Memo

To: Dave Bishop, Ben Rohrbach - Nashville District Corps of Engineers (Corps)

From: Stuart Stein and Karsten Sedmera - GKY & Associates, Inc. (GKY)

CC: Tim Begley - Crossville Utility District

Date: September 15, 2015

Re: Cumberland County Regional Water Supply Plan – Task 3: Water Needs Summary Memo

Attachments: Appendix A – Data Collection / Analysis
Appendix B – Additional Analysis – Meadow Park Lake & Fox Creek Lake
Appendix C – Systems Model Schematic

1.0 Background

This memo summarizes GKY's work on Task Order DX01 under Contract W91237-14-D-0001, which represents a continuation of study for the Cumberland County Water Supply Plan. It builds upon work completed in Task Order DX06 under Contract W91237-09-D-0004, and previous work completed by the A/E in support of the Plan. This technical memorandum summarizes the history of GKY's involvement with the Cumberland County Regional Water Supply project, data collection for this task, additional analysis to support the systems model, assumed water demands, systems model setup, systems model analysis/results, identification of areas of need, and potential recommendations for future water supply alternatives.

2.0 History of Project

The Cumberland County Regional Water Supply Study was established by an agreement between the U.S. Army Corps of Engineers (Nashville District) and the City of Crossville, Tennessee. The Cumberland County Regional Water Supply Study has the goal of identifying a long term solution to Cumberland County's water supply needs.

GKY began its involvement in the Water Supply Study in 2005. GKY completed a land-use evaluation for future County population growth, water needs analysis, water conservation analysis, and yield analysis for existing sources. The memos and reports completed documenting this work will be referenced throughout this memo. The significant reports and memos completed by GKY are as follows:

- *Cumberland County Regional Water Supply - Water Needs Assessment and Water Conservation Plan,* dated March 2009. (herein referred to as GKY Water Needs Report)
- *Cumberland County Regional Water Supply – Drought Identification and Existing Sources Yield Analysis,* dated January 2010. (herein referred to as GKY Existing Yield Report)
- *Cumberland County Regional Water Supply – Task1 Technical Memorandum, dated October 26, 2012. (herein referred to as GKY Demand Analysis and Existing Model Report)*
- *Cumberland County Regional Water Supply – Task 2D.1 System Model Development, Regional Water Supply Need Determination, and Water Supply Alternatives Yield Evaluation Presentation, dated February 5, 2013. (herein referred to as GKY System Model Development Presentation).*

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Work detailed in this Technical Memorandum for Task 1 and Task 2 is thus a continuation of the Cumberland County Water Supply Study.

3.0 Data Collection / Analysis

Task 1b tasked GKY with updating and extending the storage/area/elevation (S-A-E) data for the all but Otter Creek Lake and for the new Fox Creek Lake using recent high resolution digital elevation data provided by the Corps.

3.1 Lake Bathymetry Updates

GKY used the Corps-supplied survey data (dwg files) and recent high-resolution digital elevation data to update and vertically extend the S-A-E data for all of the Cumberland County sources/lakes except for Otter Creek Lake. The digital elevation data was only used to obtain above-normal pool data for Meadow Park Lake. The below-normal pool elevation for Fox Creek Lake was obtained via linear extrapolation of the S-A-E data obtained from the survey data at and above-normal pool. The new S-A-E data sets for Meadow Park Lake (MPL), Lake Holiday (LH), Fox Creek Lake (FCL), and Lake Tansi (LT), as they were updated in OASIS, are given in Table 12, Table 13, Table 15, and Table 15 in Appendix A.

3.2 Sequent Peak Analysis for Meadow Park Lake and Fox Creek Lake

Sequent peak analysis was used to assess the potential yield for the newly proposed water supply infrastructure. The sequent peak algorithm is used to determine the maximum constant withdrawal (firm yield) from a water source. Meadow Park Lake was evaluated for various increases in usable storage associated with various dam raising alternatives. As can be seen in Figure 1 in Appendix B, the current yield for Meadow Park Lake is approximately 3.5 million gallons per day (MGD). The knee of the storage-yield curve occurs at a storage of approximately 4,500 to 5,000 acre-feet, which corresponds to raising the dam by approximately 18 feet.

The Crab Orchard Utility District specified that Fox Creek Lake will be able to be drawn down by three feet (from a normal pool elevation of 1850.48 feet to 1847.48 feet) through pumping water to Otter Creek Lake. The usable storage associated with this potential drawdown is approximately 433 acre-feet. The yield associated with this usable storage is approximately 0.6 MGD, as shown in Figure 2 in Appendix B.

4.0 Assumed Water Demand

Table 1 shows the resulting water needs projections from the 2012 GKY Demand Analysis and Existing Model Report, including the outside projected transfers to Falls Creek Falls and Grandview.

Table 1: Projected Total Water Needs (MGD).

Service Area	2006	2016	2026	2036	2046	2056
Crab Orchard	1.17	1.54	2.17	3.01	3.89	4.14
Crossville (Total)	2.95	3.47	3.87	4.01	4.19	4.37
Crossville (MPL/Holiday)	*2.27*	*2.73*	*3.08*	*3.21*	*3.38*	*3.54*
Crossville (MPL/Holiday Optional)	*0.43*	*0.45*	*0.47*	*0.48*	*0.49*	*0.5*
Crossville (MPL Only)	*0.25*	*0.29*	*0.32*	*0.32*	*0.32*	*0.33*
South Cumberland	0.56	0.83	1.32	1.74	2.12	2.38
West Cumberland	0.24	0.26	0.29	0.31	0.34	0.4
Falls Creek Falls	0.00	0.03	0.07	0.10	0.13	0.17
Grandview	0.09	0.11	0.14	0.17	0.20	0.25
Total	***5.01***	***6.25***	***7.85***	***9.35***	***10.87***	***11.71***

Furthermore, the following seasonal multipliers from the 2012 GKY Demand Analysis and Existing Model Report modulate the water needs projections in this study.

- **Summer** – 1.12 (applied to 122 days per year, June - September)
- **Winter** – 0.94 (applied to 243 days per year, October - May)

5.0 Systems Model

OASIS is a water system modeling software system developed by HydroLogics, Inc. This study utilized the OASIS version 3.12.000 that is available on the "OASIS Virtual Server" at the Tennessee Technological University.

5.1 Model Scenario Assumptions

The 2012 GKY Demand Analysis and Existing Model Report details almost all of the assumptions that GKY originally leveraged to create an OASIS model schematic and attributes for the Cumberland County Water System, which we will refer to as the primary basis for our "Existing Conditions" model scenario. The only attributes that differ from the 2012 memo for our "Existing Conditions" model scenario relate to the Storage-Area-Elevation data for Meadow Park Lake (MPL), Lake Holiday (LH), and Otter Creek Lake (OCL), which we already described in Section 3.1 of this memo, and to the Fox Creek Lake schematic elements described later in this section and which were only activated in Scenario 7A1 and 7A2. The final model schematic, which we used in the all of the Scenarios, is presented in Figure 3 of Appendix C.

The assumptions for Scenarios 2A, 3A, and 5A1/6A3, which relate to WTP capacity constraints, institutional constraints, and Crossville to South Cumberland and Crab Orchard physical interconnection constraints are described in full detail in Section 5.0 of the 2012 GKY Demand Analysis and Existing Model Report and in the 2013 Systems Model Development Presentation. As such, we will not reproduce the details for these model parameters here.

Scenario 1A, which relates to 10% and 20% reductions in usable storage for MPL, LH, and OCL, were obtained by performing linear interpolation between the storage and elevation records for each source. The original and altered elevations for the dead storage for each source are given in Table 2.

