REPORT

Multi-Reservoir Yield and Operations Analysis

CAMP DRESSER & McKEE INC.
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City of Shawnee, Oklahoma

March 2012

CDM Smith

REPORT

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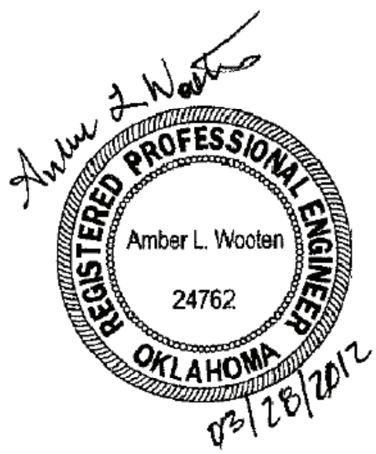

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Acronyms

AF	acre-feet
AFY	acre-feet per year
BOR	U.S. Bureau of Reclamation
cfs	cubic feet per second
City	City of Shawnee
MG	million gallons
mgd	million gallons per day
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
OCWP	Oklahoma Comprehensive Water Plan
OWRB	Oklahoma Water Resources Board
PCDA	Pottawatomie County Development Authority
SCS CN	Soil Conservation Service curve number
TOC	total organic carbon
USACE	U.S. Army Corps of Engineers
USDA	United States Department of Agriculture
USGS	United States Geological Survey
VBA	Visual Basic for Applications
WSEL	water surface elevations
WTP	water treatment plant

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Section 1
Executive Summary

The City of Shawnee (City) contracted with CDM Smith to evaluate its three municipal water supply reservoirs: Twin Lakes #1 and #2 (collectively called Twin Lakes) and Wes Watkins Reservoir. The primary purpose of this project is to establish the expected water supply capacity from each reservoir when operated individually and when operated as part of a complete water supply system. Other project tasks included evaluation of each reservoir's watershed and development of drought management plan. This report documents the methods and results of the hydrologic assessment and provides recommendations for future actions.

For the purpose of this study, firm yield is defined as the average daily withdrawal from a water supply system that can be sustained through the available record of inflows without entirely depleting the system storage. The available record of inflows (1953 to 2011) includes the drought of record which is defined as the period July 1954 to April 1957. This analysis was conducted in accordance with the guidelines established in the 2012 update to the Oklahoma Comprehensive Water Plan (OCWP). Hydrologic estimates of streamflow for both of the ungaged contributing watersheds within the system were generated using transposition by area ratio method and a dynamic simulation model was used to simulate the drawdown and recovery of the multiple reservoirs.

The firm yield estimates for the Twin Lakes (in this study, Twin Lake #1 and Twin Lake #2 were modeled as a single reservoir with two connected volumes as described in Section 6.1) and Wes Watkins are presented in Table 1-1. The table lists the firm yield of the reservoirs operating individually, and also conjunctively, in the preferred operating mode of balancing water surface elevation and constraining withdrawals to permit allowances.

Table 1-1: Firm Yield Estimates for Period of Record Including Drought of Record (July 1954 to April 1957)

Reservoir	Firm Yield (mgd)	Permit Limit (mgd)	Available to Shawnee (mgd)
Twin Lakes	5.5	7.1	5.5
Wes Watkins	3.0 [A]	3.8 [B]	2.3 [B]
System Total – Combined Individual Yield	8.5	10.9	7.8 [B]
Balance Water Surface Elevation, No withdrawals from the Wes Watkins Recreation Pool	8.2	10.9	4.7 [B]

[A] Firm yield of Wes Watkins Reservoir without withdrawals from the recreational pool. Removing the recreational pool constraint in the model, the firm yield of Wes Watkins increases to 4.4 million gallons per day (mgd).

[B] Pottawatomie County Development Authority (PCDA) holds the permit for Wes Watkins. Approximately 3.8 mgd is allocated to Shawnee. The remaining approximately 0.7 mgd is allocated to Tecumseh. The permit limit in the table reflects the allocation amount to Shawnee. The amount available to Shawnee is the amount of water from the firm yield available to Shawnee if Tecumseh takes its full 0.7 mgd allocation.

A windshield survey of the watersheds for Twin Lakes and Wes Watkins was completed March 1, 2011. No significant low flow impediments were discovered. No actions are recommended at this time.

The drought management plan evaluated drought response triggers related to infrastructure and physical water availability. Generally, voluntary rationing should be used when there is a low risk of water shortage occurring. Voluntary rationing is recommended when either Twin Lakes or Wes Watkins reaches elevation 1064. Mandatory restrictions are reserved for when the risk of water shortage is higher. Mandatory rationing is recommended in four stages based on decreasing levels at Twin Lakes and increasing treated water production rates. The drought management plan is provided in Section 9 of this report.

1.1 Conclusions

At the conclusion of this study, Shawnee has enough raw water from their reservoirs, Twin Lakes and Wes Watkins, under the balanced surface water elevation operational scenario (firm yield of 8.2 mgd based on physical availability, 4.7 mgd available to Shawnee when additionally limited by permit constraints) to meet the current projections for 2060 average annual day water demands of 4.7 mgd. The firm yield analysis shows that the Twin Lakes use permit (approximately 7.1 mgd) exceeds the firm yield (5.5 mgd). It is not recommended that Shawnee withdraw the full permit amount from Twin Lakes, unless temporarily in a coordinated system operation with the Wes Watkins reservoir. Finally, the drought triggers identified in the Section 9 can provide adaptive management based on climate and demand.

Section 2
Introduction

2.1 Project Objectives

The City has three surface water reservoirs: Twin Lake #1 and #2 (collectively called Twin Lakes) and Wes Watkins Reservoir. This study has the primary purpose of determining the firm yield of the reservoirs when they are operated individually (updating previous studies) and operated as a system (previously unknown). This section reviews key aspects of the project's scope of work.

2.1.1 Watershed Assessment

This task required review of aerial photographs and topographic maps and windshield survey of both of the Twin Lakes and Wes Watkins watersheds to qualitatively assess how effectively the watersheds contribute to the storage reservoirs, deliver water, and determine if there are any measures that may potentially reduce unwanted diversions or restrictions in the mobility of runoff to the reservoirs. Results from this task are included in Section 4 of this report.

2.1.2 Hydrologic Inflow Estimates

This task required estimating the inflow to the reservoirs. Initially, runoff estimates were calculated using the five methods adopted by the Oklahoma Water Resources Board as part of the 2012 update to the OCWP reservoir yield methodology. These estimates were compared to back-calculated net inflows created using operating logs between 2006 and 2010. More information on this task is provided in Sections 5 and 7 of this report.

2.1.3 Model, Yield, and Operation Analysis

These tasks required development of a dynamic simulation model, then using this model to determine firm yield, defined as the maximum withdrawal amount calculated based on the 1952 – 2010 period of record (which includes the driest period of record) that can be met 100 percent of the time, for the individual reservoirs and firm yield when the three reservoirs are operated as a system. Sections 6 and 8 describe work completed and results from these tasks.

2.1.4 Drought Management Analysis and Response Plan

This task required development of a drought management and response plan based on the hydrologic evaluations described above. This plan was intended to define actions to be taken by the City when certain conditions develop that negatively impact water supply capabilities. Should water demands exceed OCWP projections, other operational scenarios may be employed by the City to increase available raw water. Reservoir operational scenarios and their corresponding firm yield are presented in Section 8 of this report. Through conversations with City staff, a drought management plan was developed and is presented in Section 9 of this report.

2.1.5 Other Tasks

Other tasks required gathering existing data from the City and others, meeting with City staff, and documentation of results. This report in its entirety serves to document the project methods and findings.

2.2 Definition of Firm Yield

For the purpose of this study, "Firm Yield" is defined as the average daily withdrawal from a water supply system that can be sustained through the drought of record without entirely depleting the system storage. In some cases, noted throughout, this definition is modified such that storage does not drop below critical levels, or that withdrawals comply with all available permit constraints. The drought of record is defined as the period of 1954 - 1957. Previous studies of Twin Lakes and Wes Watkins utilize different terms and definitions when discussing yield. In this study, terminology consistent with the previous study will be used and definition of terms provided so that a clearer understanding can be made between previous work and this project.

This study has focused on the hydrologic availability of water. The yield values reported are based on water availability (which is independent of infrastructure and permit constraints) and also on operational and permit compliance. Methods used for the firm yield estimates comply with the prescribed methods in the 2012 update to the OCWP.

Section 3
Description of Shawnee Water Supply System

The City of Shawnee currently has three surface water supply sources, illustrated in Figure 3-1. This section provides descriptions of each of these sources.

3.1 Twin Lakes

Shawnee Twin Lake #1 and #2 (collectively called Twin Lakes) are located approximately 8 miles west of the City on South Deer Creek. The reservoirs are connected by an equalizing channel at an approximate elevation of 1063.0 feet NAVD88. Twin Lake #1 was constructed by the City in approximately 1953 with Twin Lake #2 constructed in approximately 1960. The water from these reservoirs is fully allocated to the City through their current permit of 8,000 acre-feet per year (AFY). The intake elevation at Twin Lake #1 is 1042.5 feet; the intake elevation at Twin Lake #2 is 1042.5 feet. The principal spillway elevation is 1073.5 feet (based on conversations with City staff, the spillway was raised one foot from the elevation shown on the record drawings).

3.2 Wes Watkins Reservoir

Wes Watkins Reservoir was constructed in 1997 by the Natural Resources Conservation Service (NRCS) for flood control, recreation, and water supply. The lake is operated by the Pottawatomie County Development Authority (PCDA). PCDA holds the only permit for the reservoir (5,000 AFY). Through long-term contracts, PCDA allocated approximately 4,250 AFY to Shawnee and 750 AFY to Tecumseh Utility Authority. The recreation pool is defined at El. 1062.0. The principal spillway elevation is 1074.0 feet.

3.3 Use of Supplies

Based on conversations with City staff, the City historically has utilized only raw water from the Twin Lakes due to high total organic carbon (TOC) levels in Wes Watkins. Recently, due to modifications at the water treatment plant (WTP), the City has begun using raw water from Wes Watkins to meet water demands. It is anticipated that future operations will include blending of raw water supplies.

Table 3-1 summarizes the key characteristics of the reservoirs in the Shawnee system. These values are approximate, but small deviations in these values do not affect firm yield estimates.

Table 3-1: Reservoir Characteristics

Reservoir	Available Storage (acre-feet) [A, B]	Available Storage (MG) [B]	Max Surface Area (acres)	Depth of Usable Storage (feet)	Drainage Area (square miles)
Twin Lake #1	20,335	6,626	1,324	31.0	32
Twin Lake #2	8,928	2,909	776	31.0	
Wes Watkins	13,993	4,559	1,142	29.7	39

[A] Acre-feet (AF). One AF is approximately 325,850 gallons (or 0.33 million gallons [MG]) of water.

[B] The storage amount corresponds to the available volume above the lower intake elevation

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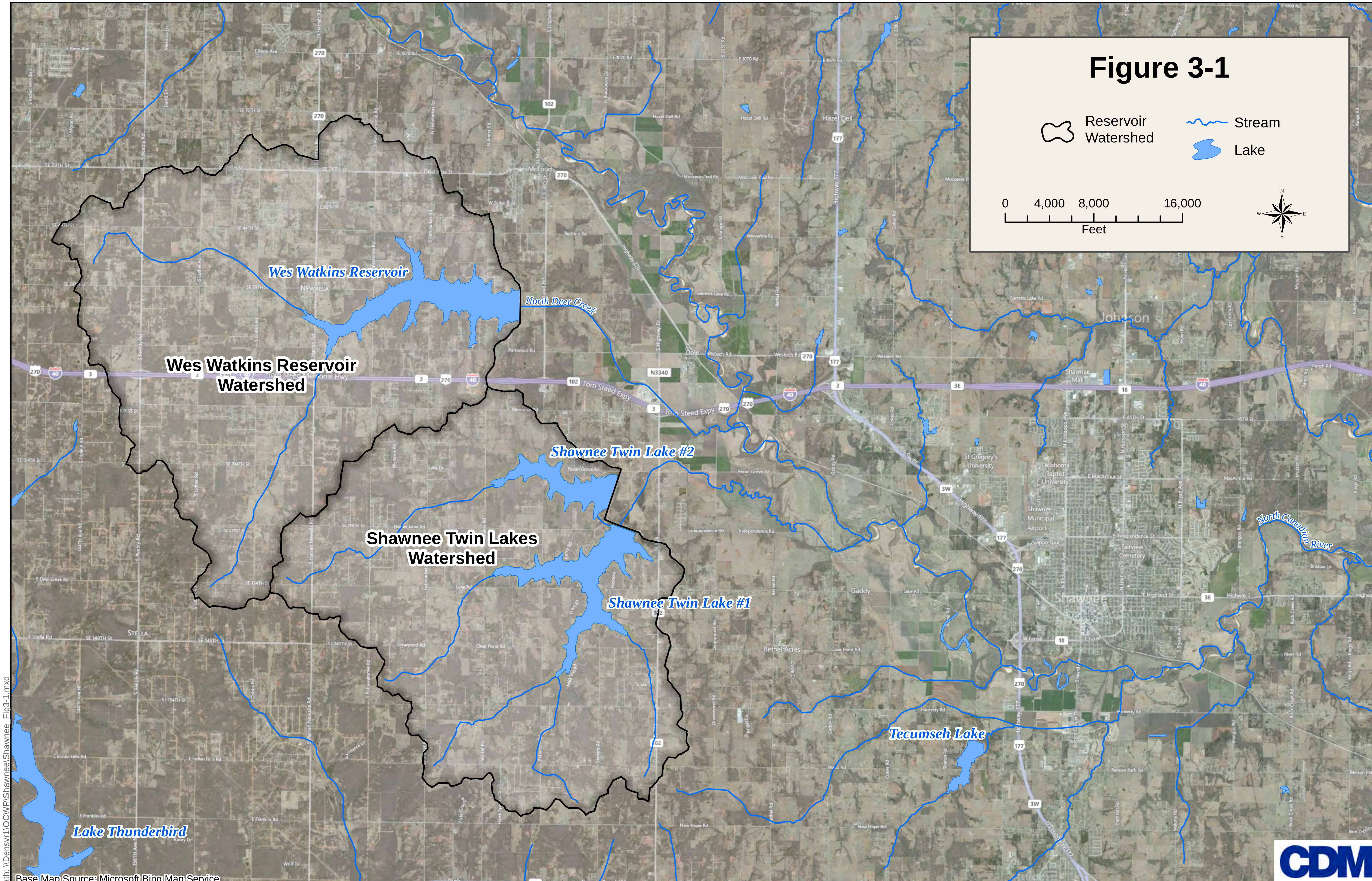

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Section 4
Watershed Assessment

A field assessment was made on March 1, 2011. This section presents findings from this investigation.

4.1 Twin Lakes

Shawnee Twin Lakes #1 and #2 (collectively called Twin Lakes) have a combined drainage area of approximately 32 square miles. Land use in the watershed is primarily grasslands and shrubland, as illustrated in Figure 4-1. Many of the rural residential homes have small stock ponds. During the field assessment no significant crop fields were noted. Residential dwellings are located adjacent to the lakes.

