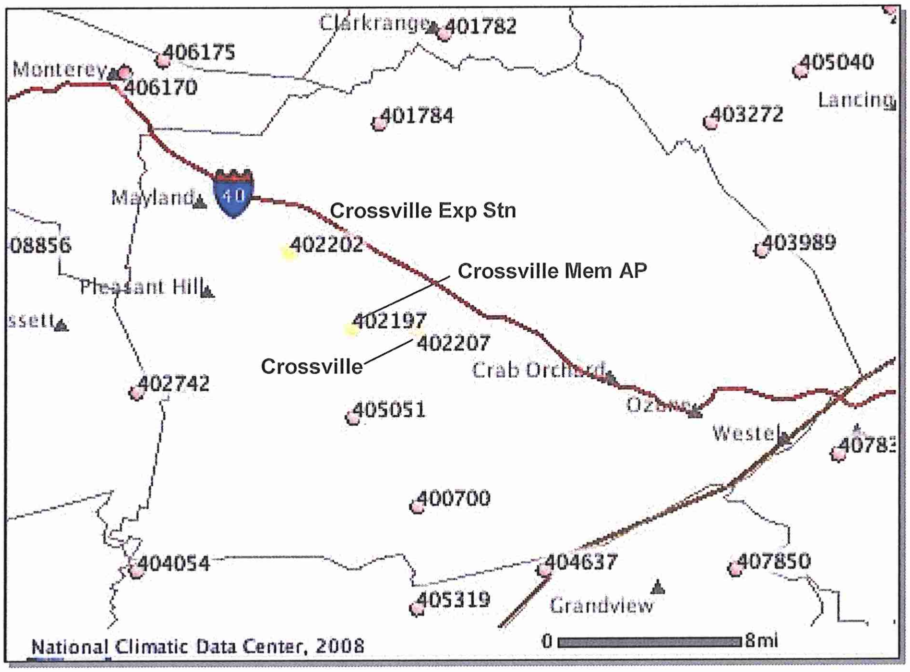
3. Computing the SPI in Cumberland County

It was not known at which duration the critical drought for Cumberland County occurs. 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, and 48 month durations. It was hypothesized the critical drought would be in the 6 – 18 month range. Especially when computing the SPI at long durations, it is important to have a long, complete monthly precipitation record.

Due to Cumberland County's location on a plateau in a mountainous region with moderate topographic influence, the precipitation records should be from stations located within or in very close proximity to Cumberland County. Three stations, identified in Table 2, were considered for use in an SPI analysis. The *Crossville* station is considered as an earlier extension to the *Crossville Mem Ap* station's record. Thus, the combined record covers the period from 1949 to 2008. Their locations are identified in Figure 2. Stations can be identified on the map by their COOP ID number.

Table 2 - Precipitation gages considered for SPI analysis

Station	COOP ID	County	Lat/Long	Period of Record	Elevation
CROSSVILLE Ed & Research (also, CROSSVILLE EXP STN)	402202	Cumberland	36°01'N / 85°08'W	1913-2008	1810'
Crossville Mem AP	402197	Cumberland	35°57'N / 85°05'W	1954-2008	1867'
Crossville	*402207*	*Cumberland*	*35°57'N / 85°02'W*	*1949-1954*	*1850'*



National Climatic Data Center, 2008

Figure 2 - Map of Selected Stations in Cumberland County

SPI analyses were completed for two stations: CROSSVILLE EXP STN, and CROSSVILLE MEM AP (with 5 years from CROSSVILLE 402207). The CROSSVILLE EXP STN was the more valuable station as the record is nearly twice as long. This report details the results for the CROSSVILLE EXP STN, but the full results from the CROSSVILLE MEM AP station are in the Drought Identification Memo in the addenda.

The total record of the Crossville Exp Stn spans from September 1913 to May 2008. Precipitation for 19 months out of a total of 1108 was computed based on other stations. The Drought Identification memo in the addenda details the nearby, auxiliary stations used to fill in the gaps in the monthly precipitation, and the methods for doing so. Table 3 contains summary statistics for Crossville Exp Stn. March is the month with the highest average precipitation, while October has the lowest average.

Table 3 - Summary statistics for Cumberland County precipitation (Monthly, in inches unless otherwise noted)

Station:	CROSSVILLE EXP STN
Yearly Average (in)	57.11
Mean	4.76
Median	4.36
Standard Deviation	2.50
Coefficient of Variation	0.53
Minimum Month	0.00
Maximum Month	16.73
March Mean	5.60
October Mean	3.14
Record Length (mo.)	1108

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 index reports drought periods as a normalized Z-score, the dry periods can easily be identified because the SPI value is negative. The results for the Crossville Exp Stn follow.

Crossville Education and Research Station (CROSSVILLE EXP STN)

As a preliminary tool for rapid evaluation of the most critical droughts, a plot of the SPI over time at all durations in the analysis was created. Figure A.1 (Appendix A, end of document) displays a surface plot with time (months) along the vertical axis, the duration of analysis on the horizontal axis and the SPI value indicated on the legend. The wettest periods are denoted by dark blue, while the driest are shown in deep red.

Figure A.1 clearly identifies the dry periods in the redder colors. Interestingly, while the droughts are relatively easy to identify, their severity varies according to the duration of interest. Some droughts are short and intense, while others do not become severe until the longer durations. For instance, the drought of 1952 was very intense, but ended fairly quickly with higher rainfall, whereas a series of smaller droughts in the late 1980s contributed to a rather serious drought at the 42 month duration.

Using the multiple duration SPI chart, seven potentially critical droughts were identified. Table 4 displays the most critical SPI values at various durations for the seven droughts. The approximate time periods of the most critical 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 (within each column) is highlighted in bold, and the most critical duration for each individual drought (i.e. within each row) is indicated in italics.

Table 4 - Critical 3 to 48 months duration SPI values for droughts at Crossville Exp Stn

Drought	3	6	9	12	15	18	24	30	36	42	48
1924-1926	-2.49	-2.71	-2.73	**-2.83**	***-2.86***	-2.53	-2.69	-2.49	-2.41	-2.22	-2.01
1930-1934	-2.18	-2.25	-2.38	-2.55	***-2.86***	**-2.81**	**-2.77**	-2.45	-2.39	-2.28	**-2.59**
1940-1942	**-2.66**	***-2.92***	-2.53	-2.48	-2.37	-2.57	-2.48	**-2.59**	**-2.62**	-2.16	-2.14
1952-1953	-2.54	-2.89	***-2.95***	-2.21	-1.78	-2.14	-1.93	-1.94	-	-	-
1980-1982	-2.1	-2.44	*-2.82*	-2.51	-2.03	-1.83	-	-	-	-	-
1986-1988	-1.8	-1.99	*-2.35*	-2.11	-2.18	-2.25	-1.74	-2.03	-1.94	**-2.33**	-2
2006-2008	-2	-2.17	-2.55	*-2.56*	-2.18	-2.18	-1.91	-1.83	-1.9	-	-

Table 4 indicates the difficulty in identifying a single most critical drought. By SPI value alone, the 1952-1953 drought at the nine month duration appears to be the most severe. 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) given the same record, so more critical droughts at longer periods may not show as impressive SPI values as shorter duration droughts. Nonetheless, it is potentially significant that all seven droughts report their most critical SPI values at durations between 6 and 15 months. Additionally, no less than five drought periods can claim to have the most severe drought at some duration. The two remaining droughts have the second most critical SPI value for at least one duration.

Notably, the drought of 2007, though indeed severe, was not the most severe drought at any duration as measured by SPI value. Of course, the longer duration SPI values could become more critical if the remainder of 2008 and future years are dry.

The SPI can easily be used to determine meteorological drought length. The drought length is simply the number of consecutive months the SPI, computed at any duration, is continuously negative. Additionally, at least one month in the period must have an SPI value of -1 or less.

Table 5 illustrates how the drought length is calculated. The 1952-1953 drought is selected as a sample case. The computed SPI values for the 3 and 6 month SPI durations for each month are displayed. Yellow indicates negative SPI values. The drought begins when the SPI values become negative. So the drought begins in April 1952 at the 3 month duration, and June 1952 at the 6 month duration. Orange shading highlights the first month the drought has an SPI below -1. This is the qualification for being a true drought instead of simply a mild dry spell. The number of consecutive months the SPI values remain negative (are still yellow) is the drought length. In Table 5, the 3-month duration SPI has a drought length of 10 months, while the 6-month duration has a length of 11 months.

Table 5 - Computation of drought length for the 3, 6 month duration SPI in the 1952-1953 drought

Month	Year	3m SPI	6m SPI
3	1952	0.38	1.37
4	1952	-0.66	1.17
5	1952	-0.53	0.54
6	1952	-1.51	-0.62
7	1952	-1.76	-1.64
8	1952	-2.1	-1.78
9	1952	**-2.54**	-2.65
10	1952	-2.35	**-2.89**
11	1952	-1.44	-2.85
12	1952	-1.21	-2.64
1	1953	-0.35	-1.58
2	1953	0.12	-0.83
3	1953	0.15	-0.69
4	1953	0.34	-0.07
5	1953	0.06	0.06

Using this approach, Table 6 presents the drought length of all of the major droughts as identified by their patterns SPI scores. At the bottom, the average dry spell length is presented. (Dry spells are identified when the SPI value is continuously negative, though it need not reach -1 as in a drought.)