Table 2: Scenario 1A Reductions in Dead Storage Elevations.

Source	Original	10% Reduction	20% Reduction
Meadow Park Lake	1805.60	1807.46	1809.04
Lake Holiday	1746.20	1748.14	1749.91
Otter Creek Lake	1755.00	1757.08	1759.04

Scenario 4A, which relates to increasing Lake Holiday's service area scenario consists of shifting the aggregation of Crossville water demands between model demand nodes 10 and 11. Prior to Scenario 4A, model node 11 for each benchmark year is assigned the summation of "MPL only" and "MPL/Holiday/Additional" demand rows in Table 1, while model node 12 is assigned to the "MPL/Holiday" row of Table 1. From Scenario 4A and on the "MPL/Holiday/Additional" row is instead added to model node 11. This Scenario was first described in the 2013 Systems Model Development Presentation. However, for clarity sake, the aggregate demand levels for model nodes 10 and 11 before and after Scenario 4A are listed in Table 3.

Table 3: Demand Allocation for Crossville Model Nodes 11 & 12 by Scenario.

Model Scenarios	Model Node	2006	2016	2026	2036	2046	2056
1A – 3A	11	0.68	0.74	0.79	0.80	0.81	0.83
	12	2.27	2.73	3.08	3.21	3.38	3.54
4A –	11	0.25	0.29	0.32	0.32	0.32	0.33
	12	2.70	3.18	3.55	3.69	3.87	4.04

For Scenarios 6A1, 6A2, 7A3, and 5A4, which relate to increasing the usable storage capacity of Meadow Park Lake, we simply increase the elevation of the Upper Rule (i.e. Zone D in OASIS) and upper level rule constraint from the existing MPL normal pool by the amount desired. Table 4 shows the before and after Upper Rule elevations assigned to reservoir node 10.

Table 4: Increase in Meadow Park Lake Upper Rule Elevation Scenarios.

Parameter	Original	Raise 18.5 feet	Raise 20 feet
Upper Rule Elevation & Constraint	1818.20	1836.70	1838.20

Scenarios 7A1 and 7A2, where we add the Fox Creek Lake (FCL) water supply input to Otter Creek Lake (OCL), require two new model nodes and three new arcs, as depicted in the upper right-hand corner of Figure 1 in Appendix C. The OASIS model schematic includes new elements for Fox Creek Lake (i.e. "Fox Creek Lake" or reservoir node 035), its outfall-receiving stream (i.e. "FCL Out", or terminal node 350), its watershed inflow (i.e. the "035" time series arc), and two node-connecting arcs. The storage/area/elevation relationship and reservoir rule pattern for FCL, which represent the top 3 feet of FCL storage and constrain the model to the usable storage therein (i.e. over 433 acre-feet), are given in the two parameter tables in Figure 4 in Appendix C. The area-averaged daily FCL upstream inflow in the 035 time series shown in Figure 5 in Appendix C for the simulation period has a long-term average of about 1.64 cfs. Furthermore the two node-connecting arcs have the following characteristics.

- Link "FCL to OCL" represents the outflow from Fox Creek Lake (FCL) to Otter Creek Lake (OCL) with a Max Flow Pattern that constrains the outflow to 1.0 MGD (or 3.0 acre-feet/day, or 1.55 cfs).
- Link "FCL Out" represents the overflow from FCL, when the inflow to FCL causes the lake elevation to exceed the normal pool elevation of 1850.46 feet.

5.2 Model Priority and Weight Adjustments

All OASIS model nodes and arcs furthermore have priority and weight settings that must be adjusted to obtain the desired releases from the interconnected system of reservoirs to best satisfy all of the demands given all of the system flow and level constraints. For the purpose of this Task Order, there are no constraints that warrant setting any node to a priority value greater than 1. On the other hand, similar to the previous task, the only the arcs that warrant any weight and thus a priority of 1 to encourage flow are the arc from Lake Holiday (reservoir node 20) to its own demand node (node 12) and from Lake Tansi (reservoir node 15) to the Crossville WTP (node 1). Both of these arcs were assigned a low weight equal to 1.

All of the reservoir and demand nodes have a priority of 1 in order to set weights that generally encourage flow from reservoirs to demand nodes in the absence of a constraint that either prevents or limits the flow in a given arc. As such, all of the demand nodes have weights greater than all of the reservoir Zone B through D weights (i.e. Zones B through D represent the usable storage), but less than the Zone A weights (i.e. Zone A referring a reservoir's Dead Storage or un-usable storage).

After testing different values for the reservoir versus demand node weights for all of the different types of Scenarios in this Task Order, we found that there was no advantage to varying the weights between different scenarios. In fact, varying the weights between Scenarios only makes it more difficult to compare the different Scenarios, which primarily only add or remove different system constraints, on equal terms. However, this exercise did help us settle on an "optimal" set of reservoir and demand node weights in general that allow the system to work "optimally" no matter what constraints are effective in a given model Scenario. These weights are given in Table 5 and Table 6.

In general, all of the similar reservoir Zones have roughly the same weighting, except in the case where a given reservoir (e.g. Lake Tansi and Fox Creek Lake, which are low-volume "supportive" reservoirs) is given a lower weight in order to favor releasing its usable storage.

Table 5: Reservoir Node Weights.

Node #	Node Name	Zone D	Zone C	Zone B	Zone A
10	Meadow Park Lake	-1	10	400	600
15	Lake Tansi	-1	5	100	500
20	Lake Holiday	-1	10	400	600
30	Otter Creek Lake	-1	10	400	600
35	Fox Creek Lake	-2	5	350	550

The slight difference in demand node weights, on the other hand, reflects a general preference for the reservoirs to prefer supplying local demands before supplying any "outside" demands.

Table 6: Demand Node Weights.

Node #	Node Name	Weight
11	Crossville – MPL	500
12	Crossville – MPL-LH	500
21	COUD	500
31	SCUD	490
41	WCUD	490
51	GUD	490
61	FCFUD	490

6.0 Systems Model Analysis

For the purposes of this task, firm yield was defined as the maximum amount of treated water that can be delivered to the Cumberland County Water Supply System without any of the UDs experiencing shortage. The demand was set for the future benchmark years based on the water needs projections listed in Section 4. Modeling was performed for all of the 10-yr benchmark projections. Once a shortage, or failure, occurred anywhere in the system it was determined that the preceding benchmark year defined the firm yield for the system. For example, if the UDs had no shortage using the 2016 benchmark demands, which totals 6.25 MGD (i.e. neglecting the seasonal multipliers), and a shortage was encountered using the 2026 benchmark demand, which totals 7.64 MGD, then the systems firm yield is reported as 6.25 MGD.

We will begin this discussion by first listing a summary of all of the Scenario simulations that we ran in Table 7, along with the last benchmark year in which no shortages occurred. The first listing in Table 7 simply serves as a point of reference regarding the "Existing Conditions" model first described in the 2012 and 2013 Task deliverables. After this, the first thing to note in this table is that each subsequent pairs of Scenarios listed there result from a continuation of the two different reductions in usable storage that constitute Scenario 1A – namely 10% and 20% reductions in usable storage already described. Each pair of subsequent Scenarios to rows 2 and 3 then build upon previous Scenarios as noted in the "Description" column of Table 7. The wavy-lined boundaries after Scenario 4A simply help the reader recognize that the last 18 scenarios represent four different sequences of Scenarios. While the Scenarios in the fourth sequence (i.e. the last two simulation rows) were not part of the scope, we were compelled to run it in order to help justify our final recommendations. The "Last Year of Firm Yield" column, which lists all of the benchmark years, thus denotes the last year of firm yield achieved in each Scenario with bold font and yellow highlight – yielding a pseudo-graphical representation of the firm yield achieved in each Scenario.