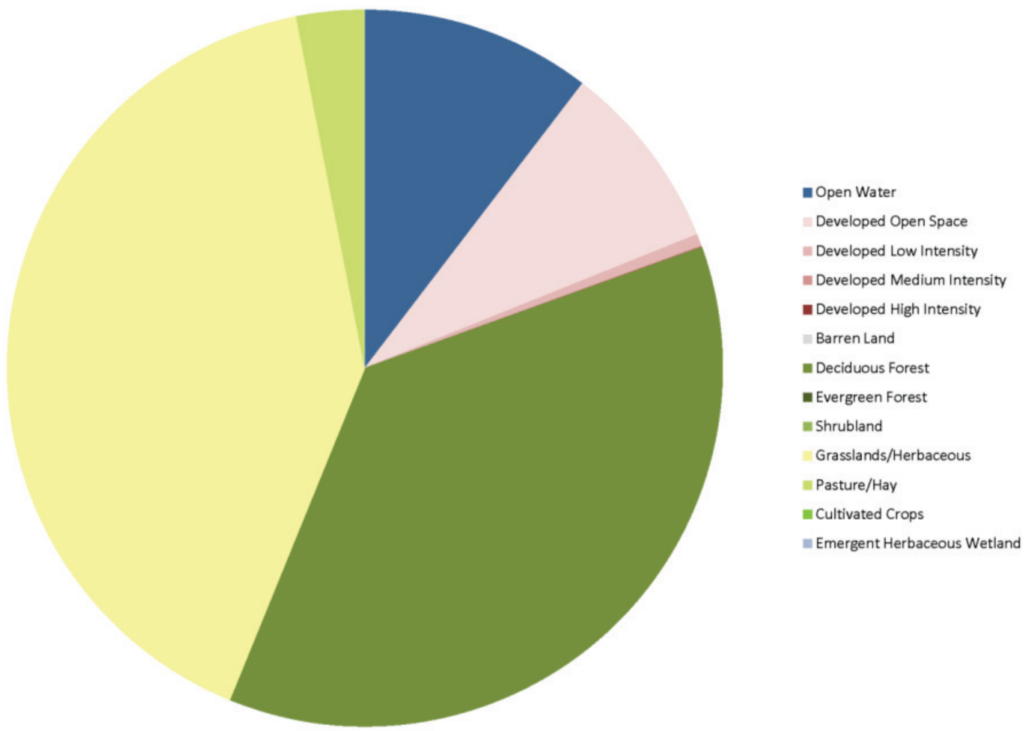

Figure 4-1: Land Use in the Twin Lakes Watershed

No specific diversions or restrictions in the mobility of runoff enroute to the reservoirs were found at the time of the windshield survey. The photographs below indicate typical conditions found in the Twin Lakes watershed. All photographs taken during the field visit are included in Appendix A.

Several blockages, like overgrowth or debris in ditches or flow paths, were discovered. While these may prevent low flows from reaching the reservoirs, they may aid in filtration. Filtration occurs as a function of the dense vegetation abutting the stream corridors that takes up nutrients and can help reduce nutrient inflow into the reservoirs.

Figure 4-2: Typical open field in Twin Lakes Watershed; Photograph 4 taken near intersection of N333 and E119

Figure 4-3: Stream near intersection of N333 and E118 (Photograph 8)

Figure 4-4: Drainage ditch filled with leaves and other debris; Photograph 6 taken near intersection of N333 and E118

Figure 4-5: Drainage ditch along N333 (Photograph 7)

Figure 4-6: Disturbed land near intersection of N333 and E118 (Photograph 7a)

Figure 4-7: Private residence with several large diameter drainage pipes; Photograph 29 taken near S. Pottawatomie and Hackney

Figure 4-8: Large tree debris in drainage channel; Photograph 32 taken near intersection of Home Lake Road and Mustang

Due to the small amount of area owned in the watershed, most of the impediments are outside of Shawnee's jurisdiction. No actions are recommended at this time.

4.2 Wes Watkins Reservoir

Wes Watkins Reservoir has a drainage area of approximately 39 square miles. Land use in the watershed is primarily grasslands and shrublands as illustrated in Figure 4-9. Many of the rural residential homes have small stock ponds. There is more low density development in the Wes Watkins watershed than in the Twin Lakes watershed. Unlike around the Twin Lakes, there is a green space around Wes Watkins that prevents development directly adjacent to the lake.

No specific diversions or restrictions in the mobility of runoff enroute to the reservoir were found at the time of the windshield survey. The photographs below indicate typical conditions found in the Wes Watkins watershed. All photographs taken during the field visit are included in Appendix A.

Due to the small amount of area owned in the watershed, most of the impediments are outside of Shawnee's jurisdiction. No actions are recommended at this time.

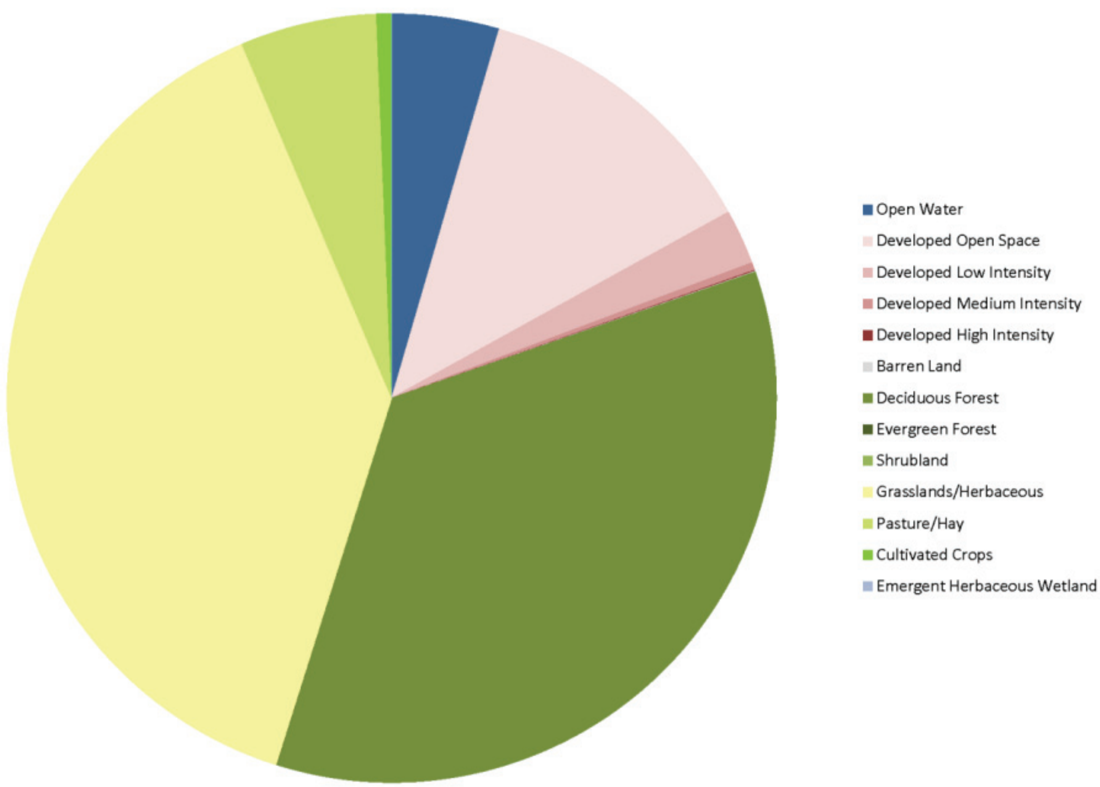

Figure 4-9: Land Use in the Wes Watkins Watershed

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Section 5
Firm Yield Methodology

This section discusses the approach for determining the firm yield for the Twin Lakes and Wes Watkins Reservoir. This approach was adopted by the Oklahoma Water Resources Board (OWRB) as part of the 2012 update to the OCWP (OCWP Technical Memorandum is attached in Appendix B).

Firm yield, defined as the maximum daily demand that can be fully met with reservoir withdrawals throughout the period of analysis without entirely depleting the system storage, is dependent on the amount of flow into the reservoir, the storage capacity of the reservoir, reservoir evaporation and other losses, reservoir operational constraints, and the seasonal pattern of water demands placed on the reservoir.

5.1 General Approach

As part of the 2012 update to the OCWP, a standard method for determining reservoir yield was developed. The tool was developed around single reservoir systems and was modified for this project to accommodate multiple reservoirs systems. The OCWP approach built on standard practices of the United States Bureau of Reclamation (BOR) and the United States Army Corps of Engineers (USACE). The OCWP approach has the following criteria (only criteria applicable to this project are listed here, a complete list is available in Appendix B):

- *Definition of firm yield* – Firm yield, as defined for this project and OCWP, is the amount of water that can be withdrawn from a reservoir each year including the years of the critical drought of record without the reservoir (or its designated storage pool) going dry.
- *Period of record* – For the North Canadian River major river basin, in which both Twin Lakes and Wes Watkins Reservoir are located, the period of record must include 1940 – 1995. For this project, a period of record from 1940 – 2010 is used and includes the drought of record which occurred from 1954 – 1957.
- *Time step* – This project follows the OCWP approach of using a monthly timestep.
- *Seasonal demand fluctuations* – The OCWP applies monthly percentages to annual demand based on historical data. For this project, daily influent flow data to the Shawnee WTP taken from monthly reports was used to determine monthly percentages.
- *Inflows* – Gage data should be used if available. When it is unavailable, transposition from nearby gaged basins is acceptable. Neither Twin Lakes nor Wes Watkins had gage data available. Section 7 discusses how inflow was estimated for this project.

- *Sedimentation* – The OCWP uses measured data from nearby similar reservoirs to develop sediment loading rates. The loading rates are then applied over the specified sedimentation period (either 100 years or the project-specific planning period) to estimate the total loss of available storage. For this project, it was considered that sedimentation would not have impacted the conservation pool because there is significant permanent (also called dead) storage below the lower intake of the reservoirs. In Twin Lakes below the lower intake there is approximately 1,259 acre-feet (or 410 MG) of permanent storage, which is 4 percent of the overall storage. In Wes Watkins there is approximately 307 acre-feet (or 100 MG) of storage, which is 2 percent of the overall storage.

- *Operational flows* – The OCWP tool is configured so that water above the top of the conservation pool at the end of each month "spills" so that the model never ends a month with water above the conservation pool. This project follows the OCWP approach.

- *Operating logic* – Because the OCWP tool was designed around a single reservoir, evaluation of operating decisions was unnecessary. For this project, since it is a multiple reservoir system, the method was modified to include prioritization of sources in some operational scenarios. These scenarios included: (1) balancing the water surface elevations (WSEL) of the two reservoirs to ensure that neither one was drawn down more than a couple feet below the other, (2) shared withdrawals from both reservoirs until there was a danger of lowering the WSEL of Wes Watkins below the recreational pool at which point withdrawals are made exclusively from Twin Lakes, and (3) system optimization where Wes Watkins was operated above its average annual firm yield until a drought condition when withdrawals were shifted to Twin Lakes.

- *Pool constraints* – The OCWP defines the bottom of the "available water" as the lowest level at which municipal and industrial withdrawals can physically be taken or the bottom of the conservation pool, whichever is higher. In this project multiple analyses were completed, some used the lowest intake elevation as the bottom of available water while others used Wes Watkins's recreational pool elevation as the bottom of the available water.

- *Seepage* – The OCWP method allows seepage to be applied if it is deemed significant. In this project approximately 0.5 cubic feet per second (cfs) was used to account for seepage at Twin Lakes and Wes Watkins. Visual inspections of seepage at three times throughout the project showed only small amounts of seepage in winter and spring and almost no seepage in the summer.

- *Reservoir evaporation* – This project follows the OCWP approach of calculating evaporation using the reservoir surface area elevation at the beginning of each monthly time step. Evaporation was estimated using 33 years of pan evaporation data from the Lake Overholser gage in Oklahoma City, which was obtained from the Yield Analysis of Shawnee Lakes 1 & 2 Technical Report 89-5. Precipitation data was estimated from daily rainfall data obtained for the entire simulation period from the Shawnee Municipal Airport.

- *Tools* – For this project the OCWP spreadsheet tool was modified to accommodate a multiple reservoir system.

5.2 Inflow and Other Model Parameters

The OCWP identified five methods for estimating and applying inflow time series. These methods are described below.

- *United States Geological Survey (USGS) stream gages* – For basins with USGS stream gages immediately upstream of the reservoir, these gages should be the primary source of reservoir inflow data. This method is not applicable to this project because no USGS gages were located immediately upstream of either Twin Lakes or Wes Watkins Reservoir.

- *Net inflow estimates from operating logs* – For reservoirs with substantial monthly operating logs, water balance calculations can provide reliable estimates of net hydrologic flux into or out of a reservoir. Data from the City's WTP between January 2006 and January 2010 was used to calculate inflows for Twin Lakes. Short periods of withdrawal from Wes Watkins reported during fall of 2009 and spring of 2010 were incorporated into the analysis. Since operating data did not extend back to the drought of record, this method was not used to estimate inflows for the entire period of record. However, the inflow estimates from other methods were compared to the net inflow estimates from operating log as a confirmation of the validity of the estimation. More information on how this method was used in this project is available in Section 7.

- *Streamflow transposition by area ratio* – For basins with no streamflow records, a surrogate gage is used to generate new synthetic monthly time series of flows or to fill in gaps in existing data. Surrogate gage is based on proximity to the reservoir and similarities in drainage basins. This method was selected to estimate inflows to Twin Lakes and Wes Watkins. Section 7 provides details on use of this method.

- *Statistical record extension* – For basins with partial streamflow records upstream of the reservoir, periods of missing streamflow data can be filled based on the flow in nearby measured streams using the Maintenance of Variance Extension (MOVE.2) statistical technique. The selection of an appropriate reference gage is an important aspect of applying the MOVE.2 technique. Selection of reference basin should have a similar basin size, land use, soils, and slopes to the basin with missing data. This method offered no additional accuracy over the streamflow transposition by area ratio method, see Section 7 for more information.

- *Soil Conservation Service curve number (SCS CN) approach for runoff flow* – Used in combination with area ratio method, the SCS CN may be used to estimate the runoff fraction of the streamflow record using precipitation records. This method offered no additional accuracy over the streamflow transposition by area ratio method, see Section 7 for more information.

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Section 6
Model Description

6.1 Model Description

A simulation model of the Shawnee water supply system was developed in order to evaluate the effects of storage, operations, and hydrologic inflow on the system yield. The model uses flows from the hydrologic time series described in Section 7 as input and routes flow through the system hydrologically. Mass balance computations are performed at each storage reservoir and the calculations include withdrawals, releases, seepage, surface precipitation, and surface evaporation as shown in Figure 6-1 and 6-2.

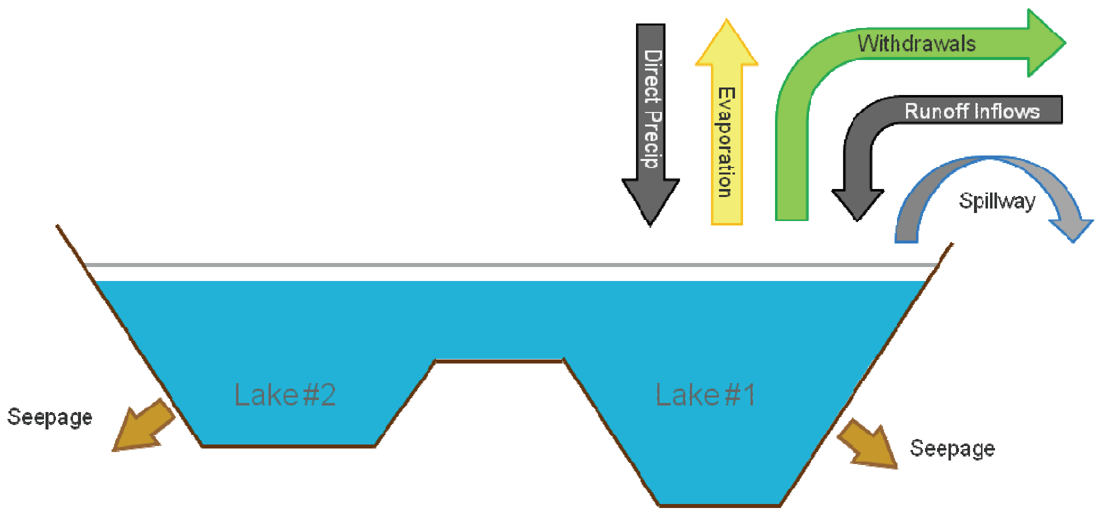


Figure 6-1: Mass balance for Twin Lakes with high water surface elevation

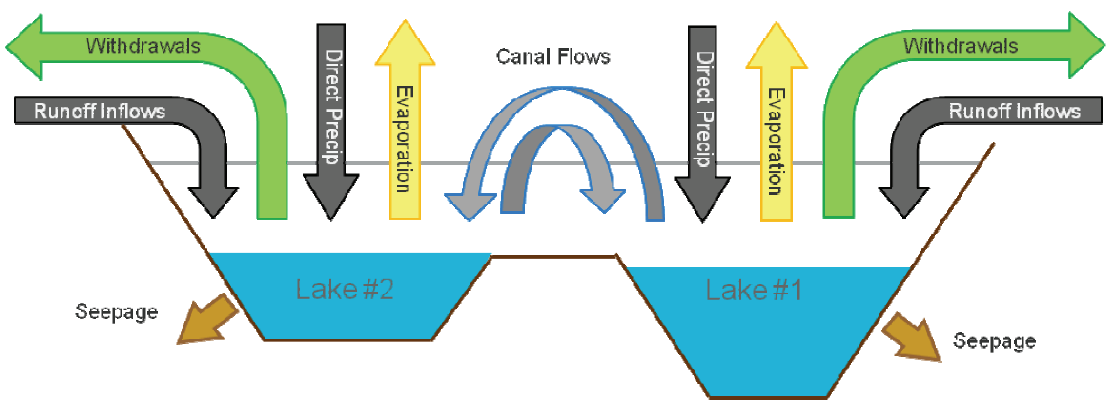


Figure 6-2: Mass balance for Twin Lakes with lower water surface elevation

Figure 6-1 illustrates mass balance for Twin Lakes when the WSEL is above the equalization canal. The mass balance for Wes Watkins is similar to this figure. Figure 6-2 illustrates the mass balance for Twin Lakes when the WSEL is below the equalization canal. With a lower WSEL, the inflow to the each lake is calculated individually.