The drought years identified in the left column are a rough indication of periods during which the driest weather occurred. At long SPI durations, the drought length may be quite long, as it may take several months (or even years) of above average precipitation to return the SPI value to being positive after a prolonged dry spell. Additionally, the longer durations allow smaller dry periods to extend the drought length after major droughts.

Table 6 is useful for assessing drought length, but it should be noted that the observed drought length is only slightly correlated with the critical SPI value for each duration. Additionally, the 2007 drought has not yet abated for durations from 6 to 48 months, so the reported lengths could lengthen depending on future rainfall. Ongoing droughts are indicated in *italics.*

Table 6 - Drought length (months) at 3 - 48 months durations at Crossville Exp Stn

Drought	3	6	9	12	15	18	24	30	36	42	48
1924-1926	16	34	38	40	37	37	37	38	47	51	55
1930-1934	24	23	25	81	79	85	95	98	103	169	173
1940-1942	15	35	33	33	34	37	44	62	58		
1952-1953	10	11	11	30	32	32	39	44	47	43	47
1980-1982	12	16	16	18	20	23	24	29	37	38	43
1986-1988	18	17	17	44	41	42	39	41	39	42	34
2006-2008	11	*19*	*17*	*19*	*19*	*24*	*19*	*16*	*15*	*15*	*12*
Avg. Dry Spell Length	**4.1**	**5.8**	**8.0**	**9.0**	**10.3**	**10.0**	**11.8**	**17.0**	**19.2**	**21.2**	**15.3**

The average length of the droughts has a strong relationship with the duration at which the SPI is calculated. This is unsurprising, since the SPI is calculated based on the rainfall total in the duration of analysis, and therefore smaller, shorter dry and wet periods get smoothed out. At long enough durations, the drought length may include several smaller droughts. The 1930s drought is an excellent example. Based on the 42 or 48 month SPI, the drought of the early 1930s would seem to extend to 1945. (The drought length is spread across the two accordingly in Table 6.) In fact, there were several shorter droughts (e.g. the 1940 -1942 drought) in that period, and the wet periods were simply not wet enough to end the long term drought. The Drought Identification Memo analyzes the wet-dry transitions and the lengthening of droughts at longer analysis durations in much greater detail.

5. SPI Conclusions

Cumberland County, TN, 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. Cumberland County's location on the top of a plateau makes its water supply vulnerable during long periods of lower than normal precipitation. Determining the firm yield of the existing water supplies must start with an analysis of historic precipitation records to help identify the most severe drought.

The Standardized Precipitation Index was used to identify the particularly dry periods in Cumberland County's rainfall record. The CROSSVILLE EXP STN gage, with over 90 years of monthly records, is the primary basis for analysis. The CROSSVILLE MEM AP gage was used for cross validation. The SPI was calculated at durations ranging from 3 to 48 months.

By using the SPI, seven potentially critical droughts have been identified. The most severe drought 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 1925 – 1926, 1930 – 1934, 1940 – 1942, and 1952 – 1953 appear the most likely to be the critical drought. The 2007 drought closely follows, and may yet prove to be the critical drought since it has not yet fully abated according to the SPI analysis. No single drought however, was the most severe at all of these durations based on the SPI analysis alone.

Therefore, to identify the critical drought sequence for each water supply reservoir, a sequent peak analysis will have to be performed 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. In the next section, simulated streamflow generated in HEC-HMS using the Crossville Exp Stn daily rainfall record is used as the hydrologic input.

The timing of the critical drought for each reservoir depends in part on the hydrology, but also on the characteristics of the reservoir including the ratio of surface area to watershed area, and importantly, the amount of storage capacity in relation to the average inflow.

Existing Reservoir Yield Analysis

1. Introduction

In the previous section, a drought identification exercise was performed to investigate the severity of the 2007 drought relative to the other major historical droughts. While it was found that the 2007 drought was not likely to be the drought of record, it remains unclear which drought is the critical drought for the Cumberland County reservoirs. The drought identification exercise identified several droughts that could be the most severe depending on the drought duration considered.

This yield analysis attempts to resolve the issue of which drought is critical for each of the reservoirs and then determine the firm yield for each. The analysis is complicated somewhat, however, by the lack of historical records pertaining to the reservoirs' inflows, withdrawals, overflows and water levels. Thus, the general methodology involved generating simulated historical inflow sequences based on precipitation data using HEC-HMS. Those inflows were then used in a traditional sequent peak analysis to solve for the firm yield. Considering that there is some ambiguity about the available storage in each reservoir, storage-yield curves were generated as a useful tool.

2. Reservoir Description

Cumberland County's three primary reservoirs (Lake Holiday, Meadow Park Lake, and Otter Creek Lake) have all been remarkably reliable over their history; they have never been in failure. Still, there is a great deal of uncertainty about the characteristics of the County's reservoirs and their firm yields.

The first set of discrepancies is related to the storage capacity. For the purpose of this analysis, storage capacity reflects the amount of storage actually available for withdrawal, if it is possible to obtain this information. That is, if the water intakes are 10 feet from the bottom of the lake, the bottom 10 feet of the lake will not be included in the storage capacity estimate. Current and prior storage capacity estimates vary widely for the three lakes.

The physical parameters of the reservoirs and their watersheds are listed in Table 1. Watershed delineations were performed in ArcHydro using DEMs created from Cumberland County's most recent 20-ft contours. A 2-ft contour layer was available, but elevations were not referenced, and the 2-ft contours were created from the 20-ft contours anyway, so no additional detail was to be gained from using them. After using ArcHydro to automatically perform the delineations, the boundaries were manually verified and corrected (slightly) using the County's contours, aerial photos and basin drainage boundaries in the National Hydrography Dataset (NHD) as a guide. The water surface area of the lakes was delineated manually using the water surface features from the NHD, water polygon areas in the SSURGO database, contours, and aerial photos as a guide. In general, the area calculations from the various sources were all found to be within approximately 5% of each other.

Establishing the storage volume for each reservoir is important for determining yield. An estimate of storage volume for Otter Creek Lake was provided by Crab Orchard Utility district. Storage volume for Meadow Park Lake was found in literature, but the Lake Holiday storage volume was unknown, and could not be provided at the time by Crossville Utility district. As a result, we contacted the TN Safe Dams program to check what estimates were available. Records were available for all three reservoirs. The Holiday Hills Dam is currently undergoing upgrades, and the cited Safe Dams estimate for Lake Holiday indicates what the storage (as well as surface area, pool elevation, etc.) will be when the upgrades are completed.

Consider Otter Creek Lake as an example. The Safe Dams records cite 227.8 million cubic feet (MMcf) as the storage, but Crab Orchard utility cites just 165.8. This discrepancy is most likely due to the Safe Dams perhaps using the Top of Dam elevations, and the other estimates reflecting normal pool elevation.

Crab Orchard utility provided reservoir plans from which an elevation-area table was created by using AutoCAD to digitize the contours. Using this information, a stage-storage table was created and the storage volume was calculated.

The calculated storage was 163.7 MMcf, which pretty closely matches the Crab Orchard estimate. It can't be easily determined why the current Safe Dams estimates appear so high, except if they used different contours or contours with different spacing. Or, their estimates may include storage to the top of dam or a different pool level.

Table 7 - Reservoir and watershed properties

		Lake Holiday	**Meadow Park Lake**	**Otter Creek Lake**
Total Storage	*MMcf*	302.6 (sd) 155.2 (ece)	187.3 (sd) 133.7 (l) (ece)	227.8 (sd) 163.7 (c) 165.8 (ud)
Available Storage	*MMcf*	133.4 (ece)	102.4 (ece)	83.69 (c)
	MG	998.2 (ece)	765.68 (ece)	625.97 (c)
Lake Surface	*ac*	223 (g) 230 (sd)	260 (g) 255 (l) 274 (sd)	115.85 (g), 120 (sd)
Watershed area	*sq mi*	8.46 (g) 8.14(l)	5.10 (g) 5.19 (l)	2.78 (g)
Normal Pool (elev)	*ft*	1768.38 (sd) 1761.28 (ece)	1817.5 (sd) 1817.5 (l)	1775 (sd)
Low Intake (elev)	*ft*	1742 (ece)	1806.5 (ece)	1755 (ud)
Sediment Pool	*ft*	1740 (sd)	1789.5 (sd)	1690 (sd)

Legend		
	(sd)	most recent TN Safe Dams estimate
	(g)	computed in GIS
	(c)	computed from plan/other data
	(ud)	estimate from utility district
	(l)	value found in literature/previous studies
	(ece)	provided by Environmental and Civil Engineering Consultants

Perhaps more important to the study of the lakes as water supply sources is the amount of available storage for water supply. For the purposes of this study, the available storage is determined by calculating the volume of water that can be held above the elevation of the lowest intake that is used for water supply and below the invert of the lowest uncontrolled spillway (usually well approximated by the normal pool). Using available storage is important because it excludes the storage volume that can't be reached by the utility's intakes. The available storage estimates for Lake Holiday and Meadow Park Lake were calculated based on the stage-storage information and intake elevations provided by Environmental and Civil Engineering Services. These figures include the modifications to the Holiday Hills Dam on Lake Holiday. The intake elevation on Otter Creek Lake was provided by Crab Orchard Utility District, and the available storage was calculated from the stage-storage information that was computed from the plans.