For example, Scenarios with "2056" in bold and highlighted font means that there were no simulated shortages given the 2056 benchmark demand level – and thus the firm demand is at least as much as the 2056 benchmark demand level. For any Scenario with an earlier date highlighted (e.g. 2016 for "Existing"), the following subsections will describe why the next benchmark year simulation (e.g. 2026 for "Existing") failed to meet the demand. This table is thus a convenient reference for the rest of our discussion.

Table 7: Summary of the 24 Model Scenario Simulations Highlighting the Last Year of Firm Yield.

Scenario	Description	Last Year of Firm Yield
Existing	Base model with no upgrades	**2016**,2026,2036,2046,2056
1A_10%	Reduce usable storage in MPL, LH, OCL by 10%	**2016**,2026,2036,2046,2056
1A_20%	Reduce usable storage in MPL, LH, OCL by 20%	**2016**,2026,2036,2046,2056
2A_10%	1A_10% & relax WTP constraints (TDEC req.)	**2016**,2026,2036,2046,2056
2A_20%	1A_20% & relax WTP constraints (TDEC req.)	**2016**,2026,2036,2046,2056
3A_10%	2A_10% & remove institutional constraints	2016,**2026**,2036,2046,2056
3A_20%	2A_20% & remove institutional constraints	2016,**2026**,2036,2046,2056
4A_10%	3A_10% & increase LH service area (existing connections)	2016,**2026**,2036,2046,2056
4A_20%	3A_20% & increase LH service area (existing connections)	2016,**2026**,2036,2046,2056
5A1_10%	4A_10% & relax physical interconnection constraints	2016,2026,2036,**2046**,2056
5A1_20%	4A_20% & relax physical interconnection constraints	2016,2026,**2036**,2046,2056
6A1_10%	5A1_10% & increase MPL usable storage by 18.5 feet	2016,2026,2036,2046,**2056**
6A1_20%	5A1_20% & increase MPL usable storage by 18.5 feet	2016,2026,2036,2046,**2056**
7A1_10%	6A1_10% & add FCL reservoir to COUD	2016,2026,2036,2046,**2056**
7A1_20%	6A1_20% & add FCL reservoir to COUD	2016,2026,2036,2046,**2056**
6A2_10%	5A1_10% & increase MPL usable storage by 20 feet	2016,2026,2036,2046,**2056**
6A2_20%	5A1_20% & increase MPL usable storage by 20 feet	2016,2026,2036,2046,**2056**
7A2_10%	6A2_10% & add FCL reservoir to COUD	2016,2026,2036,2046,**2056**
7A2_20%	6A2_20% & add FCL reservoir to COUD	2016,2026,2036,2046,**2056**
5A3_10%	4A_10% & add FCL reservoir to COUD	2016,2026,**2036**,2046,2056
5A3_20%	4A_20% & add FCL reservoir to COUD	2016,2026,**2036**,2046,2056
6A3_10%	5A3_10% & relax physical interconnection constraints	2016,2026,2036,**2046**,2056
6A3_20%	5A2_20% & relax physical interconnection constraints	2016,2026,2036,**2046**,2056
7A3_10%	6A3_10% & increase MPL usable storage by 20 feet	2016,2026,2036,2046,**2056**
7A3_20%	6A3_20% & increase MPL usable storage by 20 feet	2016,2026,2036,2046,**2056**
5A4_10%	4A_10% & increase MPL usable storage by 18.5 feet	2016,**2026**,2036,2046,2056
5A4_20%	4A_20% & increase MPL usable storage by 18.5 feet	2016,**2026**,2036,2046,2056

For reference, we should note that the existing system's firm yield is 6.25 MGD, corresponding to the 2016 benchmark year. In the 2026 benchmark year, the existing system is expected to experience frequent shortage at the South Cumberland UD and brief shortages at both external UDs (i.e. Falls Creek Falls and Grandview) all primarily due to a combination of water treatment plant limitations and institutional constraints. The South Cumberland shortage over the simulation period peaks at approximately 0.52 MGD.

Also since many of the Scenarios fail in a given year due to shortages in demand during the most severe drought periods and highest seasonal demand (i.e. recall the summer demand multiplier in Section 4 of this report) we will refer to these austere conditions as "the most austere drought and demand conditions" here-on-out.

6.1 Task 1a Scenarios

The first Scenario pair in Table 7 (rows 2 and 3) relates to Scenario 1A, which represents 10% and 20% margins of safety, or two different levels of additional stress on the system's usable storage at MPL, LH, and OCL (OASIS reservoir nodes 10, 20, and 30 in Figure 3). As such, it is notable that the firm yield remains at 6.25 MGD, corresponding to the 2016 benchmark year for both margins of safety. However, in the 2026 benchmark year the existing system shortage now spreads to the Crab Orchard UD for both margins of safety, primarily because the extra stress on the already limited usable storage in OCL (i.e. which is relatively small compared to the MPL and LH sources) leaves it vulnerable to depletion in the most austere drought and demand conditions, especially given the institutional constraints. Thus, the South Cumberland and Crab Orchard shortage peaks at approximately 2.54 MGD in Scenario 1A-10% and at approximately 3.94 MGD in Scenario 1A-20% at the 2026 benchmark demand level.

The next Scenario pair in Table 7 (rows 4 and 5) relates to Scenario 2A, which represents the first infrastructure upgrades – namely lifting the water treatment plant (WTP) capacity constraints at MPL, LH, and OCL (i.e. OASIS arcs 1-2, 20-12, and 30-5 in Figure 3) plus the safety factors from Scenario 1A. It turns out that while lifting the WTP capacity constraints helps the South Cumberland UD and external UDs meet the 2026 benchmark demand, it does nothing to relieve the additional stress on the limited usable storage in OCL, which is still vulnerable to depletion in the most austere drought and demand conditions, especially given the institutional constraints. Thus, the firm yield for both instances of Scenario 2A remain at approximately 6.25 MGD corresponding to the 2016 benchmark year, and Crab Orchard shortage at the 2026 benchmark peaks at approximately 2.0 MGD for both safety factors.

The next Scenario pair in Table 7 (rows 6 and 7) relates to Scenario 3A, which represents the next collective set of infrastructure upgrades – namely removing the institutional constraints (i.e. affecting OASIS arcs 2-41, 2-21, 4-61, 5-2, and 5-51). It's worth noting, however, that several of these pipes still have infrastructure limits. Even so, lifting the institutional constraints successfully moves the safe yield up to 7.85 MGD corresponding to the 2026 benchmark for both safety factors. This is largely due to the fact that lifting the institutional constraints allows MPL to assist OCL with supplying Crab Orchard's 2026 demands, even though OCL is still vulnerable to depletion in the most austere drought and demand conditions. In the 2036 benchmark year, however, the infrastructure limits prevent MPL from providing all of Crab Orchard's 2036 demands. Thus, the Crab Orchard shortage peaks at approximately 1.49 MGD with either safety factor at the 2036 benchmark demand level.