The model was programmed to perform mass balance computations using a monthly timestep.

Operating rules are programmed into the model to replicate actual operating procedures and decision processes used by Shawnee.

6.2 Simulated System Element Details

The general mass balance equation for each reservoir in the simulation model is stated in Equation 6-1. The input and output variables are described in detail in the following sections.

$$S_T = S_{T-1} + Q_r + P_T - E_T - Seepage_r - \sum Withdrawals - Spill_r$$

Equation 6.1. Mass Balance Equation

where:

- S_T = Reservoir storage for present time period
- S_{T-1} = Reservoir storage for previous time period
- Q_r = Runoff
- P_T = Precipitation
- E_T = Surface evaporation from reservoir
- $Seepage_r$ = Seepage loss from reservoir
- $\sum Withdrawals$ = Sum of withdrawals from reservoir
- $Spill_r$ = Spill Volume

6.2.1 Runoff

Runoff is calculated according to the process described in Section 7. Runoff inflow is estimated from the incremental streamflow recorded between two gages on Little River (USGS gage numbers7230000 and 7230500) using the area ratio method defined in Section 5. These gages have a coincident 58-year period of record that includes the data during the drought of record. Runoff is estimated for each reservoir on a monthly timestep and added as an input into the simulation model.

6.2.2 Precipitation

Direct precipitation is defined as the rainfall that falls on the surface of the reservoir. Precipitation is collected from the National Weather Service (NWS) National Climatic Data Center. Direct precipitation is calculated as the product of the surface area of the water body at the beginning of the month and the sum of daily precipitation data occurring in the month. Precipitation data for this project was estimated using information from Shawnee Municipal Airport (COOP ID #348110).

6.2.3 Evaporation

Pan evaporation data was collected from the NWS gage on Lake Overholser in Oklahoma City. Pan evaporation data was multiplied by pan coefficient of 0.7 to convert to free air evaporation. Free air evaporation is then multiplied by the surface area of the reservoir to arrive at the evaporation loss value for use in Equation 6.1.

6.2.4 Seepage

Seepage is the transfer from an above ground reservoir storage to the adjacent surface water features (e.g., seepage ditch) and groundwater storage under and surrounding the reservoir. Seepage is a function of water levels in the reservoir and the surrounding aquifer, soil characteristics, and reservoir design. Because of these dependencies, seepage losses can vary greatly. Based on visual observations of seepage in January, March, and June 2011, a value of 0.5 cfs per lake was used. Seepage from Twin Lakes and Wes Watkins is minimal and dependent on WSEL. In this simulation, in each timestep seepage losses from each reservoir are treated as a function of water surface elevation.

6.2.5 Withdrawals

Withdrawals from Twin Lakes and Wes Watkins are used to satisfy the water demands of Shawnee. (Tecumseh also has rights to withdraw water from Wes Watkins, but to date has not used this raw water supply.) Withdrawals occur daily and are dependent on many factors including time of year, weather, etc. During the model calibration process, observed withdrawal data from logs was used for Twin Lakes. To simulate demand variability over the course of the year, demand was adjusted using a multiplier that varied monthly. Demand is higher in the summer, when temperatures are higher and precipitation amounts are lower. These multipliers are summarized in Table 6-1.

Table 6-1. Demand Multiplier Summary

Month	Demand Multiplier
January	0.93
February	0.75
March	0.90
April	0.91
May	0.99
June	1.10
July	1.21
August	1.29
September	1.09
October	1.06
November	0.89
December	0.89

6.2.6 Spillage

When a reservoir's capacity is exceeded, overflow or spillage occurs. Spillage is calculated in the simulation model when the WSEL at the end of the month exceeds the reservoir capacity. Spilled water is lost from the water supply system. For reference, Table 6-2 lists the spill elevations for each reservoir.

Table 6-2. Spillway Elevations

Reservoir	Spillway Elevation (ft NAVD88)
Twin Lakes [A]	1073.5
Wes Watkins	1074.0

[A] A single spillway is used for both Twin Lake #1 and #2

6.3 Simulation Software

CDM Smith used Microsoft *Excel* 2007 with Visual Basic for Applications (VBA) to simulate the Shawnee Reservoir system. For each simulation, a workbook with live equations and links was built that stores the set of input data for the 58-year period of historic simulation. The water balance described in Equation 6-1 was computed for each monthly time step. Using an *Excel* spreadsheet for the simulation preserves every calculation in the reservoir simulation giving the user flexibility in the quality control process. A user-defined VBA function was used for interpolating the stage-storage relationship in each time step.

Separate *Excel* spreadsheets were built for each operational scenario including individual operation of each reservoir, the optimized system operation, operation for balanced WSEL between reservoirs, operation maintaining permit restrictions, and system operation for the preservation of the recreational pool on Wes Watkins.

6.4 System Model Calibration

Reservoir system models are normally verified by comparing simulated fluctuations on WSEL to data records of water levels. To simulate drawdown between January 2006 and January 2011, WTP flows were used to estimate inflow to Twin Lakes. The objective of this verification test was to assess the accuracy of the simulate inflows calculated using the area ratio method (available for the entire period of record) to reconstructed inflows using data from operating logs (available for only a short time period).

The results of the verification are shown in Figure 6-3. The WSEL shown in blue is the reservoir model output that simulates the historic operation of the Twin Lakes during the January 2006 through January 2011 calibration period. Despite some minor differences in the elevation including observed elevations during periods of spill that exceed the principal spillway elevation, the model results match the historic observations.

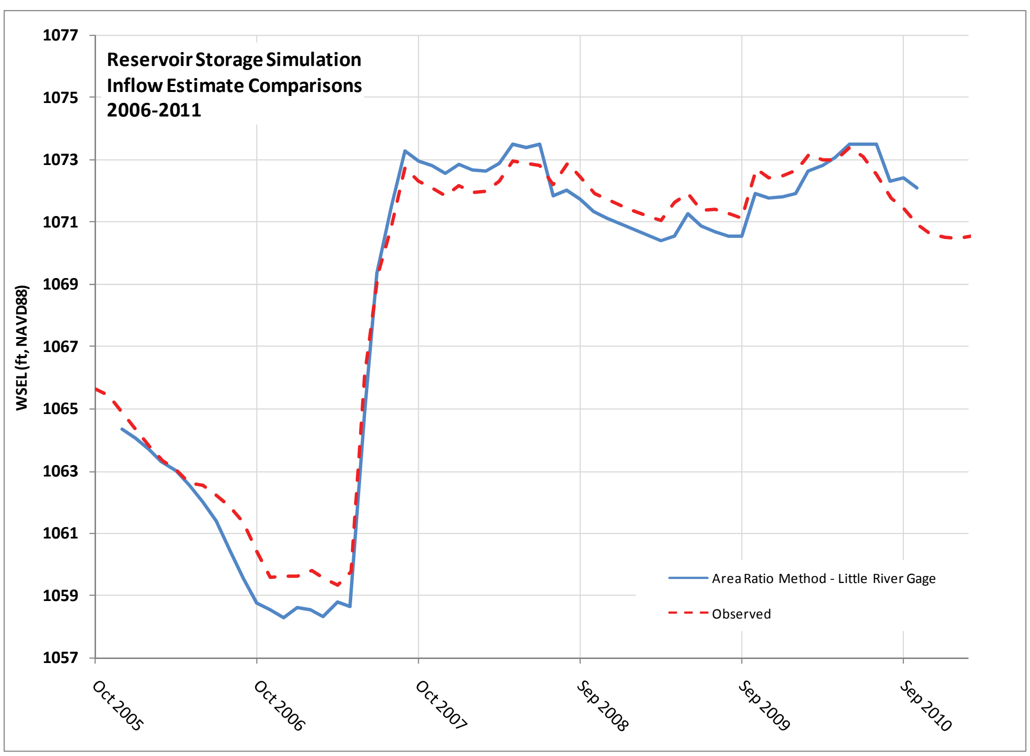


Figure 6-3. Comparison of inflows calculated using area ratio method and net inflow estimates from operating logs

Section 7
Estimation of Watershed Hydrology

7.1 Hydrologic Modeling Objectives

The firm yield study for Shawnee requires the simulation of natural streamflow inputs to two reservoirs (Twin Lake #1 and #2 are treated as a single reservoir in this study). None of the inflowing streams are currently gaged. The inflows must be estimated using either physically-based models or statistical analysis based on the hydrographic characteristics of the basin. This hydrologic analysis was conducted in accordance with the firm yield analysis adopted by the OWRB as part of the 2012 update to the OCWP, discussed in Section 5. All available techniques recommended in the OCWP for synthesizing long-term streamflow records were examined and applied, and the one that best reproduced observed reservoir dynamics from operating logs was eventually used as the basis for hydrologic inflows for this study.

7.2 Estimation of Inflow for Twin Lakes

Inflow was estimated using five methods described in the firm yield analysis method approved as part of the 2012 update to the OCWP described in Section 5:

- Method 1 – USGS stream gages
- Method 2 – Net inflow estimates from operating logs
- Method 3 – Streamflow transposition by area ratio
- Method 4 – Statistical record extension
- Method 5 – SCS CN approach for runoff flow

Method 1 – USGS Streamflow Gages: As mentioned in Section 5, Method 1 is not applicable since neither Twin Lakes or Wes Watkins have USGS gages immediately upstream.

Method 2 – Inflow Estimates from Operating Logs: For Method 2, inflow estimates for Twin Lakes were estimated using available precipitation, pan evaporation, recorded changes in reservoir elevation (storage), and withdrawal information based on Shawnee's WTP monthly operating reports. Essentially, when all of this data is present, the only missing contributor to the mass balance of a reservoir is the net hydrologic inflow (predominantly runoff), and this can be back-calculated. Figure 7-1 illustrates the estimated inflows from this method. Method 2 is the most accurate approach for estimating ungaged inflow, but the period of operational reservoir records is only January 2006 – January 2010. ***Therefore, in lieu of actual measurements of incoming streamflow, it served as a surrogate for actual inflow, and was used as the basis of comparison to determine which of the remaining methods were best for extending the inflow estimate through the drought of record.***

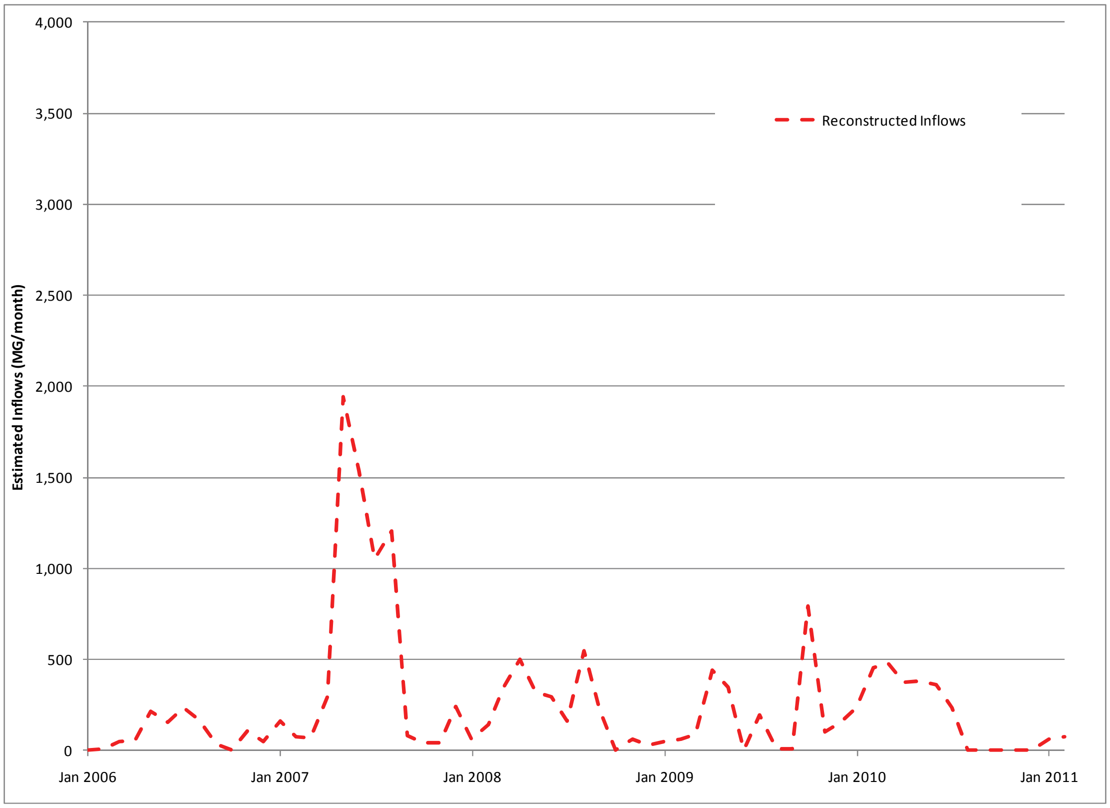


Figure 7-1: Twin Lakes Inflow Estimates Using Method 2

Method 3 – Basin Area Transposition: Two inflow estimates were developed from USGS gages, North Criner Creek (USGS Gage 7328180) and an incremental area for Little River (USGS Gages 7230000 and 7230500). These gaged records were selected because their records coincided with available period of reconstructed inflows from Method 2, and had watershed areas with similar land use characteristics. Table 7-2 in Section 7.3.1 provides a summary of the available USGS gages, including the three that were selected for estimation.

Figure 7-2 illustrates the estimated inflows from Method 3. The North Criner Creek (USGS Gage 7328180) over estimates the higher flows and does not closely correlate with the low flow periods during the period when operating information was available. The Little River (USGS Gages 7230000 and 7230500) better matches the reconstructed inflows (Method 2 described above).