The firm yield was calculated for both the available and overall storage estimates. The available storage volume selected were 133.4 MMcf for Lake Holiday, 102.4 MMcf for Meadow Park Lake and 83.69 MMcf for Otter Creek Lake, or 998.2, 765.68, and 625.97 MG, respectively. The overall storage values selected were 155.2 MMcf for Lake Holiday, 133.7 MMcf for Meadow Park Lake, and 163.7 MMcf for Otter Creek Lake, or 1161, 1000, and 1224 million gallons, respectively. These represent the most conservative storage estimates for each lake.

3. Methods

The main objective of this study is to determine the firm yields for the three primary Cumberland County reservoirs. It is not clear which methods were used in the past to determine the reservoir firm yields in Cumberland County, but there is a great deal of variation in the estimates.

Computing the firm yield for the three reservoirs was essentially a three step process:

1. Created hydrologic models of the reservoir watersheds, and used them to generate a synthetic inflow sequence based on an input of Crossville's historical precipitation record.

2. Used the sequent peak algorithm to analyze the inflow sequence and identify the critical drought.

3. Re-ran the hydrologic model for the critical drought period only, with appropriately adjusted parameters (evaporation). Then, the sequent peak algorithm was used to compute firm yield.

3.1. HEC-HMS

The HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System) model was used for a very limited and specific purpose in this application. The model was used only to transform historical rainfall values into the inflow sequences for the three watersheds. Though the HEC-HMS model is often used to compute peak flows, this study is not concerned with peak flow, as droughts are the hydrologic phenomenon of interest. As such, matching total daily volume of flow was much more important than matching the peaks.

The model set-up was somewhat atypical to capture the effects of drought on the watershed and reservoir. The following sub-sections describe the assumptions and parameterization used to build the HEC-HMS model. For this study, the most important model specifications were contained in either the Meteorological Model or the Basin Model.

3.1.1. Meteorological Model

The HEC-HMS model requires precipitation data at a daily or finer timescale. The Crossville Exp Stn precipitation gage has been recording daily precipitation values nearly continuously for over 95 years. A record length extending from September 1, 1913 to August 31, 2008 was used in this model.

Data gaps were filled with daily precipitation values from nearby stations with concurrent records. Wherever, possible, the nearby Crossville Mem Ap station was used to substitute values. In the time period before 1950, missing values were filled in from other nearby stations. When more than one station had a sufficient record to substitute values, the decision of which station to use was made first based on distance from Crossville. Elevation was also considered when two stations were roughly the same distance away.

Constant monthly evaporation was chosen as the evaporation method in the meteorological model ("Met model" in HEC-HMS). Expressed in inches per month, the evaporation rate (in addition to the constant infiltration rate) controls the rate at which water exits the single soil layer. The rate was specified by month, and each month has a constant rate for the entire simulation period. Pan evaporation data for the Crossville Exp Stn gage were used to determine the average monthly rates. The pan coefficient was assumed to be 0.7.

3.1.2. Basin Model

The Basin model for each reservoir specifies the size and hydrologic connectivity of the subbasins, the loss method, routing and storage effects, and base flow.

The goal of the HEC-HMS modeling was to generate a daily streamflow sequence for each reservoir. This study uses a simple basin set-up. Each reservoir's watershed was modeled as two subbasins. One modeled the effect of the lake's surface, and the other the remaining area in the watershed.

Effectively, the HEC-HMS model is being used to generate a streamflow record for the catchment as if the reservoir were not there. There is a problem in that the water surface acts very differently than the land surface in the interception of precipitation and evaporation. In the case of very large reservoirs (e.g. Lake Powell), the lake surface is so small compared to the total catchment that these effects are insignificant. However, the Cumberland County reservoirs make up a significant portion (as much 9%) of the watershed area and these effects cannot be ignored.

When precipitation is occurring, the lake essentially acts an impervious surface, and all the rainfall is converted directly to runoff. At all other times, the lake acts as a ponded surface with significant open-water evaporation rates that are greater than those of the surrounding land.

The preferred model set-up is to model the lake as a separate subbasin, and include the rest of the catchment in a second subbasin. In this way, the lake surface was parameterized differently to account for the differences in runoff and evaporation. In HEC-HMS, the two subbasins (Watershed and Lake) were joined at a junction. The total flow to this junction represents the reservoir inflow, which is the flow sequence that is used for determining the critical drought sequence. Figure 3 shows the Watershed and Lake subbasin set-up. Note that the Watershed subbasin does not include the area of the Lake. Boundaries and backgrounds are shown for illustration only, and do not reflect actual an actual watershed and reservoir shape.

The watershed could be broken down further into multiple subbasins, but that was not done in this study for several reasons. Firstly, the watersheds for all three reservoirs were fairly small. A GIS analysis of the land-use types and soil characteristics demonstrated that the watersheds were fairly homogenous in those regards. Most importantly, the model is run at a daily time step, and one day is a sufficient amount of time for run-off from any point in the watershed to reach the outlet. Thus, storage effects of smaller subbasins would not be important.

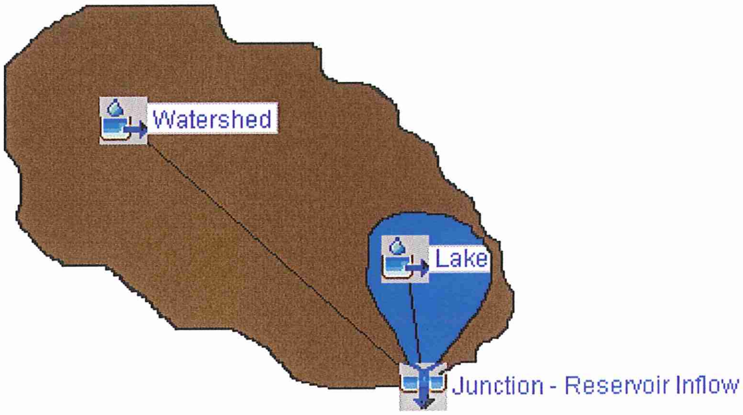


Figure 3 - Rough illustration of Basin Model set-up

After the subbasins were set up, the loss method was chosen. There are a limited number of options for running long term simulations at a daily time step in HEC-HMS. Essentially, the Deficit and Constant Loss method and the Soil Moisture Accounting method are the only potential loss methods for this study. The soil moisture accounting method is a complex model that requires a large number of parameters that are difficult to estimate with available data in the Cumberland County area. Therefore, the Deficit and Constant Loss method was chosen.

The Deficit and Constant Loss method is a very simple soil moisture tracking model. The surface soil layer is treated as a simple reservoir with two loss processes and one input. The soil layer is assumed to cover the entire subbasin with a uniform thickness. The soil layer thickness is characterized by the maximum depth, which is assumed to represent the available void space in the soil layer which can be occupied by water. Figure 4 shows a conceptual model of the single soil layer model

The soil layer loses water to deeper soil layers through infiltration. The soil layer can also lose water to evapotranspiration (ET). And of course, the soil layer receives water only through precipitation. When the soil layer is full, runoff occurs.

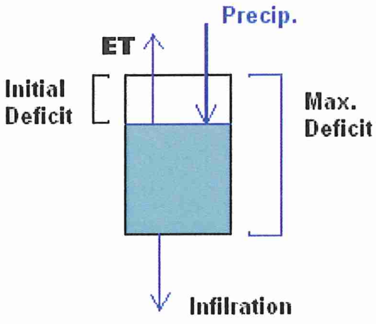


Figure 4 - Conceptual model of single soil layer "Deficit and Constant Loss" method

The constant baseflow method was selected as most applicable for this study. This method assumes constant baseflow within each month. While Eastern Tennessee has relatively little seasonality in its rainfall totals, there is a strong seasonal variation in its baseflow pattern. While there are no gages on the streams that feed the reservoirs of interest, streamflow data from several stream gages on other streams in Cumberland County and surrounding counties were downloaded from the United States Geological Survey (USGS). Using the streamflow records, the USGS's PART program was run to determine the baseflow, expressed as specific discharge (flow per unit of drainage area). No baseflow is assumed for the Lake subbasin in each reservoir's model.