The last Scenario pair in Table 7 (rows 8 and 9) in Task 1a relating to Scenario 4A, entails expanding the LH service area (i.e. switching part of MPL's Crossville demand from OASIS node 11 to 12 like described in Table 3 and enabling flow in OASIS arcs 20-24, and 20-21). Expanding LH's service area again supports a firm yield of 7.85 MGD corresponding to the 2026 benchmark for both safety factors. The primary benefit of this upgrade is that it provides more support for the Crab Orchard demand. However, in the 2036 benchmark year, the infrastructure limits still does not relieve OCL's vulnerability to dry up in the most austere drought and demand conditions. Thus, the Crab Orchard shortage over the simulation period at the 2036 demand level peaks at approximately 1.49 MGD with either safety factor.

6.2 Task 1c Scenario Sequences

In the first sequence of three Scenario pairs (i.e. Scenarios 5A1, 6A1, and 7A1), we begin with relaxing infrastructure constraints, then increasing MPL's usable storage by 18.5 feet, and finally adding the FCL water supply input to the OCL source.

Scenario pair 5A1 in Table 7 (rows 10 and 11), which relaxes infrastructure constraints entails lifting the constraints on OASIS arcs 2-4, 2-21, and 5-2). Relaxing infrastructure constraints supports a firm yield somewhere between 9.35 MGD (2036) and 10.87 MGD (2046) with 10% and 20% safety factors, respectively. The primary benefit of this upgrade is that it allows both MPL and LH to aid with OCL's demands. However, in doing so, somewhere between the 2036 and 2046 benchmark years all of the Cumberland County sources ultimately dry up in the most austere drought and demand conditions. Thus, the Crossville, South Cumberland, and Crab Orchard shortages peak at approximately 10.1 MGD with a 10% safety factor with the 2056 level of demand, whereas the shortages peak at approximately 4.3 MGD with a 20% safety factor with the 2046 level of demand.

The next Scenario pair, 6A1, in Table 7 (rows 12 and 13), involves raising MPL's dam by 18.5 feet from 1818.2 feet to 1836.7 feet (thereby adding approximately 2,257 acre-feet of usable storage to the system). Increasing MPL's usage storage by raising the dam by 18.5 feet caused the model not to experience shortage at any of the benchmark demand levels for either safety factor, and thus it at least supports a firm yield of 11.71 MGD corresponding to a benchmark year of 2056. The primary benefit of this upgrade is that it MPL now has enough firm yield to satisfy all of the system demands (assuming that the MPL infrastructure can bear the load), even in the most austere drought and demand conditions, when all of the other sources dry out. In this Scenario, the MPL water treatment plant and pipes must support over 13.2 MGD in peak seasonal demand months, and the pipes to each UD must support their respective demand flows.

The last Scenario pair, 7A1, in Table 7 (rows 14 and 15), which adds the FCL water supply input to the OCL source is arguably not necessary unless it can save the District money by eliminating the need to upgrade the supply pipes between either MPL or LH and Crab Orchard. However, this Scenario does not ultimately change the fact that OCL dries up during the most austere drought and demand conditions. This is primarily because the FCL usable storage is far smaller than what is needed to fully aid OCL during the most severe droughts at 2056 demand levels.

In the second sequence of Scenario pairs (i.e. Scenarios 6A2 and 7A2, which both again leverage Scenario 5A1, or rows 16 to 19 in Table 7) we again begin with relaxing infrastructure constraints, then increasing MPL's usable storage by 20 feet, and finally adding the FCL water supply input to the OCL source. These two Scenario pairs yield no new information since we are only increasing MPL's usable storage by another 1.5 feet. We yield almost the same results as the first Scenario sequence. The only difference is that the minimum Meadow Park Lake usable storage is almost 1.5 feet higher, while all of the other sources still dry up.

Finally, in the third sequence of Scenarios (i.e. Scenarios 5A3, 6A3, and 7A3), we change up the order of the second sequence – namely we begin with adding the FCL water supply input to the OCL source, then relaxing infrastructure constraints, and finally increasing MPL's usage storage by 20 feet.

In Scenario pair, 5A3, in Table 7 (rows 20 and 21) we first add the FCL water supply input to the OCL source, which entails enabling OASIS arc 35-30 to allow flow to OCL. Adding FCL to the OCL source increases the firm yield of Scenario 4A1 from 7.85 MGD to 9.35 MGD corresponding to benchmark year 2036 with either safety factor. This is primarily because the FCL firm yield is just large enough to satisfy the 0.4 MGD shortage at OCL in the 2036 level in Scenario 4A1 with the 20% safety factor. However, with the 2046 benchmark demand the Crab Orchard and South Cumberland demand shortages peak at approximately 2.8 MGD with either safety factor.

In Scenario pair, 6A3, in Table 7 (rows 22 and 23) we next relax the infrastructure constraints. Relaxing the infrastructure constraints now yields 10.87 MGD corresponding to the 2046 benchmark year, which is a little better than Scenario pair 5A1. However, all of the Cumberland County sources ultimately dry up in this Scenario and the level of Crossville, South Cumberland, and Crab Orchard shortages peaks at approximately

3.9 MGD with a 10% safety factor and at approximately 6.65 MGD with a 20% safety factor given the 2056 benchmark demand level.

In Scenario pair, 7A3, in Table 7 (rows 24 and 25) we again increase MPL's usage storage by 20 feet. This indeed allows MPL firm yield to meet all of the 2056 demand (i.e. 11.71 MGD) in the most austere drought and demand conditions. In this Scenario, the MPL water treatment plant and pipes must again support over 13.2 MGD in peak summer demand, and the pipes to each UD must support their respective demand flows.

In the last pair of Scenarios, Scenario 5A4, tests whether only increasing MPL's usage storage by 18.5 feet (i.e. without relaxing infrastructure constraints) can maintain a 2056 level of safe yield or not. As expected, the firm yield of this Scenario is no better than Scenario 4A. This is because MPL can only supply the systems total demand during the most austere drought and demand conditions at the 2036 demand level if the pipe infrastructure can support the respective demand flows from MPL.

6.3 Scenario Shortages Summary

Table 8 provides a summary of all of the modeled Scenarios and when the certain Utility districts experience shortages given the cumulative infrastructure upgrades implied by each Scenario. This table simply summarizes key parts from the more detailed summaries in Sections 6.1 and 6.2, above.

Table 8: Summary of Shortages by Utility and Benchmark Year.

Scenario	Year that UDs Experience Shortage
Existing	2026: S. Cumb., Falls Crk Falls, Grandview
1A_10%	2026: Crab Orch., S. Cumb., Falls Crk. Falls, Grandview
1A_20%	2026: Crab Orch., S. Cumb., Falls Crk. Falls, Grandview
2A_10%	2036: Crab Orch.
2A_20%	2036: Crab Orch.
3A_10%	2036: Crab Orch.
3A_20%	2036: Crab Orch.
4A_10%	2036: Crab Orch.
4A_20%	2036: Crab Orch.
5A1_10%	2056: All UD's
5A1_20%	2046: All UD's except Crossville (MPL only), Crab Orch.
6A1_10%	2056: None
6A1_20%	2056: None
7A1_10%	2056: None
7A1_20%	2056: None
6A2_10%	2056: None
6A2_20%	2056: None
7A2_10%	2056: None
7A2_20%	2056: None
5A3_10%	2046: Crab Orch., S. Cumb., Fall Crk. Falls
5A3_20%	2046: Crab Orch., S. Cumb., Fall Crk. Falls
6A3_10%	2056: All UD's except Crossville (MPL only), Crab Orch.
6A3_20%	2056: All UD's except Crossville (MPL only)

Scenario	Year that UDs Experience Shortage
7A3_10%	2056: None
7A3_20%	2056: None
5A4_10%	2036: Crab Orch.
5A4_20%	2036: Crab Orch.