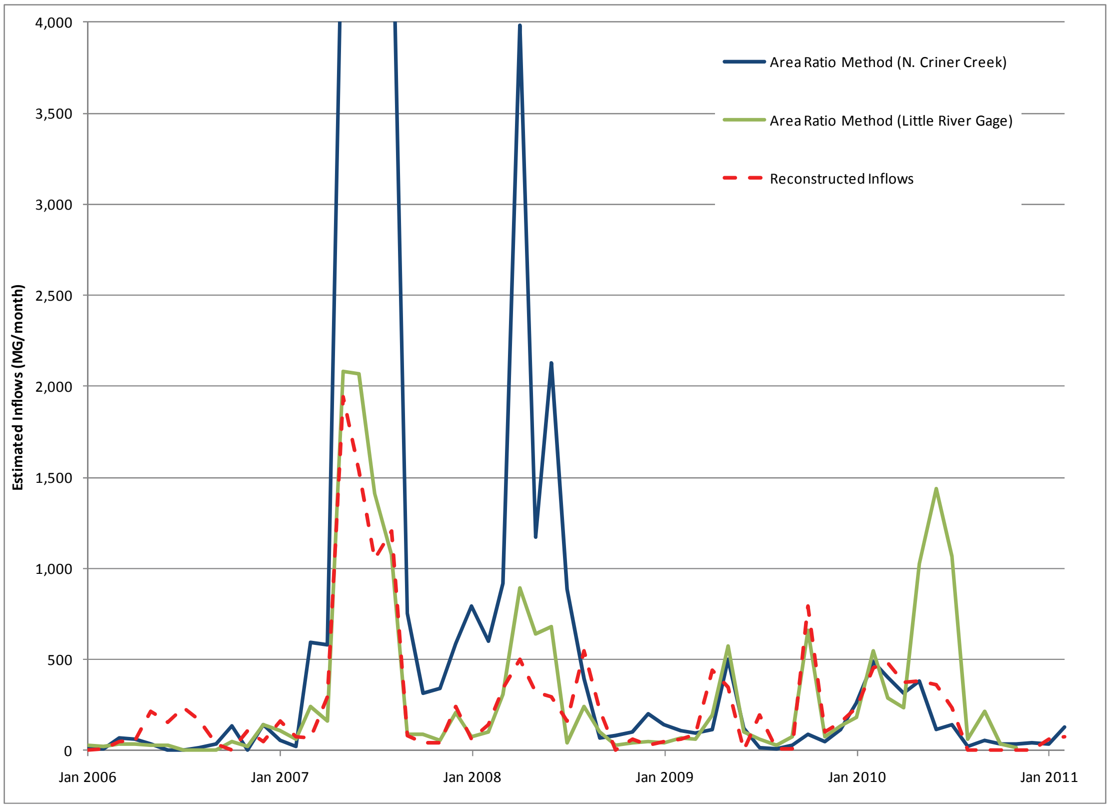


Figure 7-2: Twin Lakes Inflow Estimates using Method 3

Method 4 - Statistical Record Extension: Using the Little River gage, another inflow estimate to Twin Lakes was made using Method 4, statistical record extension. Figure 7-3 illustrates the estimated inflows. This method yielded reasonable reproduction of the reconstructed flows from Method 2 (the basis for comparison), and was further evaluated with flow frequency analysis (see below).

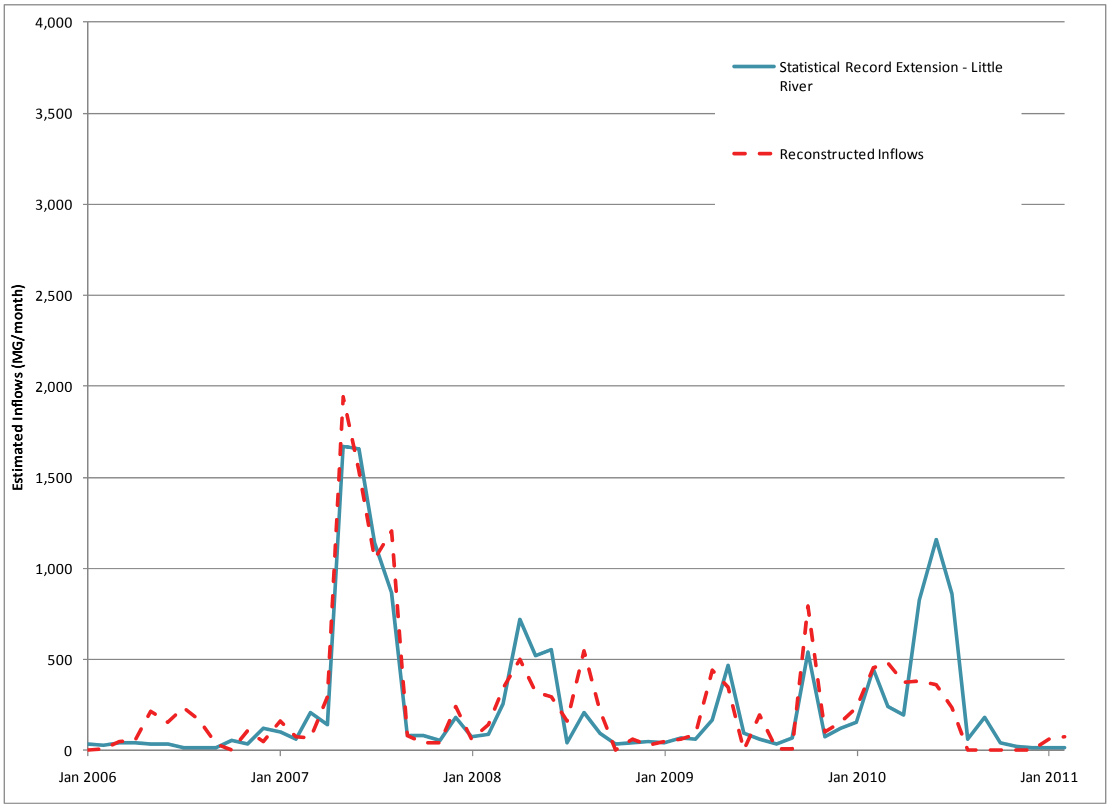


Figure 7-3: Twin Lakes Inflow Estimates using Method 4

Method 5 - SCS Curve Number Method: Finally, precipitation data from Shawnee Municipal Airport and land use and soils data from the United States Department of Agriculture (USDA) were used to determine the Soil Conservation Service (SCS) runoff curve number (CN) for subcatchment areas. The inflow estimates from Method 5 are illustrated in Figure 7-4. Generally, the SCS CN method resulted in higher inflow predictions for high to mid-flow periods and is inconsistent in predicting low flow periods. Additionally, this method is generally used only if data necessary for other methods is unavailable. That is, it is generally advisable to assume some homogeneity in regional hydrology (if climate and geography are also similar) and apply regional hydrologic data than it is to synthesize the hydrologic patterns from rainfall and soil characteristics.

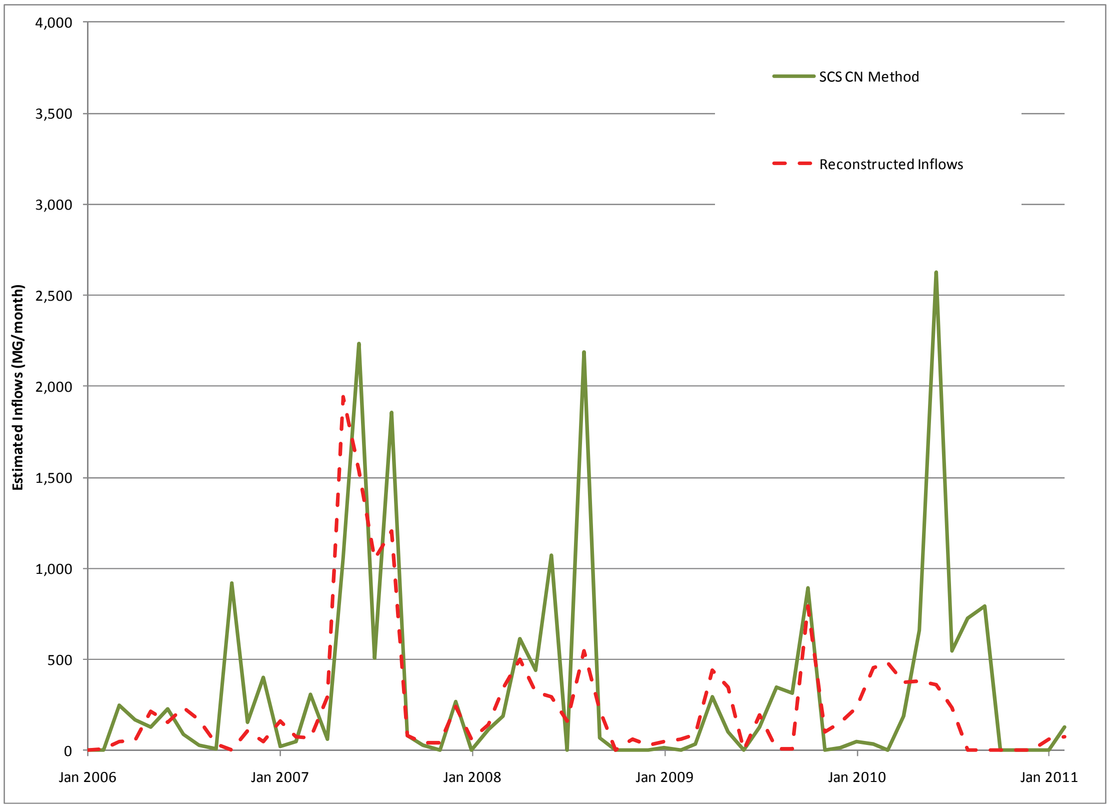


Figure 7-4: Twin Lakes Inflow Estimates using Method 5

To further compare the inflow estimates from Methods 3, 4 and 5 to the estimate based on historical operating logs (Method 2), comparative frequency exceedance plots were created. Figure 7-5 illustrates the results on a normal scale while Figure 7-6 shows results on a logarithmic scale to better illustrate differences at low flow periods. When completing a firm yield analysis, particular attention is paid to low flow periods, however the entire flow range must be evaluated. The best match to Method 2 occurs using Method 3 (streamflow transposition area ratio) with the Little River gage. While it does slightly over predict low flows, it is a better match over the entire flow range, in comparison with other methods, and is the closest predictor of low flow frequency.

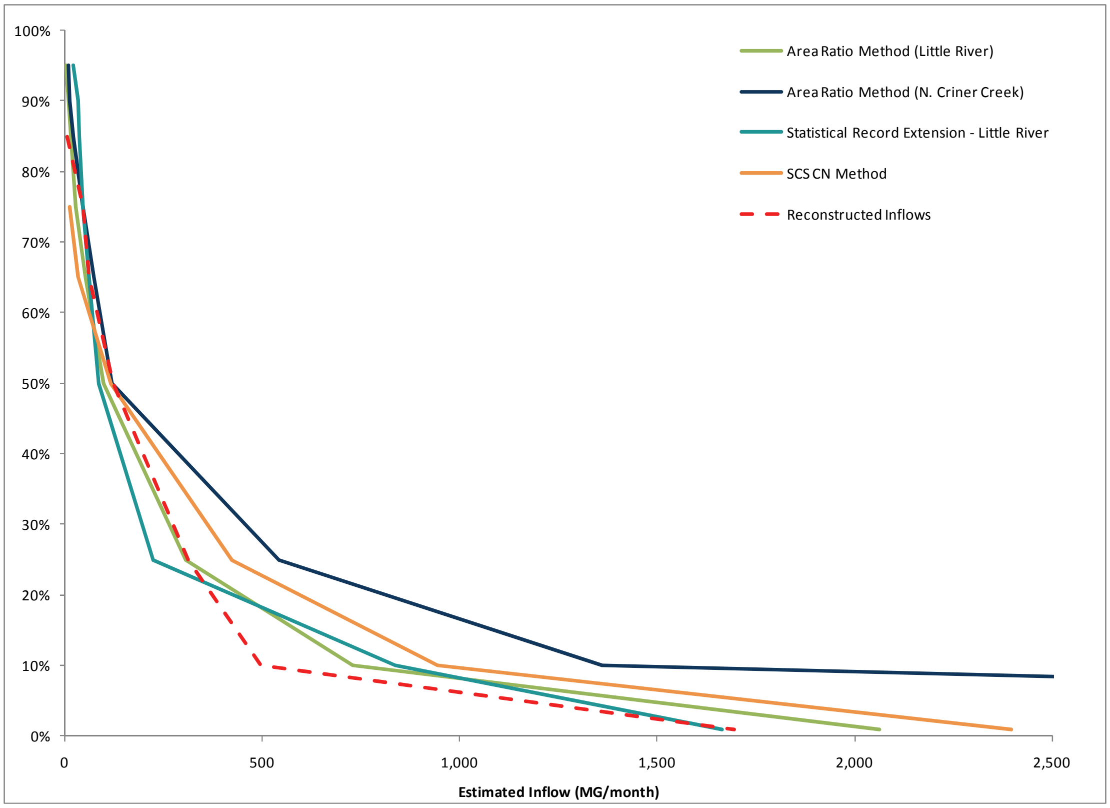


Figure 7-5: Twin Lakes Inflow Estimates Comparison of Frequency Exceedance

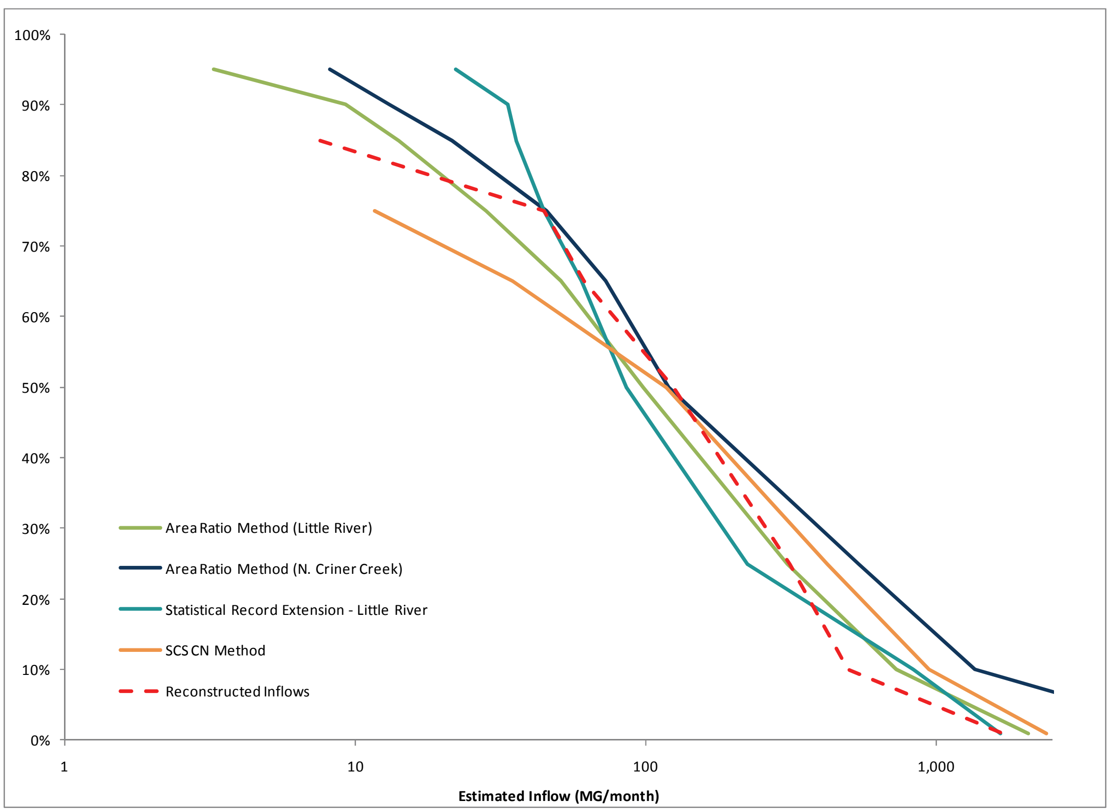


Figure 7-6: Twin Lakes Inflow Estimates Comparison of Frequency Exceedance on Logarithmic Scale

Figure 7-7 illustrates the reservoir water surface elevation of Twin Lakes calculated using the various inflow estimates. The area ratio method using the Little River gage (Method 3) closely correlates to the drawdown and recovery patterns, and more consistently follows the observed records than the other candidate methods. .