The final consideration for the basin model is the Transform method used. The scope of services suggested using the ModClark method, which requires the watershed time of concentration, and storage coefficient be specified in hours. Watershed times of concentration (Tc) for the three reservoirs' watersheds were computed via the Kerby, Kirpich, and SCS equations and were found in all cases to be less than five hours. With the model time step of one day, this factor becomes insignificant, and the model has to automatically extend Tc to allow the model to run. Therefore, the Transform option was turned off as it proved insignificant. Since the HEC-HMS model is only used in this study to compute volume of runoff and not within-day timing or peak values, this is acceptable.

3.2. Calibration

Since long term, high-quality records of the reservoirs' inflows could not be obtained, calibrating to the reservoirs' actual data could not be performed. USGS's PART model, in addition to computing baseflow, also computes the monthly streamflow as specific discharge. The mean and median discharges for each month were computed from the stations whose records were used for the baseflow estimation. Though the streamflow records are fairly well distributed through the simulation time period, they are not distributed well enough to assume that the computed average (or quantile values) of discharge are good estimators of the true average because differences in rainfall have a large effect on the quantity of discharge. Therefore, to normalize these statistics, the runoff ratio is used instead of specific discharge. Runoff ratio is calculated by dividing a month's specific discharge by the total precipitation for the same month. Thus, the discharge from the stream gages, which are all near Cumberland County, is divided by precipitation from the Crossville Exp Stn.

The calibration strategy is to get the model's monthly mean and median runoff ratio to match that of the streamflow gages as closely as possible. As an example, Figure 5 displays the calibration results for Meadow Park Lake in comparison to the monthly median and average runoff ratio for the USGS streamflow gages. The model calibration was completed by adjusting the loss parameters for the watersheds and lakes. Once the loss parameters were adjusted as well as possible, the pan coefficients were adjusted slightly to fine tune the calibration fit. Figure 5 shows the calibration is generally good, especially considering the limitations of the modeling options chosen.

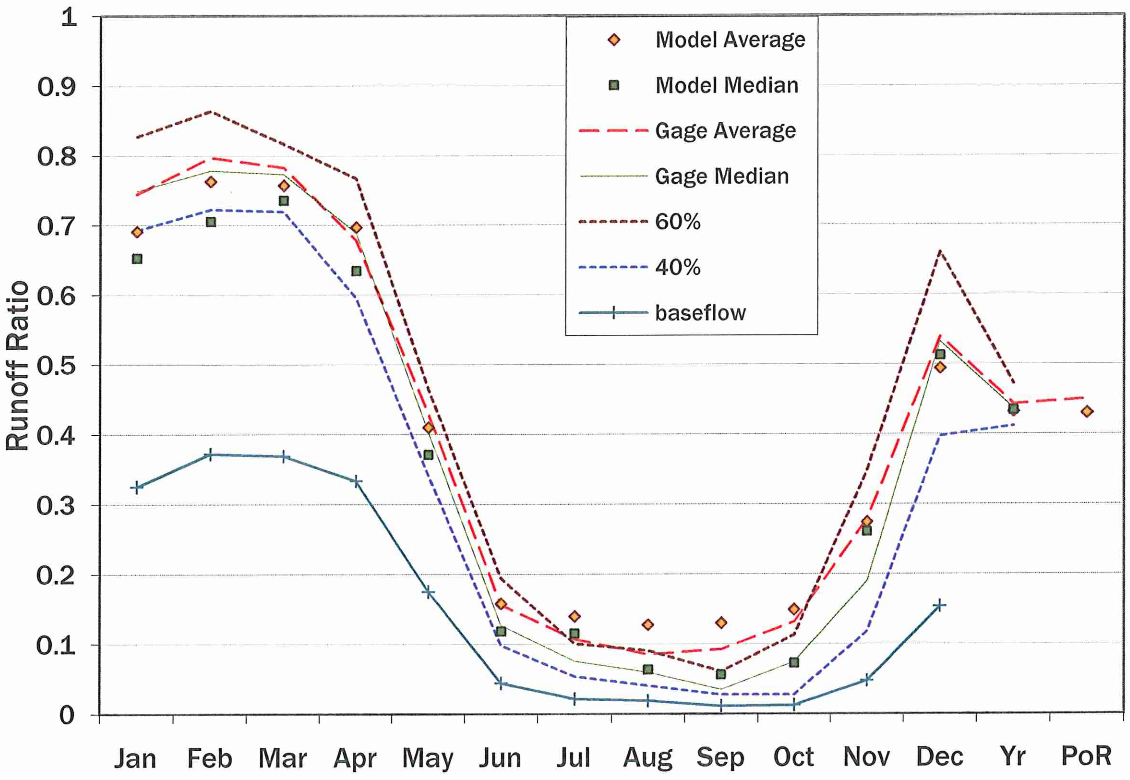


Figure 5 - Calibration chart comparing monthly average runoff ratio from the model and stream gages

Most notably, the runoff ratio for the entire period of record (PoR on the graph) was nearly a perfect match between the model and gage data. On the whole, the model values follow the general pattern of the runoff ratios month to month fairly well. The model medians drop below the model averages in the summer much as the gage medians and gage averages. The deficiencies in the calibration are that the winter months tend to somewhat underestimate the runoff ratios, while the summer months tend to overestimate, though by a lesser amount. The red and blue dotted lines indicate the 40th and 60th percentiles of the runoff ratios of the monthly USGS streamflow data to give some indication of the monthly variation in values. For the most part, either the model median, model average, or both fell within or very close to this range. Finally, the yearly total results (Yr on the graph) indicate that if anything, the model comes out as slightly conservative.

The next section goes over the calibrated parameter values for the loss method, and the monthly climate parameters.

3.3. Summary of Parameter Values

This section details the key model parameters for building the HEC-HMS models for this study. The areas of the lakes and watersheds were detailed in Section 2, and the areas as calculated by GIS (see (g) in Table 7) were used. Table 8 shows the Deficit and Constant Loss parameters for the watersheds and lakes. The first three data columns display the parameters of the watershed areas. The maximum deficit parameters were generated through calibration, but rough bounds on their values were first estimated by using Cumberland County data contained in the Natural Resources Conservation Service's Soil Survey Geographic (SSURGO) dataset. Since development in the reservoir watersheds is limited and varies over time, the imperviousness in the model was conservatively set to zero. Examination of aerial photos and parcel data showed that imperviousness was roughly 5% or less, and the majority of impervious areas were not directly connected. The HEC-HMS model, by contrast, treats all impervious areas as directly connected areas that contribute directly to flow on every rain event. Additionally, it was found that any imperviousness created significant problems in calibrating the summer flows.

The lake subbasins were assumed to behave similarly to each other, so they share a single data column. The maximum deficit is a reflection of the total number of inches of water that can be evaporated from the top of layer of soil if the soil were saturated to the ground surface. The maximum deficit places a limit on the amount on evaporation on the assumption that below a certain depth, the top layer of soil prevents solar radiation from causing further evaporation. Since a reservoir does not have any soil over its surface to block solar radiation from heat, even if the water levels drop, water can still be evaporated very easily. After several trials, it was found that eight inches was a sufficient maximum deficit to allow evaporation to occur as it would over a free surface.

A very small constant rate was assumed because no reservoir is completely sealed from ground water seepage.

Table 8 - Basin model → Deficit and Constant Loss parameters for the lakes and watersheds.

Parameter	Units	Lake Holiday Watershed	Meadow Park Lake Watershed	Otter Creek Lake Watershed	All "Lake" subbasins
Initial Deficit	*in.*	0.5	0.5	0.5	0
Maximum Deficit	*in.*	2.38	3.2	2.85	8
Constant Rate	*in./hr*	0.027	0.026	0.0265	0.005
Impervious %	*%*	0	0	0	0

Table 9 presents the values of the parameters that vary monthly. The monthly base flow which is specified in the Basin Model was only applied to the "watershed" subbasin within each reservoir's HEC-HMS model. (Groundwater can't contribute to flow when the lake's water neutralizes the hydraulic gradient necessary for it to come out of the ground.) The baseflow was specified in the model in CFS, but Table 9 gives the baseflow as specific discharge (inches over the watershed). The actual baseflow can be computed for each watershed by multiplying by the watershed area and making the appropriate time and length conversions.

The evaporation is part of the meteorological model and was input as constant monthly evaporation. The evaporation parameters were derived from 30 years of pan evaporation data at Crossville. As mentioned previously, the initial pan coefficient used in the model was 0.7.