7.0 Recommendations

All of the discussion regarding the Scenario results in Table 7 leads us to conclude that the series of Scenarios from Scenario 2A through 6A1 represents the most logical and efficient infrastructure upgrade sequence. This sequence of Scenarios is pseudo-graphically represented in Table 9, where the yellow highlight reflects our 10% safety-factor timing, and the diagonal-hatching reflects our 20% safety-factor timing for the system upgrades.

Table 9: Recommended System Upgrade Ordered Timeline.

Upgrade Description (Scenario)	<=	2016	–	2026	–	2036	–	2046	–	2056	=>
Expand WTP Capacities (2A)											
Relax Institutional Constraints (3A)											
Expand Lake Holiday Service Area (4A)											
Remove Pipe Constraints (5A1)											
Raise Meadow Park Lake Dam (6A1)											

In reality, the WTP capacity (e.g. which “begins” first in the timeline) will have to keep pace with the evolution in the total demand levels after 2026. The City and District, thus, will need to decide if it is wiser to budget for a 2056-capacity WTP (and associated pipe upgrades) by 2026 or if it is more practical to upgrade the WTP in stages. If the City and District were to decide that they wish to perform all of the infrastructure upgrades by 2026 that would eventually meet the projected 2056 benchmark demand levels, then this analysis means that they should build infrastructure that meets the capacities in the furthest-right and highlighted columns of Table 10 (for required 2056 WTP capacities) and Table 11 (for required 2056 Conveyance capacities).

If however the City and District prefer to build the infrastructure in stages, then Table 10 shows what minimum total WTP capacity will be needed at any intermediate benchmark-year build date. It should be noted that Table 10 shows that the minimum capacity for certain WTPs decrease over time (e.g. MPL’s WTP between Scenarios 3A and 4A, and Crab Orchard’ WTP after the 2026-36 upgrade) primarily because the constraints for each Scenario are different. Thus, if the City and District were to prefer to build the infrastructure in stages, they might wind up building infrastructure for a higher capacity than is eventually needed (e.g. at the Crab Orchard WTP).

Table 11 likewise shows how the minimum conveyance needs (e.g. pipe capacities) may evolve over the recommended upgrade period. Figure 3 should be used to determine how the arc-node connections relate to Cumberland County’s physical conveyances. Note that since only OASIS arcs can be assigned constraints, WTP locations are not represented in OASIS by nodes as one might suspect. Thus the arcs between nodes 1 and 2 and between nodes 30 and 5 are two examples of arcs that primarily allowed us to specify WTP constraints in Scenario 1A, and thus may or may not correspond to any actual physical conveyances.

Table 10: Required WTP Capacities for Each Benchmark Year and Cumulative Scenario-Upgrades.

Peak WTP Capacity (MGD)	Expand WTP Capacities (2A, 2016-26)	Relax Institutional Constraints (3A, 2026-36)	Expand Lake Holiday Service Area (4A, 2026-36)	Remove Pipe Constraints (5A1, 2036-46)	Raise Meadow Park Lake Dam (6A1, 2046-56)
MPL WTP	2.59	4.95	4.41	10.54	12.44
Lake Holiday WTP	3.44	3.58	4.12	4.50	4.50
Crab Orchard WTP	2.42	5.17	4.82	4.62	4.62

The same logic regarding WTP capacities, if the City and District were to prefer to build the infrastructure in stages, apply to any conveyance needs that appear to diminish over time in Table 11. Note also that while the model seems to indicate that the conveyances from MPL and LH (nodes 10 and 20) to the West Cumberland UD (node 41) do not appear to be necessary, these conveyances may still be useful for maintenance reasons.

Table 11: Required Conveyance Capacities for Each Benchmark Year and Cumulative Scenario-Upgrades.

Arc (Pipe) Name	U/S	D/S	Expand WTP Capacities (2A: 16-26)	Relax Institutional Constraints (3A: 26-26)	Expand Lake Holiday Service Area (4A: 26-36)	Remove Pipe Constraints (5A1: 36-46)	Raise Meadow Park Lake Dam (6A1: 46-56)
MPL WTP	1	2	2.59	4.95	4.41	10.54	12.44
C to SCUD	2	4	1.55	2.06	2.06	2.84	2.84
MPL WTP to Cross MPL	2	11	0.88	0.89	0.36	0.37	0.37
MPL WTP to Cross LH/MPL	2	12	0.00	0.00	0.00	3.74	4.38
C to CO	2	21	0.00	1.82	1.82	4.62	4.62
C to WC	2	41	0.00	0.00	0.00	0.00	0.00
Crossville to Grandview	2	51	0.16	0.19	0.19	0.28	0.28
Crossville to SCUD	4	31	1.47	1.94	1.94	2.66	2.66
Crossville to FCFUD	4	61	0.08	0.11	0.11	0.19	0.19
Crab Orch to Crossville	5	2	0.00	0.00	1.46	0.00	0.00
CO WTP to COUD	5	21	2.42	3.36	3.36	4.62	4.62
COUD to GUD	5	51	0.22	0.00	0.00	0.00	0.00
MPL to MPL WTP	10	1	2.59	4.95	4.41	10.55	12.44
Lake Tansi to MPL WTP	15	1	5.00	4.47	4.01	5.00	5.00
Lake Tansi to MPL	15	10	5.00	2.81	2.81	2.39	2.05
Lake Holiday to WTP	20	12	3.44	3.58	4.12	4.50	4.50
Holiday to COUD via Cross	20	21	0.00	0.00	1.82	4.62	4.62
Holiday to WCUD	20	41	0.00	0.00	0.00	0.00	0.00
OC to CO WTP	30	5	2.42	5.17	4.82	4.62	4.62
Bon De Croft to WCUD	40	41	0.32	0.35	0.35	0.38	0.45

It should be noted that in Scenario 6A1, which meets all of the benchmark demands in 2056, and which raised MPL's normal pool by 18.5 feet (i.e. to 1836.7 feet), not all of MPL's usable storage was used up. In fact, MPL still had 904 and 1568 acre-feet of usable storage left with the 20% and 10% safety factors, respectively. If we use linear interpolation to thus subtract this much usable storage from the MPL storage at 1836.7 feet, we find that MPL would need to be raised 7.8 feet (to 1826 feet) or 12.8 feet (to 1831 feet) with the 10% and 20% safety factors, respectively to just meet the 2056 benchmark demands.

Appendix A – Data Collection / Analysis

Table 12: Meadow Park Lake S-A-E Data.

Stage (ft, NAVD88)	Volume (ac-ft)	Area (ac)	Description
1792	0.000	0.000	
1793	0.011	0.045	
1794	0.140	0.215	
1795	0.529	0.684	
1796	2.368	3.694	
1797	9.205	11.009	
1798	26.301	22.079	
1799	51.896	29.079	
1800	85.170	38.188	
1801	130.198	51.234	
1802	186.791	62.274	
1802.6	226.333	69.799	Physical Constraint
1803	255.253	74.624	
1804	335.906	87.110	
1805	429.876	100.983	
1805.6	493.088	109.731	Usable Storage (Dead)
1806	538.213	115.966	
1807	661.690	130.934	
1808	799.863	145.135	
1809	951.459	158.145	
1810	1115.102	168.627	
1811	1288.597	178.142	
1812	1471.080	186.729	
1813	1662.355	195.796	
1814	1862.903	205.219	
1815	2073.046	215.529	
1816	2294.149	226.669	
1817	2526.129	237.312	
1818	2768.167	246.773	
1818.2	2817.713	262.211	Max / Initial
1820	2973.694	269.680	
1822	3158.670	298.231	
1824	3361.444	324.240	
1826	3581.515	351.315	
1828	3819.783	380.091	
1830	4076.072	406.579	
1832	4350.391	435.439	
1834	4643.894	465.454	
1836	4957.516	497.193	
1838	5292.302	530.405	
1840	5648.701	563.512	
1842	6027.576	599.396	
1844	6430.361	636.896	

Table 13: Lake Holiday S-A-E data.