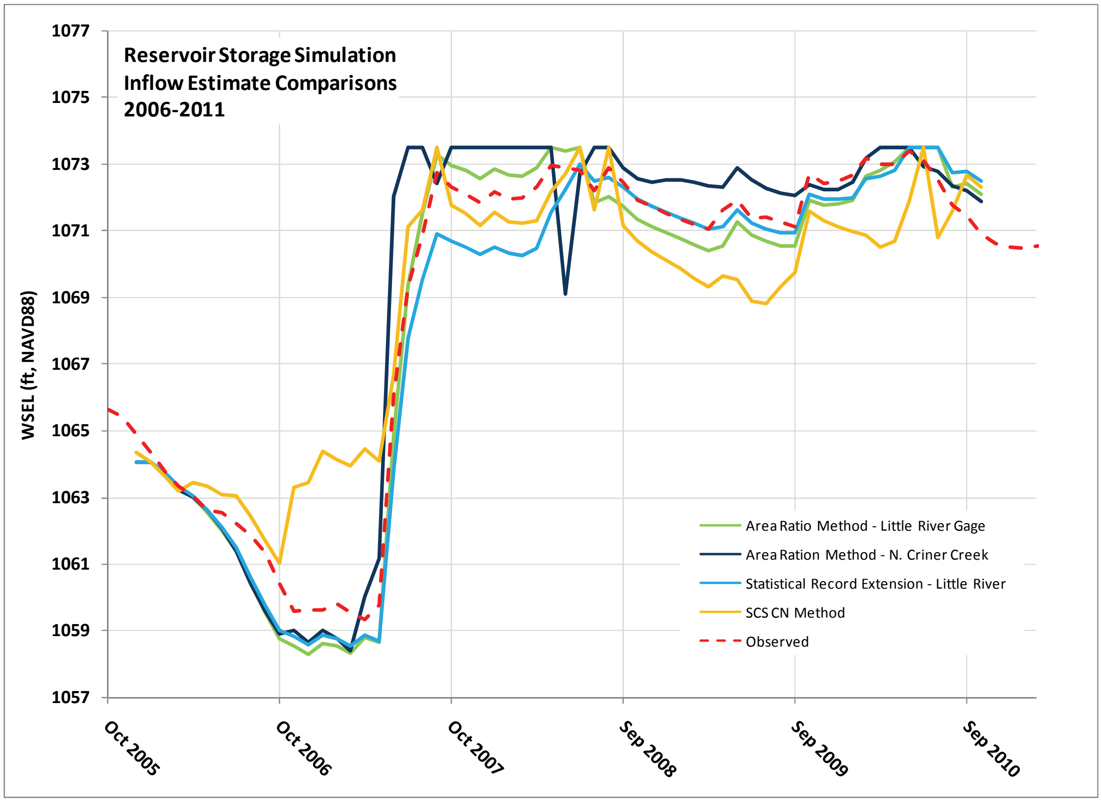


Figure 7-7: Twin Lakes Surface Water Elevation Estimates Using Various Inflow Estimating Methods

7.2.1 Inflow Recommendation for Twin Lakes

Based on the analysis of various inflow estimates, CDM Smith recommended using Method 3 Streamflow Transposition by Area Ratio with the incremental area for Little River gage. This method best estimates the historical low flow periods in 2006 – 2011 and also closely matches the overall volume in the period.

7.3 Selection of a Reference Stream Gage

This selection identified the data which were available to assist in the selection of a reference stream gage. Based upon the available data, the criteria for selection were specified and the process of selecting a references stream gage from the candidate site is discussed below.

7.3.1 Candidate Reference Gages

The basins in Table 7-1 drain directly into either Twin Lakes or Wes Watkins Reservoir. The table lists some of the key characteristics that can be qualitatively compared to the candidate reference gages, which are listed in Table 7-2 and shown in Figure 7-8.

Table 7-1. Ungaged Reservoir Basins in Shawnee Water Supply System

Drainage Basin Name	USGS Station No.	Drainage Area (square miles)	Major River Basin	Period of Record
Twin Lakes	—	32	North Canadian	—
Wes Watkins	—	39	North Canadian	—

Nine USGS streamflow gages in the vicinity of the Shawnee water supply reservoirs were identified as candidates for the reference streamgage, upon which flows into the ungaged reservoirs would be estimated. These stream gages, listed in Table 7-2 and shown in Figure 7-8, were identified based on their regional proximity. Two pairs of gages were selected as candidates for incremental flow records where an upstream record is subtracted from a downstream record to determine the incremental flow associated with the differential area between the two gaged watersheds. The process of calculating the incremental flow records removes any upstream regulation from the record. Several key hydrographic characteristics are listed with the candidate basins whenever that information was available.

Table 7-2. Gaged Reference Basin Candidates

Drainage Basin Name	USGS Station No.	Drainage Area (square miles)	Period of Record	Amount of Upstream Regulation
Dry Creek Tributary	07243000	69	1955-1994	None
N. Canadian River (Downstream)	07241800	8,831	2001-2010	Some
N. Canadian River (Upstream)	07241550	8,602	1968-2010	Some
Small Tributary	07241750	2.4	1991-1992	None
Little River (Downstream)	07230500	456	1943-2010	Some
Little River (Upstream)	07230000	257	1952-2010	Some
Little River (Incremental Area)	07230500 minus (07230000)	199	1952-2010	Removed by analysis
Upstream of Thunderbird	07229500	120	1951-1955	None
Walnut Creek Tributary	07229300	202	1965-1993	None
N. Criner Creek	07328180	7.3	1989-2010	None

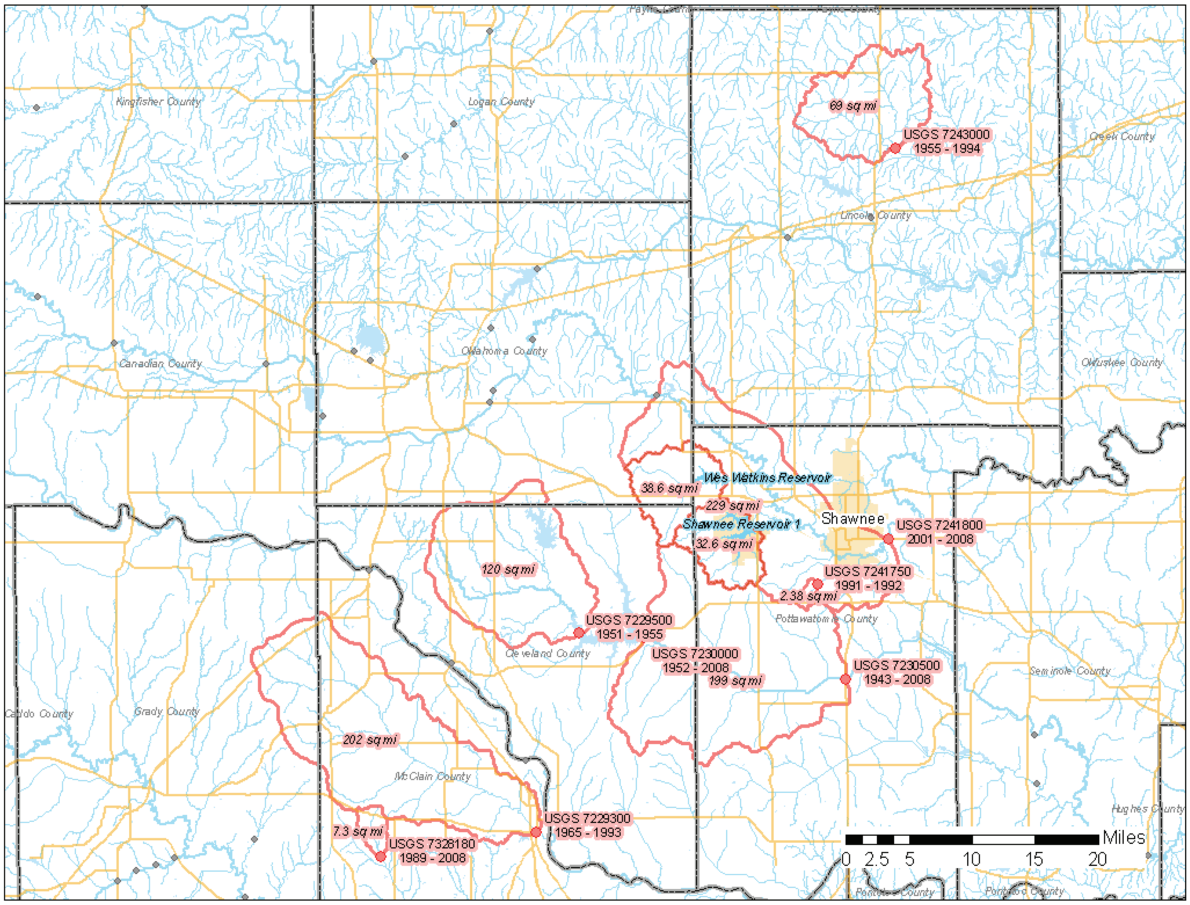


Figure 7-8: Gaged Reference Basin Candidates

7.3.2 Criteria for Reference Stream Gage Selection

The candidate reference gages were selected based on proximity to the Shawnee water supply system. The primary selection criteria were:

- Reference streamgage must be located in close proximity to the Twin Lakes and Wes Watkins reservoirs (for similarity in precipitation, geography, land use, soils, and runoff potential).
- Drainage area should be on the relative order of the watersheds in the Shawnee system if possible.
- Surficial geology (soil types and land use) should be reasonably similar to the Shawnee system if possible.
- Amount of upstream regulation should be minimal.
- The period of record must contain data between 1952 and 1960 so that inflows to the Twin Lakes and Wes Watkins can be estimated for the entire drought period. Also, because municipal reservoirs for small to mid-size cities can sometimes be more susceptible to short-term periods of extreme rainfall deficit than to longer term periods of gradually increasing deficit (as was the case in the 1950s drought of record), it is advisable for the period of record to include numerous "secondary" droughts that may not be perceived to be severe in duration, but which can rapidly deplete storage in small reservoirs.

- The period of record must also contain recent flows which can be compared with the reconstructed inflows calculated in Method 2 which are from January 2006 through January 2010.
- The area-normalized low flow statistics of the referenced stream gage should reproduce the estimated low-flow statistics for the ungaged basins, as estimated by the reconstructed inflow estimates made using operating logs.

Two streamflow records were considered in detail: North Criner Creek (USGS Gage 7328180) and incremental flow record on the Little River (USGS Gages 7230000 and 7230500). Both of these gages have records corresponding to the operating logs from Twin Lakes and were included in the analysis shown in Figures 7-3, 7-6, 7-7, and 7-8.

Ultimately the incremental flow records from the Little River (USGS Gages 7230000 and 7230500) were selected for the area ratio method for estimating inflows to the reservoir (Method 3). The 52-year record coincides with both the drought of record and the reconstructed inflow estimate. Figure 7-9 shows the long-term historic inflow estimate to the individual Twin Lakes on a log scale.

7.4 Estimation of Inflow for Wes Watkins Reservoir

Historically, Shawnee has not used raw water from Wes Watkins so operating logs were unavailable. Comparisons between Twin Lakes and Wes Watkins watersheds (see Figures 4-1 and 4-9) show similar land use patterns results. CDM Smith recommends using the same method for estimating inflows to Wes Watkins as Twin Lakes: area-ratio estimate based on 52-year incremental flow records from the Little River (Method 3). Figure 7-9 shows the long-term historic inflow estimate to the Wes Watkins reservoir on a log scale.

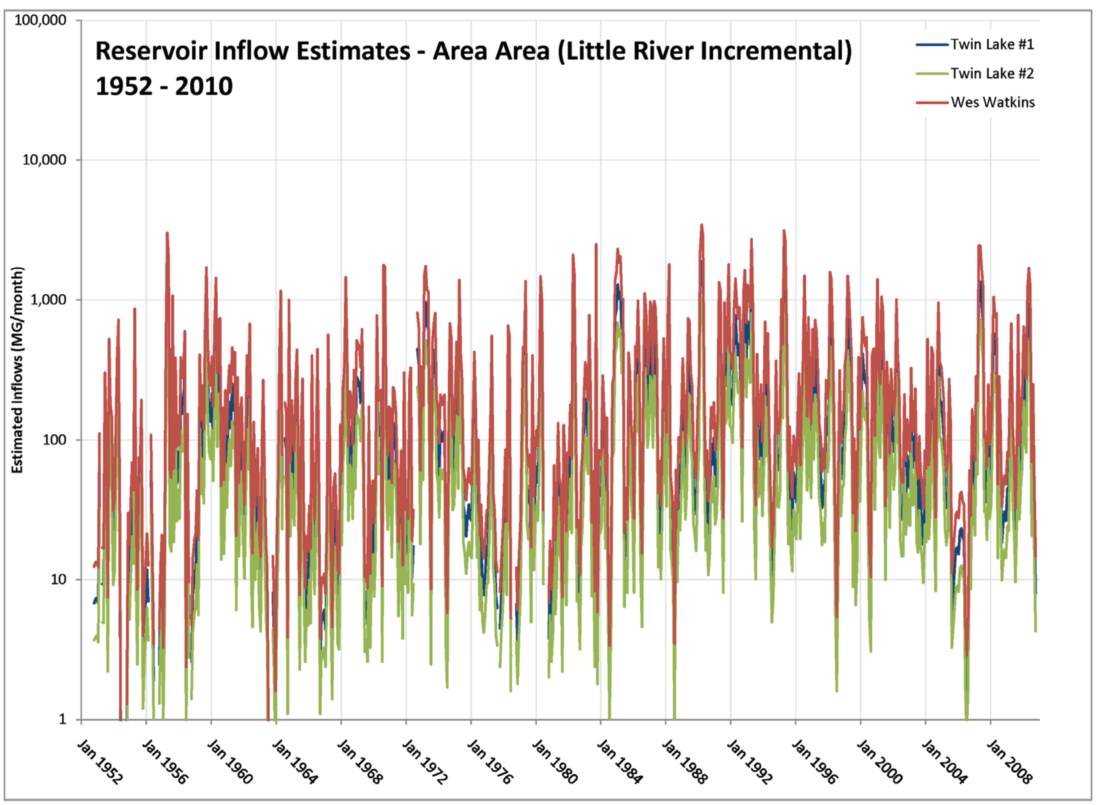


Figure 7-9: Reservoir Inflow Estimates - Area (Little River Incremental) – 1952 - 2010

Section 8
Firm Yield Results

The system simulation model, as described in Section 6, was used to estimate the firm yield of Twin Lakes and Wes Watkins. Firm yield estimates were developed for each lake individually and when operated as a system.

This analysis also produced estimates of the frequency of the system to not meet firm yield for withdrawal rates in excess of fully sustainable rates. These results are included to assist planners and decisionmakers in understanding the reliability of the system under various levels of withdrawal rates during extreme drought conditions.

Values of firm yield were determined by incrementally increasing the daily withdrawal rate until all active storage was depleted in any given time period.

Firm yield estimates represent the hydrologic availability of water provided by each reservoir. The permitted annual withdrawal allowances present an additional constraint on the water that is actually available to Shawnee. The reservoir simulations presented here include both the hydrologically-available firm yield and the annual volume that is available to Shawnee with respect to permitted allowances.

8.1 Estimates of Firm Yield– Individual Operation

The results in this section are presented as the sustainable withdrawal rates that would not cause a system failure during the period of simulated record (1953 – 2010). The following assumptions were applied to this analysis:

- Normal operating protocols and withdrawal patterns were used.
- All system requirements, such as minimum (elevation of intake) and maximum (elevation of spillway) WSELs were obeyed.