Table 9 - Monthly baseflow and evaporation parameters used in the model

Month	Basin Model→ Monthly Baseflow (in.)	Met Model → Evaporation (in.)
Jan	1.78	0
Feb	1.89	0
Mar	2.15	0
Apr	1.60	4.75
May	0.84	5.38
Jun	0.20	5.75
Jul	0.11	6.28
Aug	0.08	5.50
Sep	0.04	4.38
Oct	0.04	3.20
Nov	0.21	1.00
Dec	0.85	0

3.4. Sequent Peak Algorithm to Identify Critical Drought

The HEC-HMS model provided daily runoff as an output, and from this, the sequent peak algorithm was used to develop an estimate for the yield the reservoir can support. The sequent peak algorithm is simply a cumulative tracking of the daily (or monthly, yearly, etc) water balance for a reservoir with known inflow and a specified demand pattern. For this study, the sequent peak algorithm was computed on a daily time step, as the HEC-HMS model output was also daily.

The sequent peak algorithm is based on Equation 1.

$$K_t = (D_t - Q_t) + K_{t-1}$$ **if Kt>0, else Kt=0** **Equation 1**

Where:
K_t is the cumulative deficit at time t
D_t is the demand at time t
Q_t is the inflow at time t
K_{t-1} is the cumulative deficit at time (t-1)

Essentially, equation 1 tracks the cumulative deficit at each time step. The rate of change in the deficit for each day is equal to the demand minus the inflow for that day. Adding that difference to the cumulative deficit of the previous day (K_{t-1}) gives the current day cumulative deficit (K_t). Typically, demand is assumed to be constant each day, though the algorithm allows for the demand to vary with time. For a firm yield study such as this one, demand remains constant. Table 10 depicts a sample sequent algorithm calculation for a five day period. Demand is assumed to be 10 (volumetric units/day).

Table 10 - Example Sequent Peak Algorithm calculation

Day	Demand (D_t)	Inflow (Q_t)	D_t-Q_t	Deficit (K_t)
1	10	6	4	4
2	10	2	8	12
3	10	1	9	21 (Max)
4	10	22	-12	9
5	10	24	-14	0

Table 10 shows the progression of the cumulative deficit. At time zero, it is assumed the deficit equals zero. At day 3, the maximum deficit of 21 is reached. At day 5, instead of the deficit being equal to negative 5, the cumulative deficit simply returns to zero.

The maximum value of 21 represents the storage capacity the example reservoir must have to support the given demand. For this example, if the reservoir has a storage capacity of 21, it can support a firm yield of 10 without failing. If the reservoir could only store 18 units, the demand would have to drop until the max cumulative deficit equals 18. Solving for demand in this case yields 9 units/day. Similarly, if storage were higher, the yield would increase. By varying demand over a wide spectrum of values, a relationship between the demand (yield) and the required storage can be found for the reservoir. This is the Storage-Yield relationship. Section 3.6 further investigates this relationship for the three reservoirs. The next section, 3.5, investigates the results of the daily sequent peak algorithm and computes estimates of firm yield for the three reservoirs.

3.5. Determining Yield in Cumberland County

For each of the three reservoirs, the initial estimate of the firm yield was generated by running the entire inflow sequence generated by HEC-HMS through the sequent peak algorithm. The yield was then varied until the maximum deficit equaled the available storage of the reservoir. This yield value is the initial estimate of the firm yield.

The sequent peak algorithm can provide information in addition to the firm yield. Plotting the daily cumulative deficit effectively shows the length of droughts, the characteristics of the critical drought sequence that contains the maximum deficit, and the severity of the less extreme droughts in comparison to the critical drought.

Figures B.1, B.2, and B.3 in Appendix B show the daily cumulative deficit for the full 95 year simulation period where the maximum deficit is equal to the best estimate of lake storage for Meadow Park Lake, Lake Holiday, and Otter Creek Lake, respectively.

These plots clearly illustrate how the critical drought builds to the maximum cumulative deficit. The *critical drought (or drawdown) sequence* is the portion of the plot between the last time the cumulative deficit equals zero before the maximum value and the time the deficit reaches the maximum value. All three lakes reach a maximum deficit in early December, 1931, and have a critical drought sequence that is approximately 19 months long. The critical drought sequences have another interesting property in that they all start with a very rapid ascent in the summer and fall, and then have a winter and spring with very little refill. This first low point in the critical sequence is the highest yearly minimum point in a year after the reservoir started at a zero deficit. In all years except this one, the cumulative deficit returns to zero. For Lake Holiday, the point is denoted with a red diamond and marked with the deficit of 89. On the Otter Creek Lake plot, the comparable point is labeled as 228, but the second highest value for a comparable point occurred in the recent 2007 drought (see point labeled 103). Additionally, as of September 2008, none of the cumulative deficit plots show evidence of refill, which means the current drought would not be abated if the reservoirs were drawing at the their firm yields.

For a drought to be officially considered the critical drought, the cumulative deficit must return to zero. Otherwise, the drought sequence could continue to reach a still higher maximum within the same drought. The plots clearly demonstrate that this occurs for the 1930s drought. It seems unlikely that the drought in 2008 would become the critical drought for Otter Creek Lake given the abundant precipitation in late 2008 and 2009.

3.6. Storage-Yield Relationships in Cumberland County

The sequent peak algorithm is useful because it generates an estimate of the storage required to meet a given demand (yield). Running the sequent peak algorithm at many different yields generates a relationship between storage and yield for a 100% reliable condition. Figure 6 displays the storage yield curves for the three reservoirs in Cumberland County. The yield in MGD is displayed on the x-axis and the required storage to support that yield on the y-axis. The curve for each reservoir is indicated, along with the average inflow for the reservoir. Figure 7 shows a detailed view of the lower portion of the Storage-Yield curves.

The red diamonds on each curve show the best estimate of total storage in each reservoir. The green triangles indicate the available storage, and their x-coordinates represents the firm yield. The Storage-Yield curves are an excellent tool for analyzing the sensitivity of the yield to assumed storage. For example, if Meadow Park Lake's storage estimate was 100 million gallons too high, the yield would be reduced to about 3.8 from 4.02. Otter Creek Lake would not see such a big reduction in yield from the same storage decrease as the curve is steeper at its estimated storage capacity.