Stage (ft, NAVD88)	Volume (ac-ft)	Area (ac)	Description
1731	0.000	0.001	
1732	0.012	0.041	
1733	0.172	0.349	
1734	0.821	0.987	
1735	2.377	2.371	
1736	6.487	6.208	
1737	15.865	13.885	
1738	35.928	26.655	
1739	68.648	38.487	
1740	112.853	50.655	
1741	171.025	66.692	
1742	246.533	83.937	
1743	338.201	98.810	
1744	444.358	113.463	
1744.2	467.305	115.894	Physical Constraint
1745	563.242	123.733	
1746	691.760	133.001	
1746.2	718.522	134.604	Usable Storage (Dead)
1747	828.628	140.559	
1748	972.676	147.575	
1749	1124.002	155.102	
1750	1282.701	162.212	
1751	1448.408	169.040	
1752	1620.673	175.518	
1753	1799.092	181.255	
1754	1983.031	186.606	
1755	2172.573	192.316	
1756	2367.376	197.275	
1757	2566.999	201.859	
1758	2771.019	206.180	
1759	2979.377	210.551	
1760	3192.158	215.030	
1761	3409.478	219.629	
1761.25	3464.531	220.797	Max / Initial

Table 14: Fox Creek Lake S-A-E Data.

Stage (ft, NAVD88)	Volume (ac-ft)	Area (ac)	Description
1847.48	0	112.987	Usable Storage (Dead)
1850.48	433.294	138.113	Max / Initial

Table 15: Lake Tansi S-A-E Data.

Stage (ft, NAVD88)	Volume (ac-ft)	Area (ac)	Description
1806	0.000	0.000	
1807	0.001	0.005	
1808	0.018	0.034	
1809	0.090	0.132	
1810	0.314	0.323	
1811	0.765	0.599	
1812	1.561	1.003	
1813	2.812	1.543	
1814	4.725	2.291	
1815	7.465	3.249	
1816	11.309	4.477	
1817	16.583	6.090	
1818	23.424	7.618	
1819	31.856	9.290	
1820	42.080	11.228	
1821	54.392	13.393	
1822	68.939	15.766	
1823	85.962	18.293	
1824	105.591	21.009	
1825	128.068	23.935	
1826	153.442	26.823	
1827	181.832	30.031	
1828	213.554	33.462	
1829	248.799	37.054	
1830	287.796	41.036	
1831	331.094	45.619	
1832	379.087	50.436	
1833	432.174	55.739	
1834	490.748	61.446	
1835	555.194	67.586	
1836	626.119	74.304	
1837	703.819	81.144	
1838	788.526	88.387	
1839	880.839	96.363	
1840	981.344	104.652	
1841	1090.165	113.040	
1842	1207.605	121.969	Physical Constraint
1843	1334.307	131.476	
1844	1470.725	141.504	
1845	1617.489	152.061	Usable Storage (Dead)
1846	1774.811	162.614	
1847	1942.831	173.484	
1848	2121.975	184.831	
1849	2312.543	196.369	
1850	2514.721	208.023	
1851	2728.783	220.172	
1852	2955.158	232.601	
1853	3194.146	245.499	
1854	3446.284	258.772	
1855	3711.900	272.659	
1856	3992.023	287.590	

Stage (ft, NAVD88)	Volume (ac-ft)	Area (ac)	Description
1857	4287.287	302.957	
1858	4597.897	318.290	
1859	4923.931	333.850	
1860	5265.701	349.695	
1861	5623.441	365.856	
1861.377	5752.831	385.880	Institutional Constraint
1861.71	5887.353	403.566	Max / Initial

Appendix B – Additional Analysis – Meadow Park Lake and Fox Creek Lake

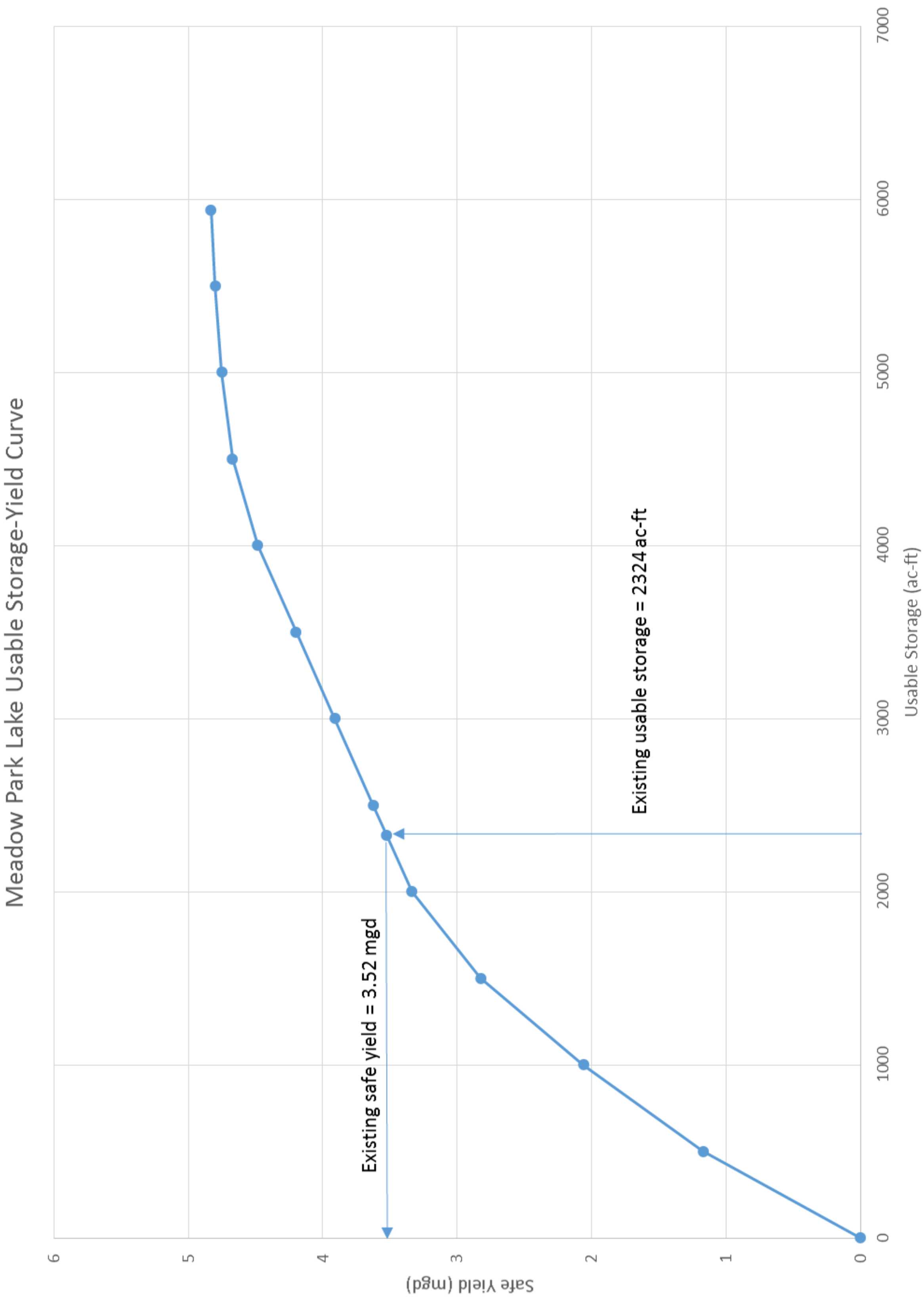

Figure 1. Sequent Peak Analysis for Meadow Park Lake.