The firm yield estimates are summarized in Table 8-1. The simulated WSEL for the firm yield is illustrated in Figure 8-1. This firm yield represents the most conservative case by assuming that Tecumseh takes its full allocated amount during drought periods. Note that, the permit amount for Twin Lakes greatly exceeds the calculated firm yield. Because more water is available from Twin Lakes during normal flow periods, no change to the permit is recommended.

The capacity of the gravity flow conduits from the reservoirs to the water treatment plant limits the flow rates that can be withdrawn from each reservoir. This capacity is a function of the upstream head in the reservoir which changes with the water surface elevation. This analysis used the raw water transmission capacity tables provided by the City (included in Appendix D). Since the raw water supply storage structure shown in these tables is bypassed, it is appropriate to use the minimum water surface elevation. When operated individually the firm yield for both Wes Watkins and Twin Lakes is below the capacity of their respective gravity conduits.

Table 8-1: Firm Yield Estimates for Drought of Record – Individual Operation [A]

Reservoir	Firm Yield (mgd)	Permit Limit (mgd)	Available to Shawnee (mgd)
Twin Lakes	5.5	7.1	5.5
Wes Watkins (no withdrawals from recreation pool)	3.0 [B]	3.8 [C]	2.3 [C]
System Total – Combined Individual Yield	8.5	10.9	7.8

[A] Firm yield is based on water availability. Existing infrastructure constraints may limit receiving the full amount of raw water available.

[B] Firm yield of Wes Watkins Reservoir without withdrawal from the recreational pool. Removing the recreational pool constraint in the model, the firm yield of Wes Watkins increases to 4.4 mgd.

[C] PCDA holds the permit for Wes Watkins. Approximately 3.8 mgd is allocated to Shawnee. The remaining approximate 0.7 mgd is allocated to Tecumseh. The permit limit in the table reflects the allocation amount to Shawnee. The amount available to Shawnee is the amount of water from the firm yield available to Shawnee if Tecumseh takes its full 0.7 mgd allocation.

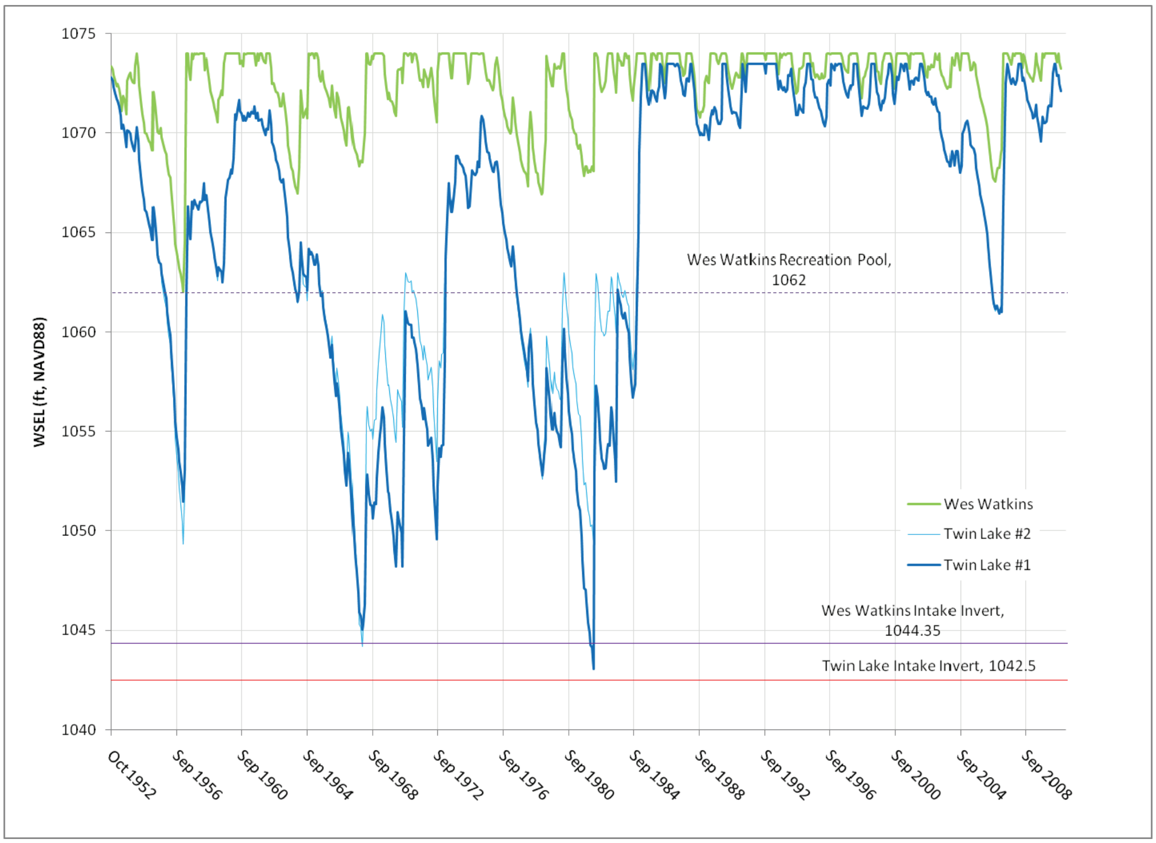


Figure 8-1: WSEL for individual reservoir operation meeting annual permit, and no withdrawals from the Wes Watkins Recreational Pool Elevation, Total Firm Yield = 8.5 mgd

If the recreation pool is made available for withdrawals, the firm yield of Wes Watkins is 4.4 mgd. After the permitted 0.7 mgd is allocated for Tecumseh, 3.7 mgd is available to Shawnee. The simulated WSEL for firm yield operation that uses the Wes Watkins recreation pool is shown in Figure 8-2. The total firm yield from both reservoirs operated individually in this way is 9.9 mgd.

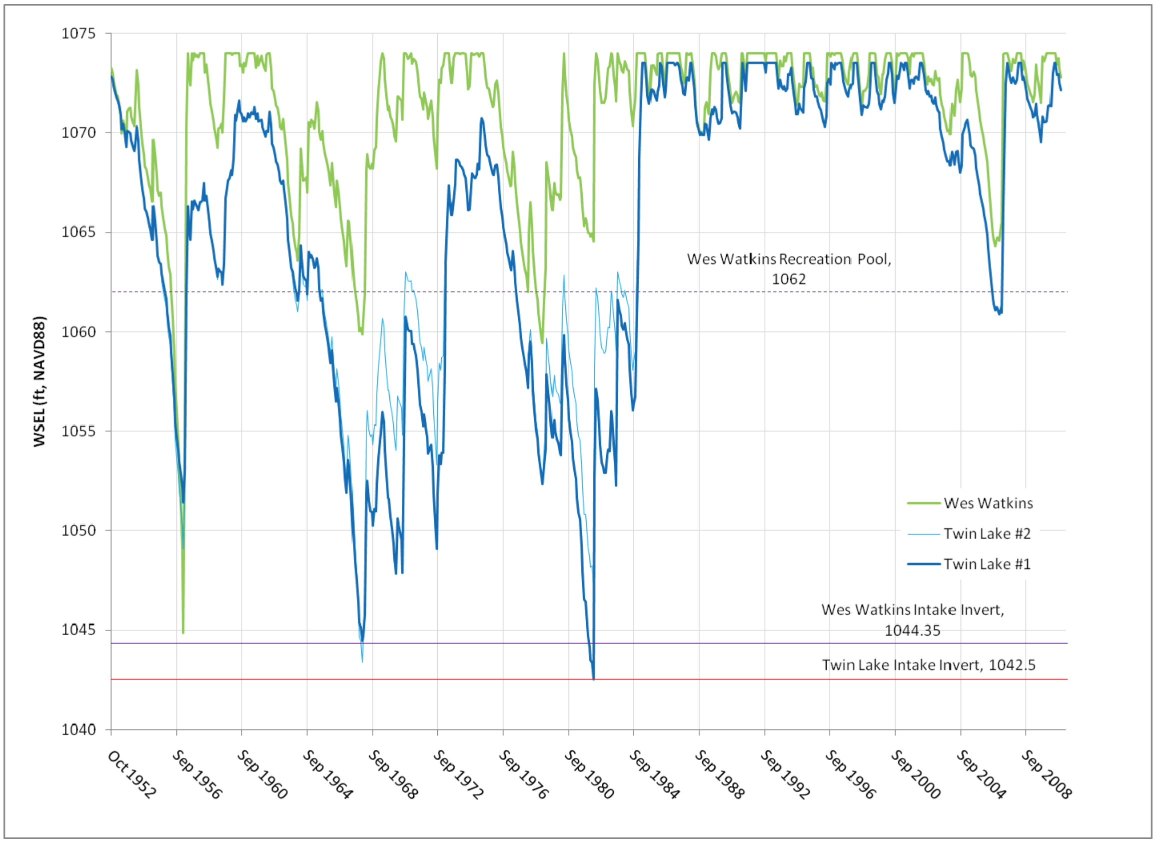


Figure 8-2: WSEL for individual reservoir operation, Total Firm Yield = 9.9 mgd

8.2 Estimates of Firm Yield – System Operation

The results in this section are presented as the firm yield withdrawal rates when Twin Lakes and Wes Watkins are operated as a system. Results are presented in Table 8-2. The withdrawal rules are based on the availability of water in each reservoir at the beginning of the month. Two general operational approaches were simulated for experimental purposes to understand the availability of water and the reliability of the system:

- Operation can prioritize the use of one of the reservoirs, withdrawing more from that reservoir during non-drought conditions, often above that reservoirs firm yield. During drought conditions as the prioritized reservoir hits a defined threshold, withdrawals are shifted to the other reservoir. This operational approach increases the firm yield of the reservoir system above the sum of the firm yield values achieved by operating each reservoir individually. Simulation of reservoir prioritization is illustrated in Figures 8-3 through 8-5.

- Operation can maintain the water surface elevation (WSEL) between the two reservoirs for aesthetic and recreational purposes. In each month, withdrawals are taken from the reservoir with the greater WSEL.

Table 8-2: Firm Yield Estimates for Drought of Record – System Operation

Optimized System Operation	Firm Yield (mgd)	Reliability of no withdrawals from Wes Watkins Recreation Pool Elevation [B]	Available to Shawnee [C] (mgd)	Reliability of no withdrawals from Wes Watkins Recreation Pool Elevation [D]
Prioritize Wes Watkins	10.1	95%	9.2	96%
Prioritize Twin Lakes	10.0	94%	9.1	97%
Prioritize Twin Lakes, No withdrawals from Wes Watkins recreation pool	9.4	100%	7.4	100%
Balance Water Surface Elevation	9.6	86%	4.1	100%
Balance Water Surface Elevation, no withdrawals from Wes Watkins recreation pool	8.2	100%	4.7	100%

[A] Firm yield is based on water availability. Existing infrastructure constraints may limit receiving the full amount of raw water available.

[B] The percent of months during the 58-year simulation period in which the Wes Watkins recreation pool was not impacted by the operation. This reliability corresponds to withdrawals at the firm yield.

[C] Amount available to Shawnee without exceeding the annual permit to either Wes Watkins (3.8 mgd) or Twin Lakes (7.1 mgd). The amount available to Shawnee also accounts for the separate volume that is allocated to Tecumseh (0.7 mgd).

[D] The percent of months during the 58-year simulation period in which the West Watkins recreation pool was not impacted by the operation. This reliability corresponds to withdrawals that meet annual permit constraints for both reservoirs.

Unlike under the individual operation of reservoirs described in Section 8-1, the withdrawals from a single reservoir under system operation may change from month to month as the availability of water and WSEL in each reservoir changes. For several months at a time the withdrawals from a single reservoir may exceed the individual firm yield for that reservoir in order to meet the operational goals of withdrawal priority or balancing WSEL. During simulated system operation at firm yield there are years where the total withdrawals from a single reservoir exceed the annual permit allowance for that reservoir. The annual permit allowances are detailed in Sections 3-1 and 3-2. In order to meet the annual permit constraints it is necessary to reduce the total system withdrawal below the firm yield. The resulting flow rate available to Shawnee under the permitted constraints is shown in Table 8-2.

Some operational simulations are more greatly impacted by the annual permit constraint than others. Operating the system with a balanced WSEL between the reservoirs results in a firm yield of 9.6 mgd. The same system operation while meeting the annual permit results in a reduction of the water available to Shawnee of 4.1 mgd. The dramatic difference between the firm yield and the available water is related to the long periods of elevated withdrawals that are required from a single reservoir under the balancing operation.

During drought conditions more withdrawals are taken from Twin Lakes which holds a larger volume of storage per unit of reservoir depth than Wes Watkins. During non-drought conditions, the reverse is true: withdrawals from Wes Wakins may exceed those from Twin Lakes since the Wes Watkins drainage area is 20% larger than that of Twin Lakes as are the associated inflows. In order to maintain balanced WSEL, Wes Watkins has to be drawn down to the same level as Twin Lakes, thereby exceeding the annual permit unless the system withdrawals are limited to 4.1 mgd. In practice, it is likely that the intent of the balanced WSEL operation could be met without restricting the system withdrawals to such an extent.

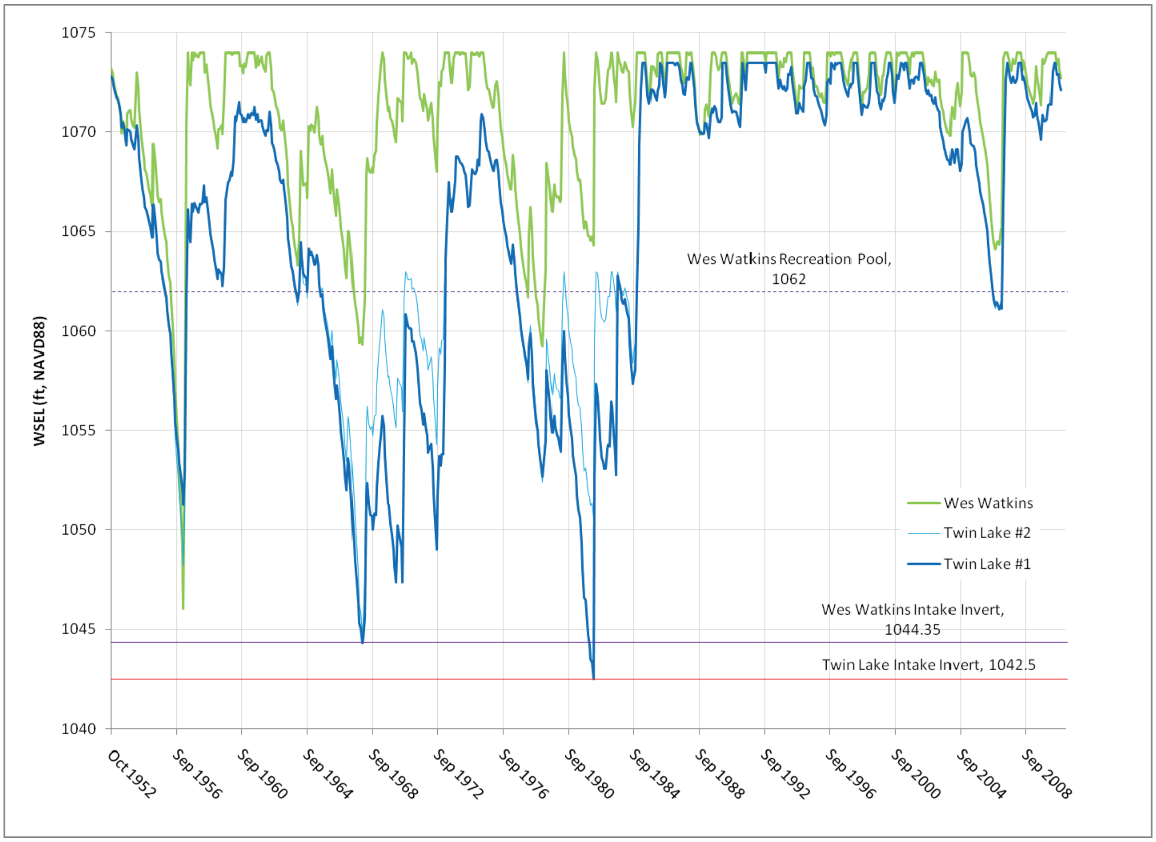


Figure 8-3: WSEL for system reservoir operation, Prioritize Wes Watkins, Total Firm Yield = 10.1 mgd