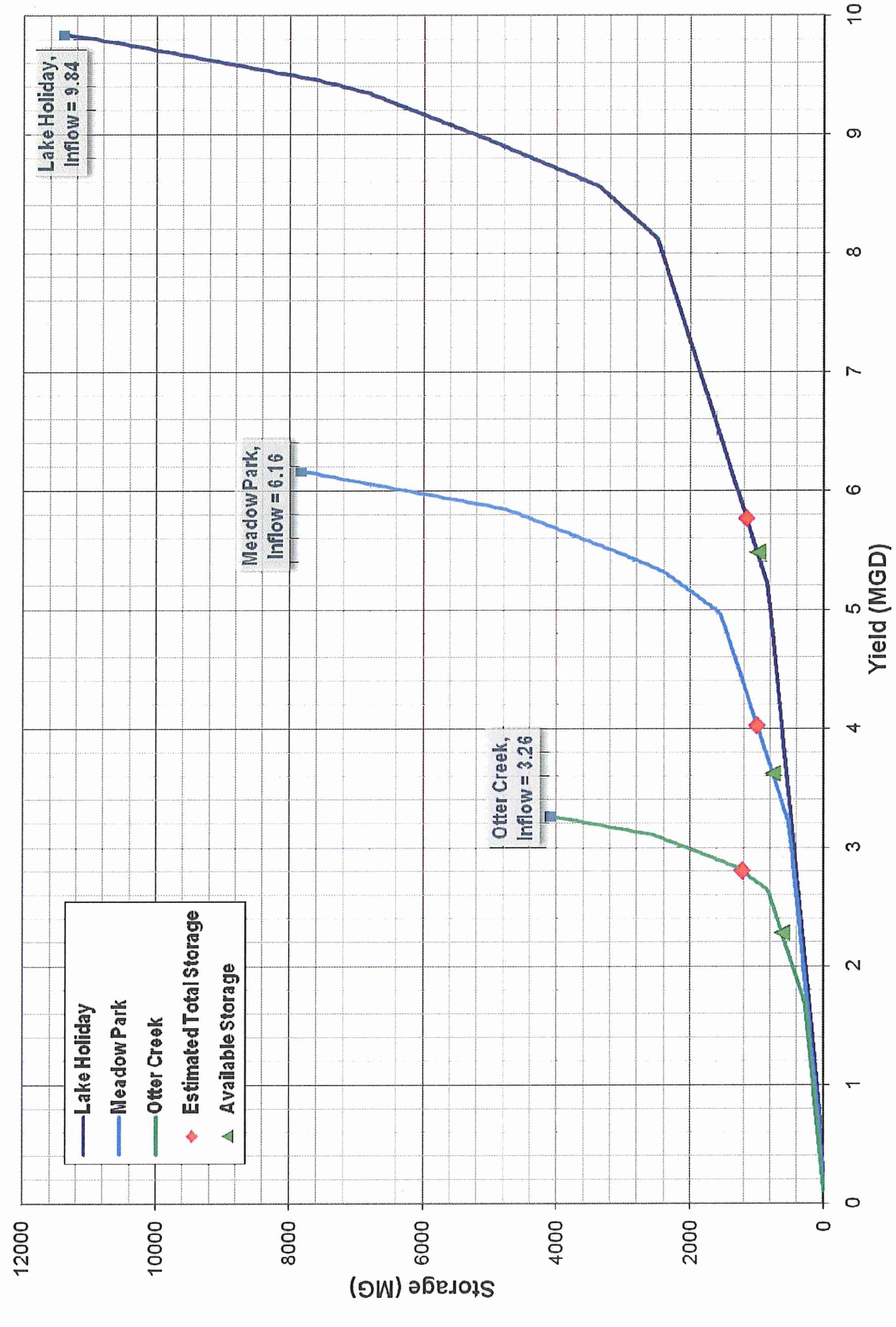


Figure 6 - Storage-Yield curves for the three Cumberland County reservoirs

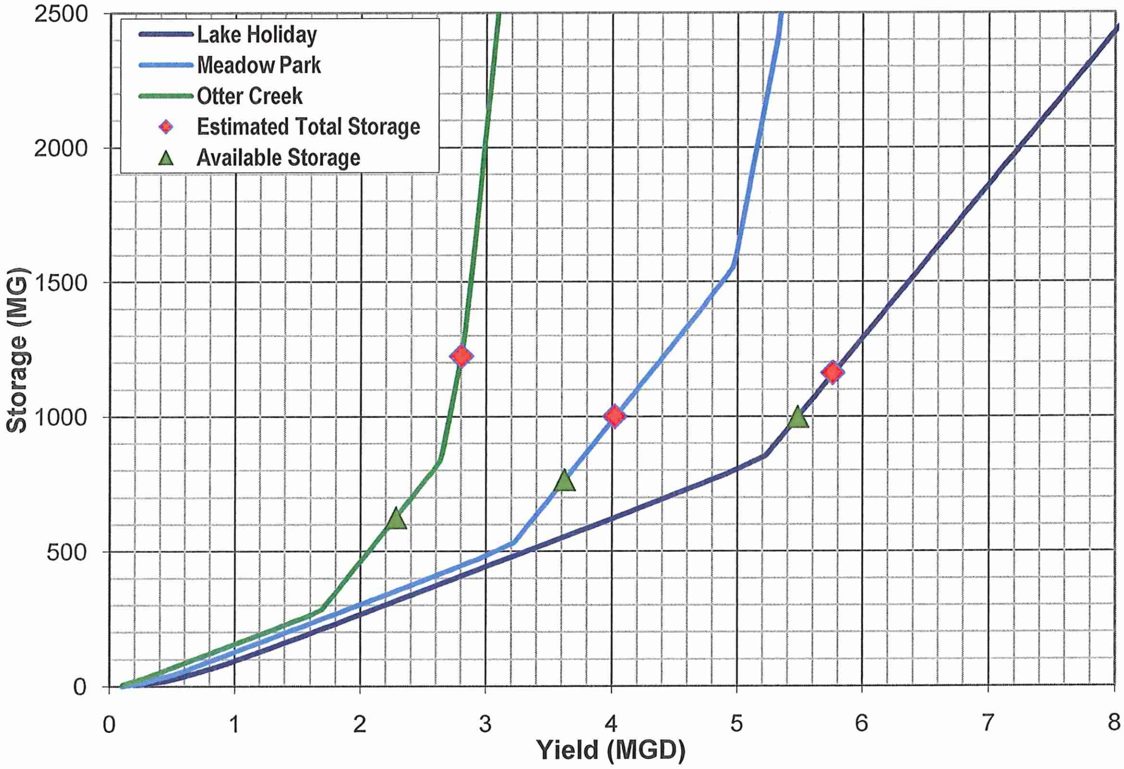


Figure 7 - Detail of Storage-Yield plot

In similar ways, these curves can guide management decisions. If the county wanted to raise only one dam, for instance, Lake Holiday or Meadow Park Lake would be preferred to Otter Creek Lake, as the current storage is on the flat part of the storage-yield and there is substantial increase in yield to be gained. Using similar logic, preventing excessive silt build-up in Lake Holiday and Meadow Park is important because even small reductions in usable storage can significantly reduce yield.

The storage-yield curves stop where the yield becomes equal to the average total inflow to the lake. This is a practical limit to the yield since withdrawals cannot sustainably exceed inputs. The shape of the curve is determined by the variability of the inflow. Since the inflow sequence for all three reservoirs is based on the same precipitation input, it is logical that the curves share a very similar shape.

4. Final Firm Yield Estimate

One major issue with long term-simulation models is that they cannot achieve the same variance achieved by natural processes without a random, stochastic component. For the Cumberland County HEC-HMS models, one main problem with the model assumptions is that parameters must remain static (year to year) over the entire modeling period. This makes the output values tend toward the mean values because the parameters such as baseflow, infiltration rate, and evaporation are based on long term averages. Nonetheless, running a long term simulation has great value in helping to determine the critical drought sequence and uncover other elements of reservoir behavior as shown in the previous section.

Since the critical drought sequence has been (convincingly) identified through the sequent peak algorithm, the model parameters can be adjusted to be more realistic for just that sequence. Then, only the critical drought sequence can be run through the HEC-HMS model. Unfortunately, limited soil moisture and evaporation data exist for the drought period, which occurred in the early 1930s. The baseflow parameters, though there is in fact very limited data from the time period, will not be adjusted. The deficit and constant loss parameters cannot be adjusted since they were used for calibration and must remain the same for consistency. Thus, only the evaporation parameters can be adjusted.

Evaporation rates may be important because many drought periods are warmer than average. The monthly evaporation rates for the original model were determined using 30 years of pan evaporation data from Crossville. There is no pan evaporation data, however, from the 1930s. Therefore, another method was used to estimate the evaporation rate for the critical drought period.

There are a wide range of evaporation estimation methods for a variety of time scales. We only consider the monthly models, which reduces the available options. The models can also require a wide range of inputs including temperature, solar irradiance, hours of daylight, wind speed, and heat flux, among others. Unfortunately, comparatively few of these variables have recorded data for the early 1930s in Cumberland County, Tennessee. For simplicity, Malmstrom's formulation (Equation 2) of Thornthwaite's method was used to provide an estimate of monthly potential evapotranspiration (PET_M), requiring only the saturation vapor pressure at the monthly average temperature ($e^*(T_{avg,m})$) as an input.

$$PET_M = 40.9 \cdot e^*(T_{avg,m})$$ **Equation 2**

Adopting these methods as a replacement for the pan evaporation may not make sense, as it would amount to a major change in methodology for an already calibrated model. Instead, the equations are used to compute adjustment factors for pan evaporation data that were used in the original model. The adjustment factor (C_{ET}, see Equation 3) for a given month is equivalent to the evaporation estimate based on the average temperature during the critical drought period divided by the estimate based on the average temperature for the period for which the pan evaporation was recorded.

$$C_{ET} = \frac{PET_M(T_{avg,criticaldrought})}{PET_M(T_{avg,pan\_rec})}$$ **Equation 3**

This factor was then multiplied by the original pan evaporation averages to produce the monthly evaporation parameters to be used in the new model. Equation 4 describes the calculation of the model input evapotranspiration (ET_{model}) in a given month, j, based on the average pan evaporation (ET_{pan}) for that month.

$$ET_{model,j} = C_{ET} \cdot ET_{pan,j}$$ **Equation 4**

The new model run was performed for a subset of the whole time period. The critical drought period can be viewed for each reservoir in the cumulative deficit charts in Appendix B. The new simulation period begins at the last time the cumulative deficit equals zero before it reaches the maximum deficit (equal to reservoir storage). The state of the full record model at the beginning of the critical drought was saved to be used as the starting state for the critical drought sequence.

Adjustment factors ranged from 0.98 to 1.24 for the months of the critical drought periods, but the large majority of the factors were between 1.00 and 1.05. As such, the firm yield would be expected to drop slightly.

When the critical drought models were run and the sequent peak algorithm applied, it was found that all three reservoirs had a slight reduction in firm yield. The timing of the peaks did not change at all and the overall drought length did not change by more than a few days. Table 11 displays the initial and final yield estimates if all of the storage in the lakes could be used. The final firm yield estimates all show roughly a 1% reduction from the initial estimates. Lake Holiday shows a slightly greater reduction.

Table 12 displays the yield estimates for the lakes using the best available estimates of their storage that can be used for water supply. For the purposes of this study, the yield estimates in this table represent the firm yield estimates for these reservoirs. The final firm yield estimates include similar evaporation adjustments as those used in Table 11.