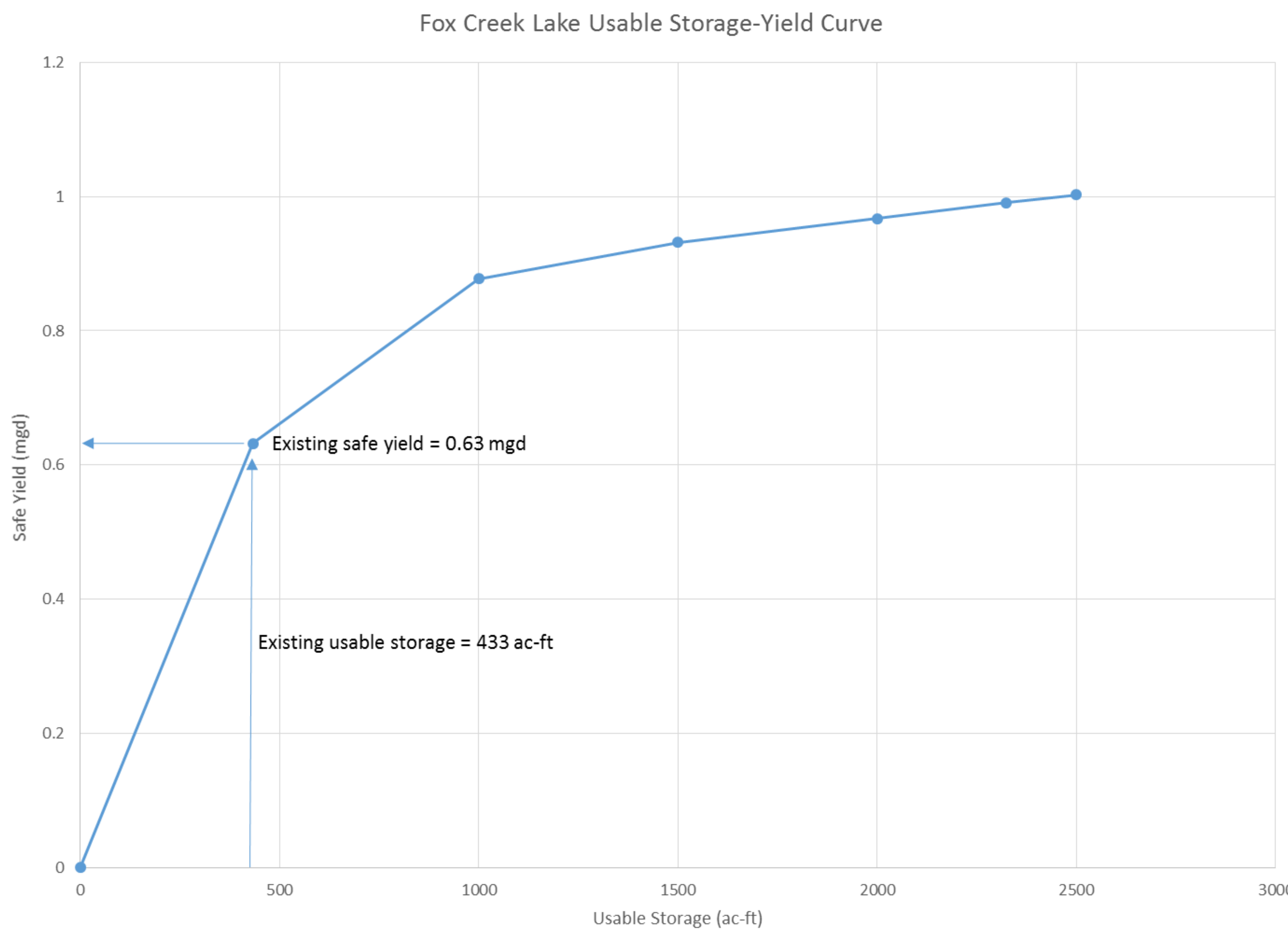

Figure 2. Sequent Peak Analysis for Fox Creek Lake.

Appendix C – System Model Schematic and Settings

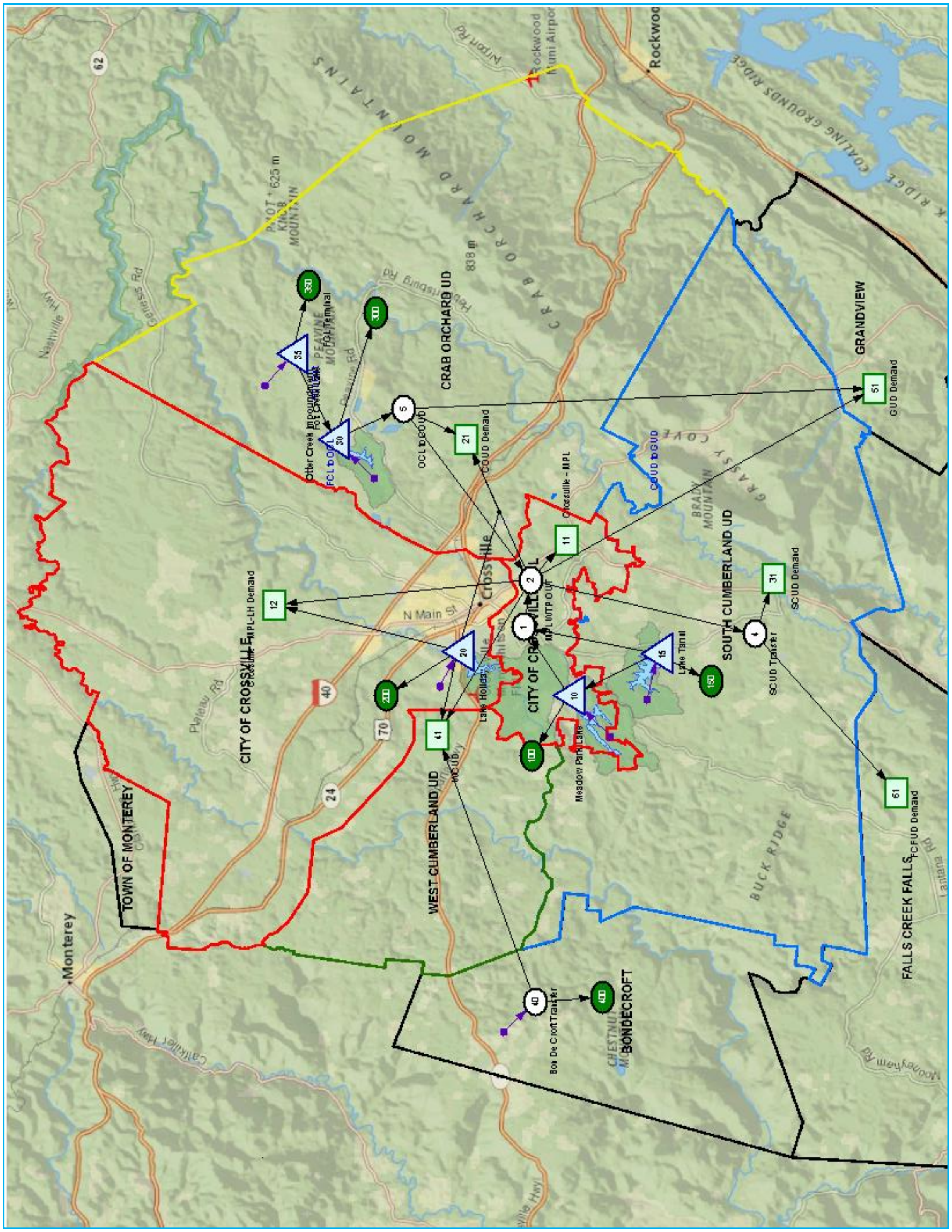

Figure 3. OASIS model schematic containing all of the elements used in the Scenarios in the Model Analysis.