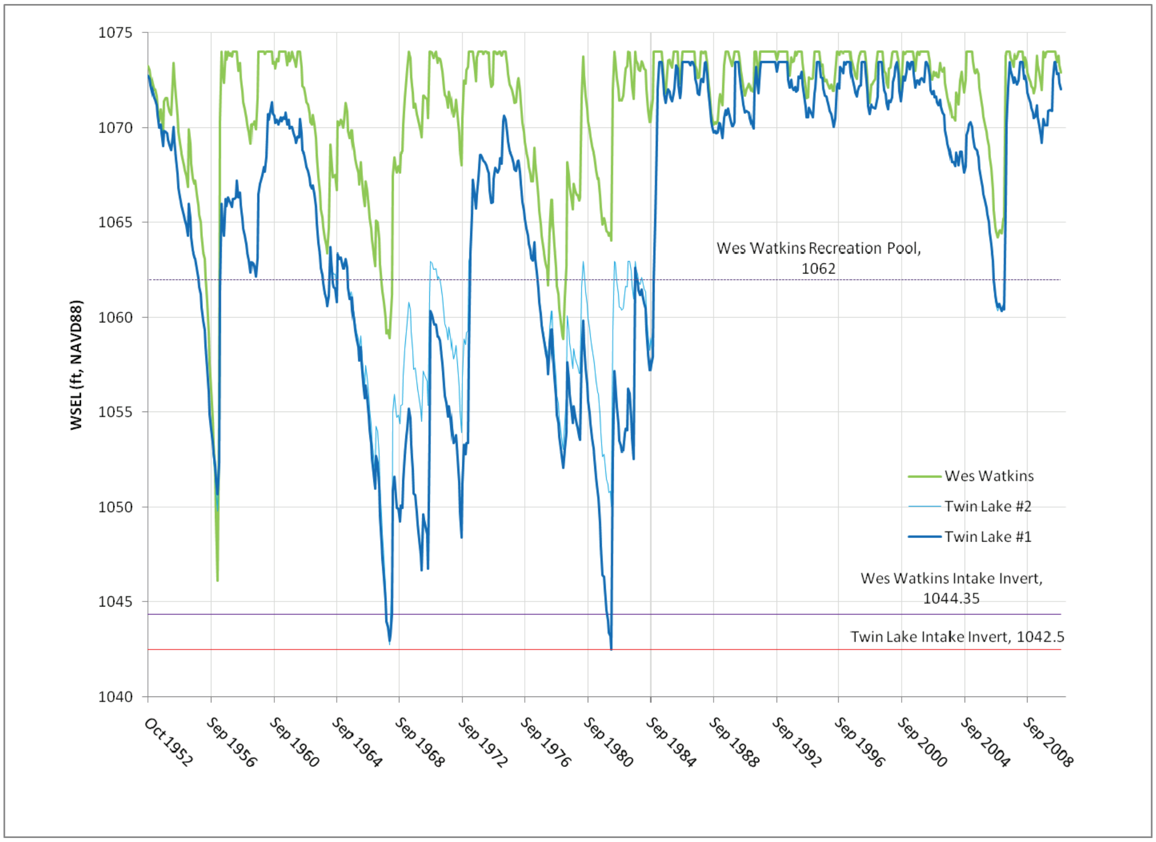


Figure 8-4: WSEL for system reservoir operation, Prioritize Twin Lakes, Total Firm Yield = 10.0 mgd

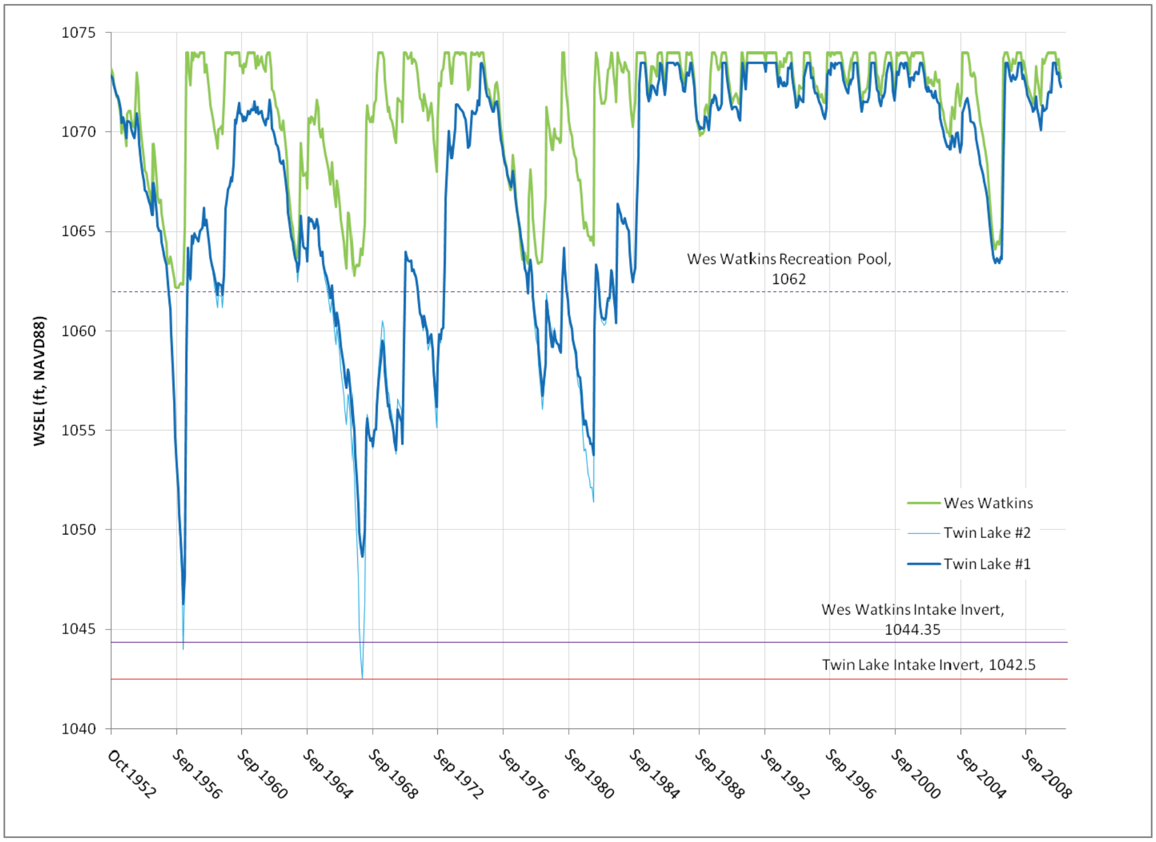


Figure 8-5: WSEL for system reservoir operation, Prioritize Twin Lakes and no withdrawal from Wes Watkins recreation pool, Total Firm Yield = 9.4 mgd

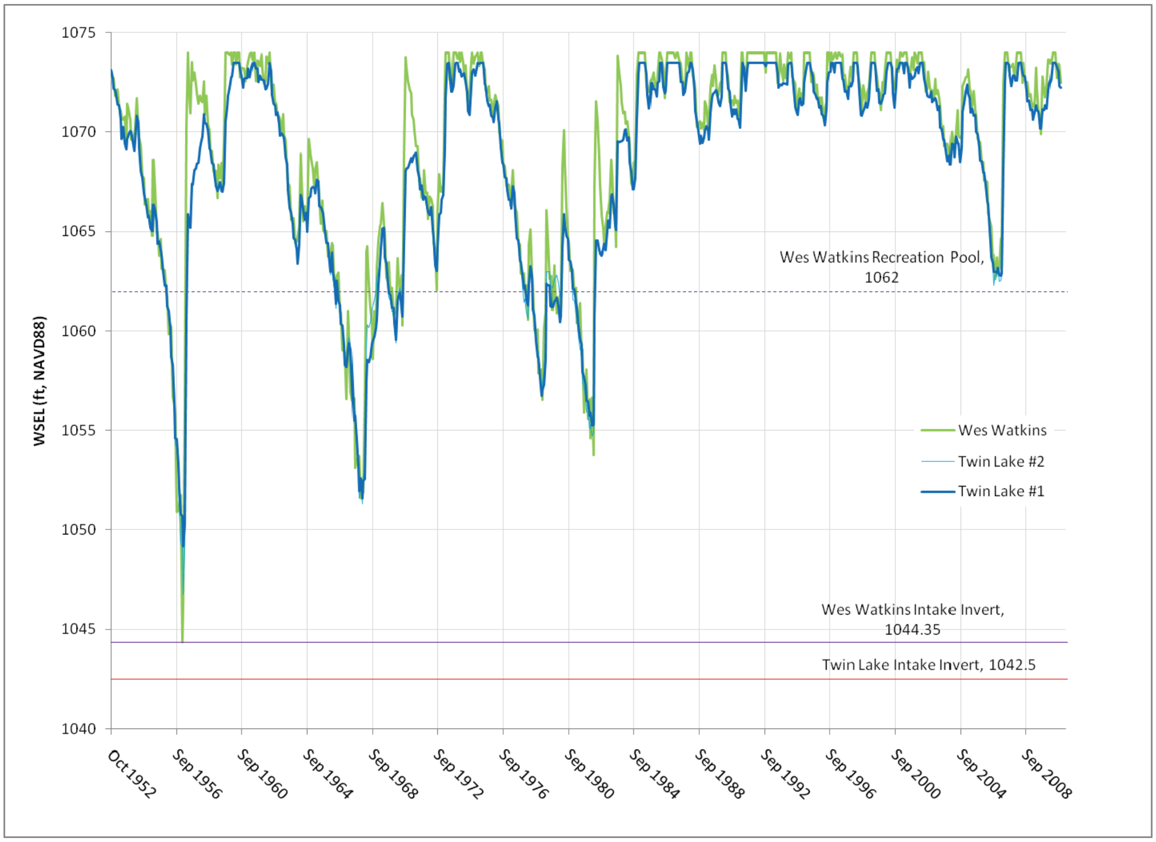


Figure 8-6: WSEL for system reservoir operation, Balance WSEL between reservoirs, Total Firm Yield = 9.6 mgd

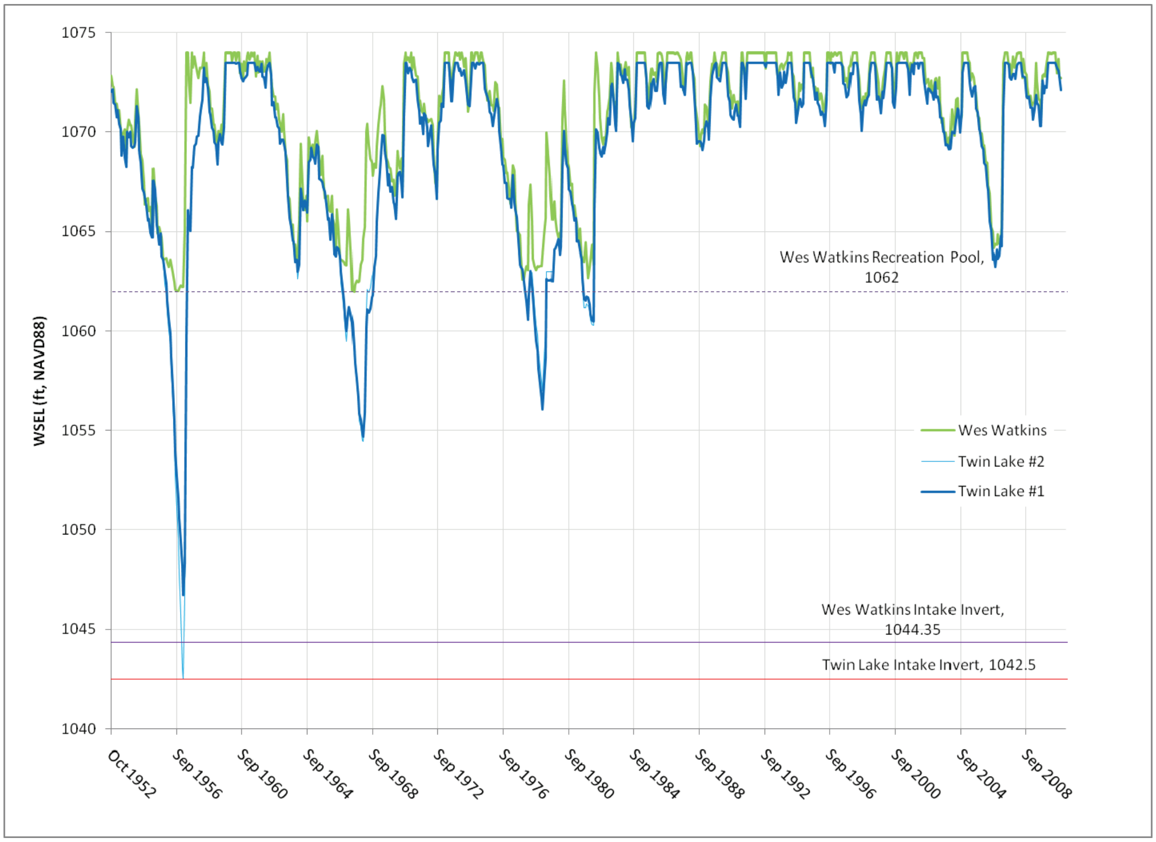


Figure 8-7: WSEL for system reservoir operation, Balance WSEL between reservoirs while maintaining Wes Watkins recreation pool, Total Firm Yield = 8.2 mgd

At times during optimized system operation the withdrawal from an individual reservoir may be higher than the firm yield of that reservoir. Unlike withdrawals taken under individual operation described in Section 8-1, flow rates under system operation may temporarily exceed the capacity of the gravity conduit system for one or more of the reservoirs. The capacity of a gravity conduit for a particular reservoir fluctuates with the water surface elevation in that reservoir. Exceeding the capacity of gravity conduit system is most likely during drought periods when the head in the reservoir is low. Using the raw water transmission capacity tables provided by the City, described above, the following occurs during the various operational scenarios:

- During the "Prioritize Wes Watkins" operation associated with a firm yield of 10.1 mgd, withdrawal from Twin Lakes exceeds the capacity of the gravity conduit 4 percent of the time, by as much as 2.4 mgd during the periods of severe drought.
- During the "Prioritize Twin Lakes" operation associated with a firm yield of 10.0 mgd, withdrawal from Twin Lakes exceeds the capacity of the gravity conduit 2 percent of the time by as much as 0.8 mgd during periods of severe drought.
- Adding the additional constraint of "No withdrawal from the Wes Watkins recreation pool" associated with a firm yield of 9.4 mgd, the gravity conduit capacity is exceeded 4 percent of the time by as much as 6.1 mgd. The capacity of the gravity conduit for Wes Watkins was not exceeded during system operation simulation.

The highest firm yield comes from prioritizing withdrawals from Wes Watkins most of the time while using the full capacity of the Twin Lakes during drought conditions. However, when constrained by the annual withdrawal allocation from Wes Watkins, the system cannot be optimized beyond the sum of the two firm yields from each individual reservoir (see Section 8.1).

The most likely to be implemented scenario considered was the balanced WSEL option. In this scenario, water is withdrawn from the two supplies in order to maintain approximately equal surface elevations. Shawnee has enough raw water from their reservoirs, Twin Lakes and Wes Watkins, under the balance surface water elevation operational scenario (firm yield of 8.2 mgd based on physical availability, 4.7 mgd available to Shawnee when additionally limited by permit constraints) to meet the current projections for 2060 average annual day water demands of 4.7 mgd. (from the 2012 update to the OCWP).