Table 11 - Yield estimates for Cumberland County based on total storage

Reservoir	Initial yield (MGD)	Final yield (MGD)
Lake Holiday	5.77	5.62
Meadow Park Lake	4.02	3.98
Otter Creek Lake	2.80	2.77
Total	**12.59**	**12.37**

Table 12 - Firm yield estimates for Cumberland County based on available storage

Reservoir	Initial firm yield (MGD)	Final firm yield (MGD)
Lake Holiday	5.48	5.34
Meadow Park Lake	3.62	3.58
Otter Creek Lake	2.28	2.25
Total	**11.38**	**11.17**

Since the three reservoirs are operated roughly independently and all three reservoirs share the same critical drought, the sum of their individual yields is a good estimate for the total yield of the water sources in the county. The final firm yield estimate in Table 12 shows that the firm yield for county water sources is 11.17 MGD. In an emergency, if every drop of water in the reservoir were available, it may be possible to achieve a total yield of approximately 12.5 MGD.

5. Conclusion

Although there are some data limitations in Cumberland County, this study detailed a simple but reasonable method for estimating firm yield for Cumberland County's reservoirs. The HEC-HMS modeling succeeded in generating the required daily reservoirs inflows with a relatively simple, but credible model. The sequent peak algorithm succeeded in identifying critical drought periods and generating an initial estimate of firm yield. Storage-yield curves for the three reservoirs have been provided as a very useful tool for understanding the reservoirs' characteristics and informing their management. The HEC-HMS model was adaptive enough to model just the critical drought sequence for each reservoir and refine the firm yield estimates.

Finally, though it seems unlikely that the 2007-2008 drought will become the critical drought, the sequent peak algorithm results show it cannot be completely ruled out. Considering that nearly 13 inches of rain fell in Crossville in the December 2008 and January 2009, it seems exceptionally unlikely that a new maximum deficit would have occurred. If the stakeholders desire more certainty on this, a follow-up study may be warranted under a new task order.

In comparing the total firm yield to the projected demand for the county, it is likely that additional sources will be needed in the medium term. Based on the Water Needs Assessment, the demand will exceed this yield by roughly 2040 for the Aggressive growth scenario, and in about 2050 for the expected growth scenario. On peak demand days, the demand will begin exceeding yield by 2028 for the aggressive scenario, and roughly 2033 for the expected growth scenario. Thus, due to the uncertainties in the water needs study and yield study, the planning horizon for securing a new source should probably be closer to 15 years than 30. It should also be noted that this type of yield study does not take into account operating policies on the reservoirs not related to water supply. Yield may be even further reduced by policies such as required releases for in-stream flow, policies to maintain pool levels for recreational boating, or others. Further study could take these policies into account.

In the future, several steps could be taken to improve subsequent studies of the reservoirs. It is of prime importance that the actual usable storage capacity of the reservoirs be identified, as this has a direct impact on the firm yield estimate. Secondly, reservoir levels, withdrawals, spills and, if possible, inflows should be measured, preferably on a daily basis.

The following section explores the link between the drought identification exercise and the firm yield analysis. While the methods have not been tested statistically, or independently verified, they do give substantial insight into the behavior of the reservoir systems with respect to the meteorological conditions.

6. Relating the Firm Yield Analysis to the Drought Identification

The two analyses in this report examined the occurrence and consequence of drought in Cumberland from a meteorological perspective as well as hydrologic/water resources perspective. In both parts of this study, the most critical drought (or drought sequence) could not be unequivocally declared, but rather, depended on other variables. In the Drought Identification portion of the study, drought severity of individual droughts varies with the analysis duration at which the SPI is calculated. The multiple-duration SPI plot illustrates this variation. For the existing yield analysis, the length of the critical drought sequence is affected by the storage capacity of the reservoir in conjunction with the inflow (and characteristics of the watershed which affect it). This relationship is shown directly as the Storage-Yield plot.

The problem is that the Storage-Yield plot and multiple duration SPI plot do not connect the drought identification and firm yield analyses. Finding a way to connect the two plots would explain a lot about the behavior of the reservoirs in response to a variety of hydrologic conditions. In the firm yield analysis, the streamflow sequence output from HEC-HMS was connected to the reservoir behavior by using the sequent peak algorithm. The sequent peak algorithm essentially plots required storage versus time, but at a given, fixed yield. Since the SPI plot is plotted on axes of time and SPI duration, it can be connected with the sequent peak algorithm through the time axis. Connecting the sequent peak algorithm plot with the Storage-Yield, however, can only be achieved by linking the yield. Thus, a way must be found to plot the results of the sequent peak algorithm on axes of yield and time.

The way to accomplish this is to plot multiple runs of the sequent peak algorithm (each at different yield) next to each other on the same plot. The result will be a plot very similar to the multiple duration SPI plot, except the sequent peak algorithm's cumulative deficit is plotted at different yields over time instead of the SPI value at different durations over time.

Figure 8 shows a schematic of how this plot might fit in with the other plots. Starting at the top right and moving counter-clockwise, the Storage-Yield plot (blue box) can be connected to the multiple yield sequent peak algorithm plot through the yield axis. Then, moving left, this new sequent peak algorithm can be connected through the time axis to the SPI plot.

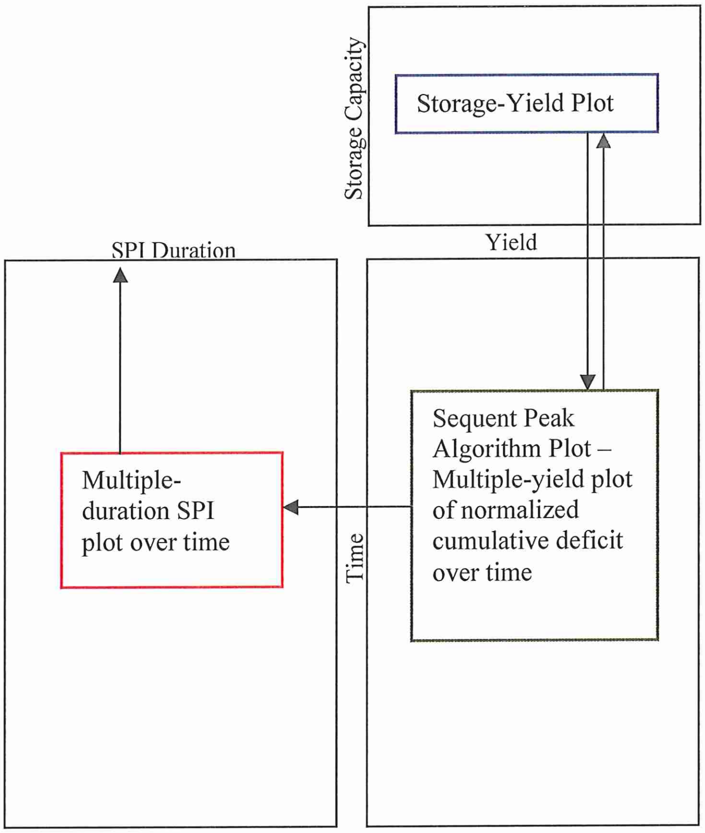


Figure 8 - Plot layout for connecting drought conditions and reservoir behavior

The sequent peak algorithm plot, which is a surface plot much like the SPI plot, must be formatted carefully to be useful. Firstly, the SPI plot and multiple-yield sequent peak algorithm plot should have comparable time axes. The SPI is calculated on a monthly basis, but the sequent peak algorithm on a daily basis. To simplify the plotting, the sequent peak algorithm's daily cumulative yield is converted to a monthly maximum series by taking the maximum cumulative yield for each calendar month. This will smooth out the variations and still capture the maxima.

The main problem with the sequent peak algorithm plot, however, is that the peak cumulative deficit (required storage) is orders of magnitude higher at higher yields than at lower yields. (That is, much more storage is required to meet higher demand levels.) The SPI plot is so effective because the SPI value is a normalized value and is fairly comparable at any analysis duration. A similar normalization must be performed to make the multiple-yield sequent peak algorithm useful. The simplest normalization for each yield value is to divide the monthly cumulative deficit by the absolute maximum cumulative deficit at that yield. This means that the maximum value on the surface plot will be one and the minimum zero, so the plot will be comparable across yields, and it will be easy to identify the time period with the critical drought for each yield.

Figure 9 shows an illustration of what the plot might look like for Meadow Park Lake. The plot is shown in perspective and for a period of just 40 years for illustration purposes. The bottom (horizontal axis) shows the yield, the axis running down the side of the plot is time, and the vertical (z) axis shows the normalized cumulative deficit. Since the plot is in perspective, and the scale is difficult to visualize, a yellow stripe on the z-axis shows when the normalized deficit is between 0.75 and 0.80, and the peaks are highlighted in magenta. This plot is interesting because it clearly shows how the timing of the critical drought can change at different yield levels.

For instance, at yields less than 3.25 or so, the maximum deficit occurs during the 1952-1953 drought (note that the perspective adjusts the apparent location). At around 3.25, it appears there are several drought periods with roughly equal magnitudes, but the 1930-1931 drought emerges as the new most critical drought period. It remains so at yield values up to 5.25 or so (including the reservoir's firm yield at 3.62). Note that as the yield approaches five, the troughs after the 1931 drought begin to disappear. At beyond five MGD, it is clear that the deficits no longer return to zero, but continue at a high level along a given yield. As yield increases, the peaks for the drought that started in 1930 do not occur until 1935, 1936, and well into the mid 1940s as yield approaches six MGD.