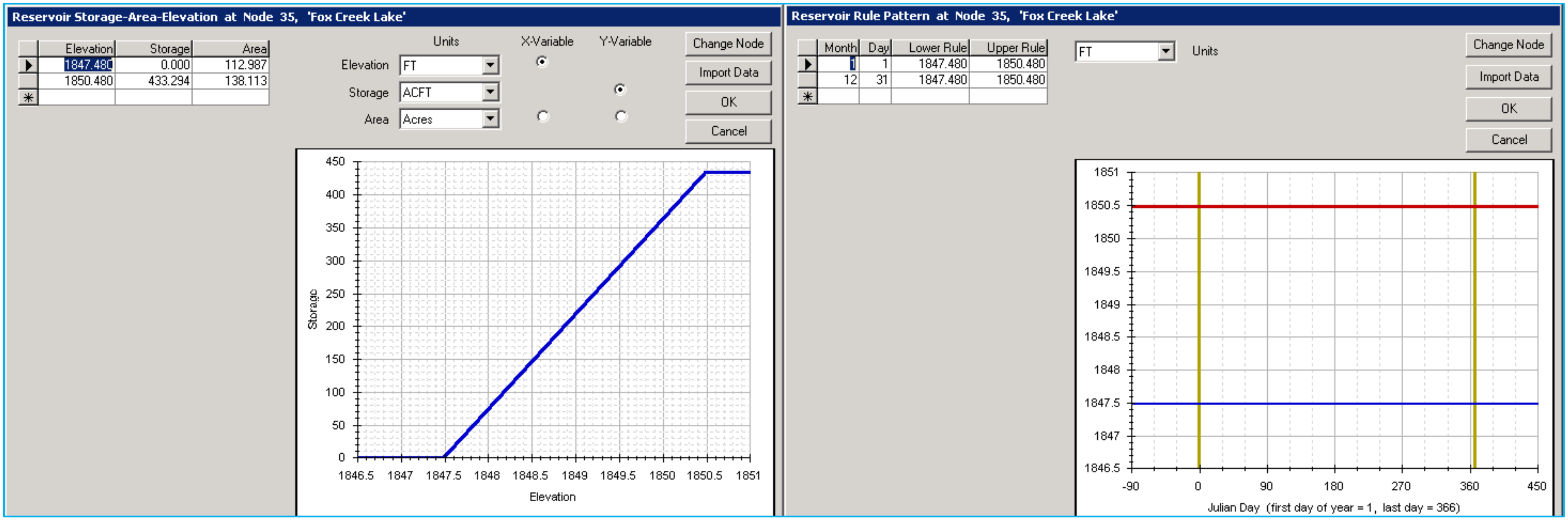

Figure 4. OASIS model parameters for the Fox Creek Lake reservoir, or reservoir node 035.

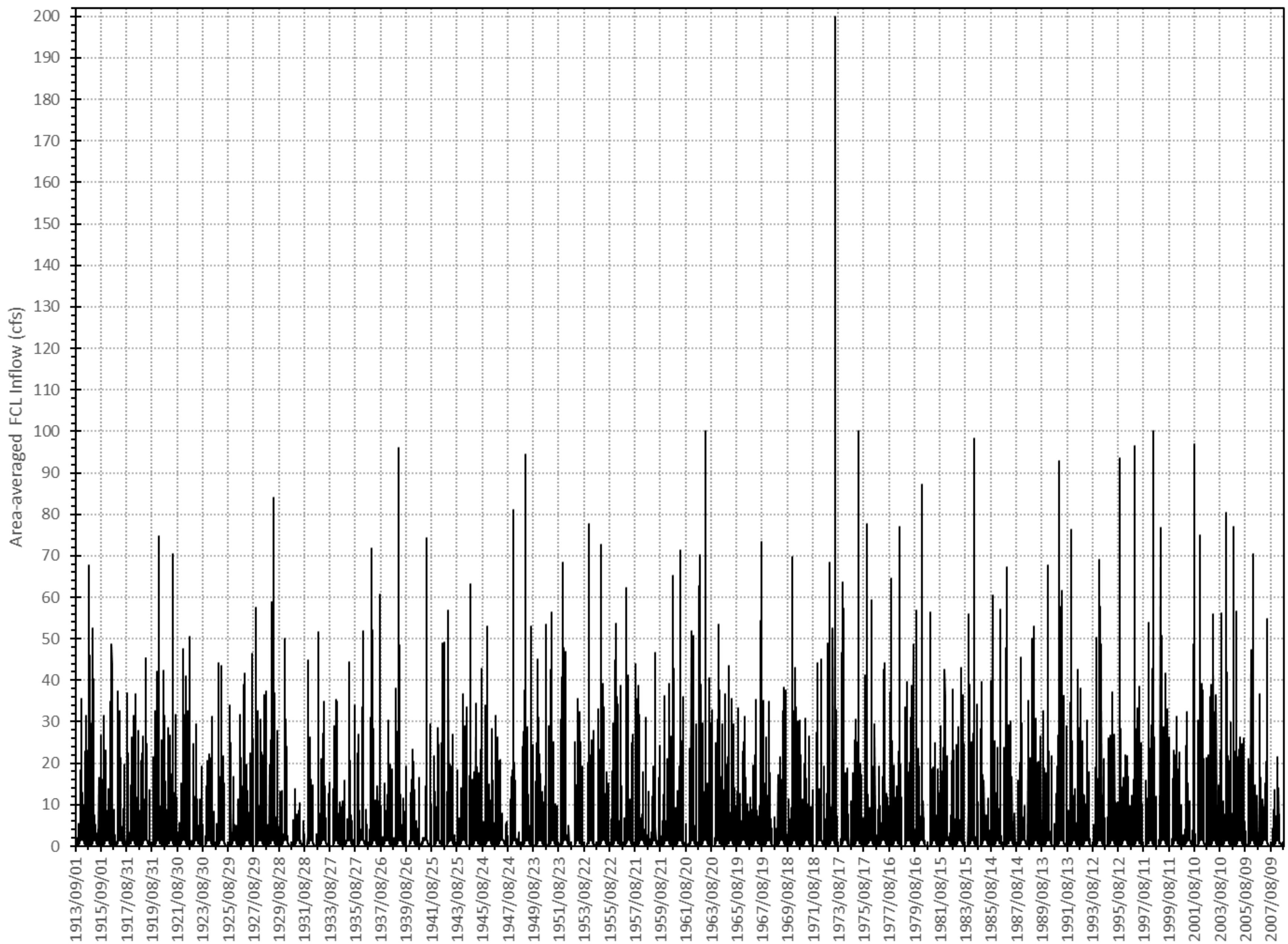

Figure 5. FCL upstream inflow time series over the simulation period.