In theory, the peaks of the sequent peak algorithm plot should correspond, temporally, with very negative SPI values on the multiple duration SPI plot. So, if they are placed side-by-side there should be strong correlation between the position of the peaks on the sequent peak plot, and the most negative SPI values (shown in red) on the SPI plot. As such, the meteorological drought conditions that caused the critical deficit can be identified. Furthermore, the position of the most critical SPI values (deep red areas) on the SPI plot's duration axis gives an approximation of the length of the drought that caused the critical drawdown sequence. Note that this process does not work in reverse. For various reasons, including the timing of the SPI values with respect to the season, a very negative SPI value does not always correspond to an absolute peak in the sequent peak algorithm.

In Appendix C, Figures C.1, C.2, and C.3 display the relevant triple plots (Storage-Yield, Multi-yield Sequent Peak Algorithm, and multi-duration Standardized Precipitation Index) for Lake Holiday, Meadow Park Lake and Otter Creek Lake, respectively. The time axes are trimmed to 1920 through 2008 since there were no major droughts between the beginning of the historical record (1913) and 1920. It should also be noted that the SPI plot and multi-yield sequent peak plots are not truly continuous on the horizontal axis. That is, the plots are only displaying data at the axis labels, and not between them. For example, on the SPI plot, the graph is correct along the vertical lines descending from 6 months and 9 months on the duration axis, but the space between them is an interpolation and doesn't represent a calculation for a duration of 7 months.

The SPI plots have also been reformatted from Figure 10. The plots are now viewed in plan view (looking down from above), and the differences in normalized deficit are viewed as different colors instead of in 3D relief. Values less than 0.79 are shown in gray, because only the peaks (values near 1) are important to this analysis. The colors then transition from yellow to red as the normalized deficit gets closer to the peaks. Maximum deficit values greater than 0.99 are shown in black to visually highlight the peaks.

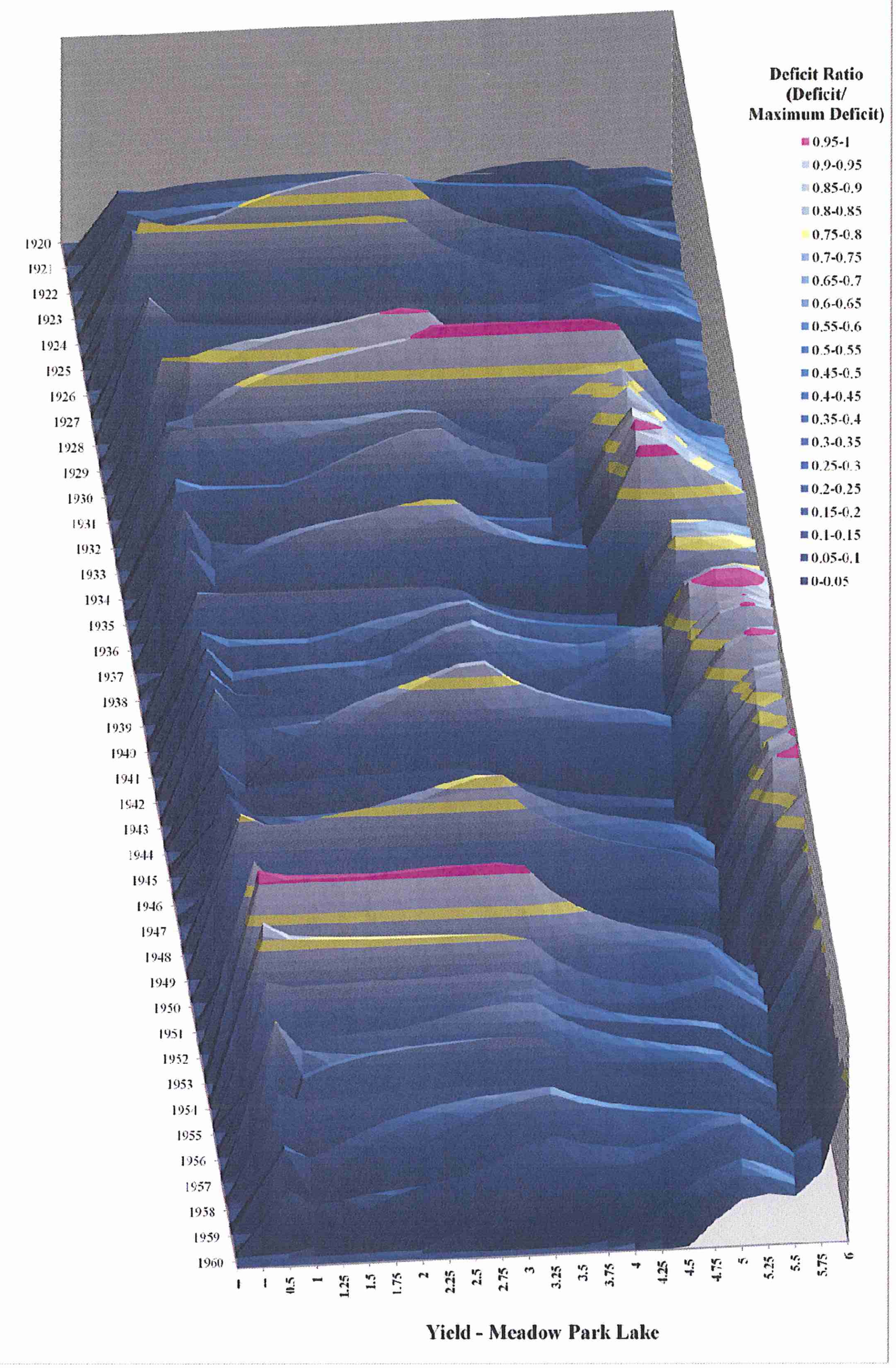


Figure 9 - Normalized monthly maximum deficit plot of the Sequent Peak Algorithm at various yields for Meadow Park Lake

Figure C.1 shows the triple plot for Lake Holiday. Lake Holiday has a storage capacity of 1161Million gallons, so starting on the Storage-Yield Plot, a green star is placed at that storage level, which corresponds to a yield (here, the firm yield) of about 5.5 MGD.

Then, trace down from this star to the multi-yield sequent peak algorithm plot, and continue until a peak is reached (a black spot on the plot). A green arrow shows this trace, and it ends at a peak in December 1931, where a green star is placed. After this point is found, stay constant along the time axis and trace across to the multi-duration SPI plot. The most critical drought duration at the given time should appear as a dark red color. Then trace up to the duration axis and find the expected duration of the drought. In this case, the red band extends from about 15-24 months duration. Since the star on the multi-yield sequent peak algorithm plot falls on the left side of the black line at the end of 1931, the left-center region of the red band on the SPI plot is chosen. So, the duration of the meteorological drought that causes the critical drought that controls the firm yield is estimated to be about 18 months for Lake Holiday.

Figure C.2 shows a similar set of plots for Meadow Park Lake. The green arrows are not shown, but the green stars mark the same critical points. Since the firm yield fell more in the middle of the black bar this time, a spot more in the middle of the multi-duration SPI plot's red bar was chosen. So, the critical drought duration is most likely approximately 18 months for Meadow Park Lake, but could be anywhere from 15 – 24 months.

Figure C.3 shows a similar set of plots for Otter Creek Lake. At the firm yield estimate for the available storage volume, the plot is similar to the other lakes. When the total storage estimate is used instead, the higher yield (2.8) falls further right on the storage-yield curve. Tracing this yield down to the sequent peak plot, the critical drought peak occurs later, in about 1936 instead of 1931. When we trace over to the SPI plot, however, the most severe drought index value encountered is just in a medium orange color range. The most likely problem is that the SPI plot does not include long enough durations, and that the critical drought length is longer than 48 months. This makes sense because the drought started in 1930, so in 1936, the critical drought sequence would be approximately 70 months.

In fact, for virtually all of the higher yields, the critical drought starts in 1930. This is the reason for the pattern of peaks gradually moving later on the right side of all three multi-yield sequent peak algorithm plots. The early 1930s drought causes very large deficits, and as yield increases, it is increasingly difficult to return the deficit to zero. Furthermore, the additional dry periods add to the deficits from that drought, and thus move the peaks later and later. When firm yield exceeds average inflow, it becomes likely that the deficit never returns to zero. Thus, yields above the average inflow are not shown.

In conclusion, this report has demonstrated a visual method for connecting the drought identification analysis to the storage-yield evaluation. In general, the drought of the early 1930s is in all cases the critical drought for Cumberland County's reservoirs. Figures C.1 through C.3 show that the meteorological drought duration corresponding to the critical drought is roughly 15-24 months for all of the lakes. Overall, these plots can give greater understanding to the decision makers as challenging drought conditions are encountered in the future.