Section 9
Drought Management Plan

The drought management plan presented in this section was developed by the City Staff using data CDM Smith developed through the yield analysis. The purpose of this plan is to define actions that will be taken when certain conditions develop from which water supply capabilities are negatively impacted. Variance from the recommendations that follow should also consider conditions that may be specific and unforecastable, such as infrastructure being unavailable, future climate patterns, and droughts worse than historic, etc.

It is the intent of this plan to use both Twin Lakes and Wes Watkins until the Wes Watkins recreational pool elevation (1062 feet) is reached. At this point, Twin Lakes will become the primary water supply source. When an elevation of 1057 feet is reached at Twin Lakes, withdrawals from the Wes Watkins recreational pool may become necessary, after receiving appropriate approvals.

9.1 Voluntary Restrictions

It is important to be constantly aware of water needs and understand that there are times when it is necessary to conserve water. Prudent use of this essential natural resource is the responsibility of every citizen. We must all take voluntary steps to conserve our water and this must be reinforced each summer, when the need for water becomes the greatest.

Voluntary restrictions begin when either Twin Lakes or Wes Watkins reach an elevation of 1064 feet.

> **At Elevation 1064, 46% storage remaining = 19,825 Ac-Ft = 6,459,976,250 Gal.**
> **At 3.5 mgd* use that would be 1,845 days supply.**
> ***million gallons per day**

Voluntary restrictions include the following:

- Turn off the tap while shaving or brushing teeth.
- Showers use less water than baths.
- Plug up the sink or use a wash basin if washing dishes by hand.
- Use a dishwasher, and, when you do, make sure it is fully loaded.
- Keep a pitcher of drinking water in the refrigerator instead of letting the faucet run until the water gets cool.
- Wash only full loads of laundry or use appropriate water level or load size selection on washing machine.
- When replacing fixtures, look for water saving features.

9.2 Level 1 – Mandatory Restrictions

Level 1 Mandatory Restrictions begin when Twin Lakes reaches an elevation of 1058 feet and/or the average weekly water treatment plant production exceeds 6.0 mgd. It is assumed that Wes Watkins remains at an elevation of 1062 feet. Mandatory restrictions include the following:

- Residential, other than household purposes: Outside water usage restricted to 6:00 pm to 10:00 am on the odd/even system defined as odd-numbered houses utilizing water on Monday and Thursday and even-numbered houses utilizing water on Tuesday and Friday during the above hours.
- Commercial: Outside water usage restricted in the same manner as residential customers.

At Elevation 1058, 29% storage remaining = 12,527 Ac-Ft = 4,081,922,950 Gal.
At 3.5 mgd* use that would be 1,166 days supply.
***million gallons per day**

9.3 Level 2 – Mandatory Restrictions

Level 2 Mandatory Restrictions begin when Twin Lakes reaches an elevation of 1057 feet and/or the average weekly water treatment plant production exceeds 6.5 mgd. It is assumed that Wes Watkins remains at an elevation of 1062 feet. Mandatory restrictions include the following:

- Residential, other than household purposes: Outside water usage restricted to 6:00 pm to 10:00 am on the odd/even system defined as odd-numbered houses utilizing water on Monday and even-numbered houses utilizing water on Tuesday during the above hours.
- Commercial: Users are required to reduce water usage by 10 percent as compared to the previous year's usage figures.

At Elevation 1057, 27% storage remaining = 11,691 Ac-Ft = 3,809,512,350 Gal.
At 3.5 mgd* use that would be 1,088 days supply.
***million gallons per day**

Note, during Level 2 Mandatory Restrictions, it may be necessary to make withdrawals from the Wes Watkins recreational pool, after receiving appropriate approvals.

9.4 Level 3 – Mandatory Restrictions

Level 3 Mandatory Restrictions begin when Twin Lakes reaches an elevation of 1056 feet and the average weekly water treatment plant production exceeds 4.0 mgd. Mandatory restrictions include the following:

- Residential, other than household purposes: Outside water usage restricted to 7:00 pm to 8:00 pm on the odd/even system defined as odd-numbered houses utilizing water on Monday and even-numbered houses utilizing water on Friday during the above hours. Water usage is limited to watering shrubs and young trees only.
- Commercial: Users required to reduce water usage by 15 percent as compared to the previous year's usage figures.
- Other: Lawn watering, refilling or adding water to public and private swimming pools and automobile washing forbidden.

At Elevation 1056, 25% storage remaining = 10,902 Ac-Ft = 3,552,416,700 Gal.
At 3.5 mgd* use that would be 1,015 days supply.
***million gallons per day; the calculation assumes that Wes Watkins remains at elevation 1062 feet**

Note, during Level 3 Mandatory Restrictions, it may be necessary to make withdrawals from the Wes Watkins recreational pool, after receiving appropriate approvals.

9.5 Level 4 – Mandatory Restrictions

Level 4 Mandatory Restrictions begin when Twin Lakes reaches an elevation of 1055 feet and the average weekly WTP production exceeds 3.5 mgd. Alternative triggers are when Twin Lakes reaches an elevation of 1054 feet and/or the average weekly water treatment plant production exceeds 3.0 mgd. Mandatory restrictions include the following:

- Residential, other than household purposes: There will be no usage authorized, other than for household purposes.
- Commercial: Users required to reduce water usage by 25 percent as compared to the previous year's usage figures.
- Other: Lawn watering, refilling or adding water to public and private swimming pools and automobile washing forbidden.

At Elevation 1055, 23% storage remaining = 10,160 Ac-Ft = 3,310,636,000 Gal.
At 3.5 mgd* use that would be 946 days supply.
***million gallons per day; the calculation assumes that Wes Watkins remains at elevation 1062 feet**

Note, during Level 4 Mandatory Restrictions, it may be necessary to make withdrawals from the Wes Watkins recreational pool, after receiving appropriate approvals.

9.6 City Code Reference

The City Code, Section 26-67 (b) (4), provides for penalties for violation of a proclamation proclaiming a water emergency:

Any person violating any provision of the proclamation, upon conviction, shall be fined as follows:

(i) First Violation - Warning

(ii) Second Violation - $150.00 fine plus costs

(iii) Third Violation - $250.00 fine plus costs

(iv) Fourth and Subsequent Violation - $500.00 fine plus costs

In addition to such penalties, the water, sewer, and garbage services furnished by the City to such person who violates any of the provisions of such proclamation shall be subject to suspension summarily and without notice.

9.7 Summary

This plan is not designed to place any individual or firm under an undue hardship but rather to ensure that the City of Shawnee has water for domestic use available throughout the year to its citizens. It is hoped that no more than steps one or two would ever be required. It is necessary, however, to have a plan in place that will permit everyone to be aware of the necessary precautions to ensure that water for domestic use is available in the City of Shawnee.

Section 10
Conclusions

10.1 Firm Yield Analysis

The primary objective of this analysis was to define the firm yield of the Shawnee raw water supply system, which includes the Twin Lakes and Wes Watkins Reservoir. For the purpose of this study, firm yield is defined as the average daily withdrawal from a water supply system that can be sustained through the available record of inflows (1953-2011) including the drought of record without entirely depleting the system storage. The drought of record is defined as the period July 1954 to April 1957.

This analysis was conducted in accordance with the guidelines established in the 2012 update to the OCWP. Hydrologic estimates of streamflow for both of the ungaged contributing watersheds within the system were generated using transposition by area ratio method and a dynamic simulation model with multiple reservoirs.

A spreadsheet simulation model was used to simulate the operation of the multiple reservoirs.

The firm yield estimates for the Twin Lakes (in this study, Twin Lake #1 and Twin Lake #2 were modeled as a single reservoir with two connected volumes as described in Section 6.1) and Wes Watkins are presented in Table 10-1. The table lists the firm yield of the reservoirs operating individually, and also conjunctively, in the preferred operating mode of balancing water surface elevation and constraining withdrawals to permit allowances.

Table 10-1: Firm Yield Estimates for Period of Record including Drought of Record (from July 1954 to April 1957)

Reservoir	Firm Yield (mgd)	Permit Limit (mgd)	Available to Shawnee (mgd)
Twin Lakes	5.5	7.1	5.5
Wes Watkins	3.0 [A]	3.8 [B]	2.3 [B]
System Total – Combined Individual Yield	8.5	10.9	7.8 [B]
Balance Water Surface Elevation, No withdrawals from the Wes Watkins Recreation Pool	8.2	10.9	4.7 [B]

[A] Firm yield of Wes Watkins Reservoir without withdrawals from the recreational pool. Removing the recreational pool constraint in the model, the firm yield of Wes Watkins increases to 3.6 mgd.

[B] PCDA holds the permit for Wes Watkins. Approximately 3.8 mgd is allocated to Shawnee. The remaining approximately 0.7 mgd is allocated to Tecumseh. The permit limit in the table reflects the allocation amount to Shawnee. The amount available to Shawnee is the amount of water from the firm yield available to Shawnee if Tecumseh takes its full 0.7 mgd allocation.

Shawnee has enough raw water from their reservoirs, Twin Lakes and Wes Watkins, under the balance surface water elevation operational scenario (firm yield of 8.2 mgd based on physical availability, 4.7 mgd available to Shawnee when additionally limited by permit constraints) to meet the current projections for 2060 average annual day water demands of 4.7 mgd (from the 2012 update to the OCWP).

10.2 Drought Management Plan

The secondary objective of this project was to develop a drought management plan. The drought management plan evaluated drought response triggers related to infrastructure and physical water availability. Generally, voluntary rationing should be used when there is a low risk of water shortage occurring. Voluntary rationing is recommended when either Twin Lakes or Wes Watkins reaches elevation 1064. Mandatory restrictions are reserved for when the risk of water shortage is higher. Mandatory rationing is recommended in four stages based on decreasing levels at Twin Lakes and increasing treated water production rates (see specific recommendations in Section 9).

10.3 Next Steps

Based on this analysis, reviewing the firm yield of the Twin Lakes and Wes Watkins should be completed again in approximately 2030. The drought management plan review should be completed in approximately 2020.

Appendix A
Windshield Survey

Appendix A
Windshield Survey

This section presents photographs taken during the windshield survey of the Twin Lakes and Wes Watkins watersheds. Figure A-1 at the end of this section illustrates locations of photographs.

Photographs from the Twin Lakes Watershed

Photo 1: Taken near intersection of New Hope and 102.

Photo 2: Taken near intersection of New Hope and 102.

Photo 3: Taken near intersection of N33 and E119.

Photo 4: Taken near intersection of N33 and E119.

Photo 5: Taken near intersection of N33 and E118.

Photo 6: Taken near intersection of N33 and E118.

Photo 7: Taken near intersection of N33 and E118.

Photo 7a: Taken near intersection of N33 and E118.

Photo 7b: Taken near intersection of N33 and E118.

Photo 8: Taken near intersection of N33 and E118.

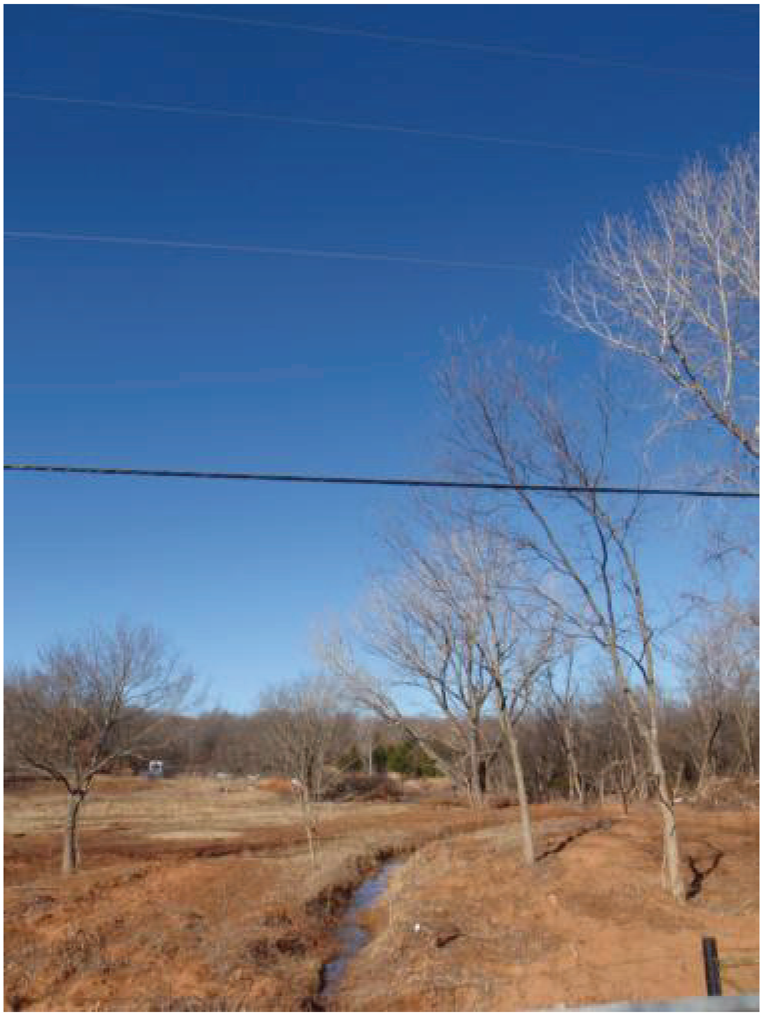


Photo 9: Taken near intersection of N33 and E118.

Photo 10: Taken along E118.

Photo 11: Taken along E117.

Photo 12: Taken along E117.

Photo 13: Taken near intersection of E117 and 102.

Photo 14: Taken along Twin Lake 1.

Photo 15: Taken along Twin Lake 1.

Photo 16: Taken along Twin Lake 1.

Photo 17: Taken along Twin Lake 1.

Photo 18: Taken along Magnro.

Photo 19: Taken along Magnro.

Photo 20: Taken along Magnro.

Photo 21: Taken along N332.

Photo 22: Taken along N332.

Photo 23: Taken along N332.

Photo 24: Taken near intersection of Walker and E117.

Photo 25: Taken near intersection of Walker and E117.

Photo 26: Taken near intersection of CR116 and Walker.

Photo 27: Taken near intersection of CR116 and Walker.

Photo 28: Taken along Walker.

Photo 29: Taken near intersection of Pottawatomie and Hackney.

Photo 30: Taken near intersection of Pottawatomie and Hackney.

Photo 31: Taken near Homer Lake.

Photo 32: Taken near Homer Lake.

Photographs from the Wes Watkins Watershed

Photo 33: Taken near intersection of SE119 and SE121.

Photo 34: Taken near intersection of SE119 and SE121.

Photo 35: Taken near intersection of SE119 and SE121.

Photo 36: Taken near intersection of SE119 and SE121.

Photo 37: Taken near intersection of SE119 and SE121.

Photo 38: Taken near intersection of SE119 and SE121.

Photo 40: Taken near intersection of Dobbs and SE104th.

Photo 41: Taken near intersection of Dobbs and SE104th.

Photo 42: Taken near intersection of Dobbs and SE104th.

Photo 43: Taken near intersection of Dobbs and SE104th.

Photo 44: Taken near intersection of Luther and 74th.

Photo 45: Taken near intersection of Luther and 74th.

Photo 46: Taken near intersection of Luther and 74th.

Photo 47: Taken near intersection of 59th and Dobbs.

Photo 48: Taken near intersection of 59th and Dobbs.

Photo 49: Taken near intersection of 59th and Dobbs.

Photo 50: Taken near intersection of 59th and Midway.

Photo 51: Taken near intersection of 59th and Midway.

Photo 52: Taken near intersection of 59th and Midway.

Photo 53: Taken along Harrah.

Photo 53a: Taken along Harrah.

Photo 54: Taken along Arena.

Photo 55: Taken along Arena.

Photo 56: Taken along Arena.

Photo 57: Taken along Parkwood.

Photo 58: Taken along Parkwood.

Photo 59: Taken along Parkwood.

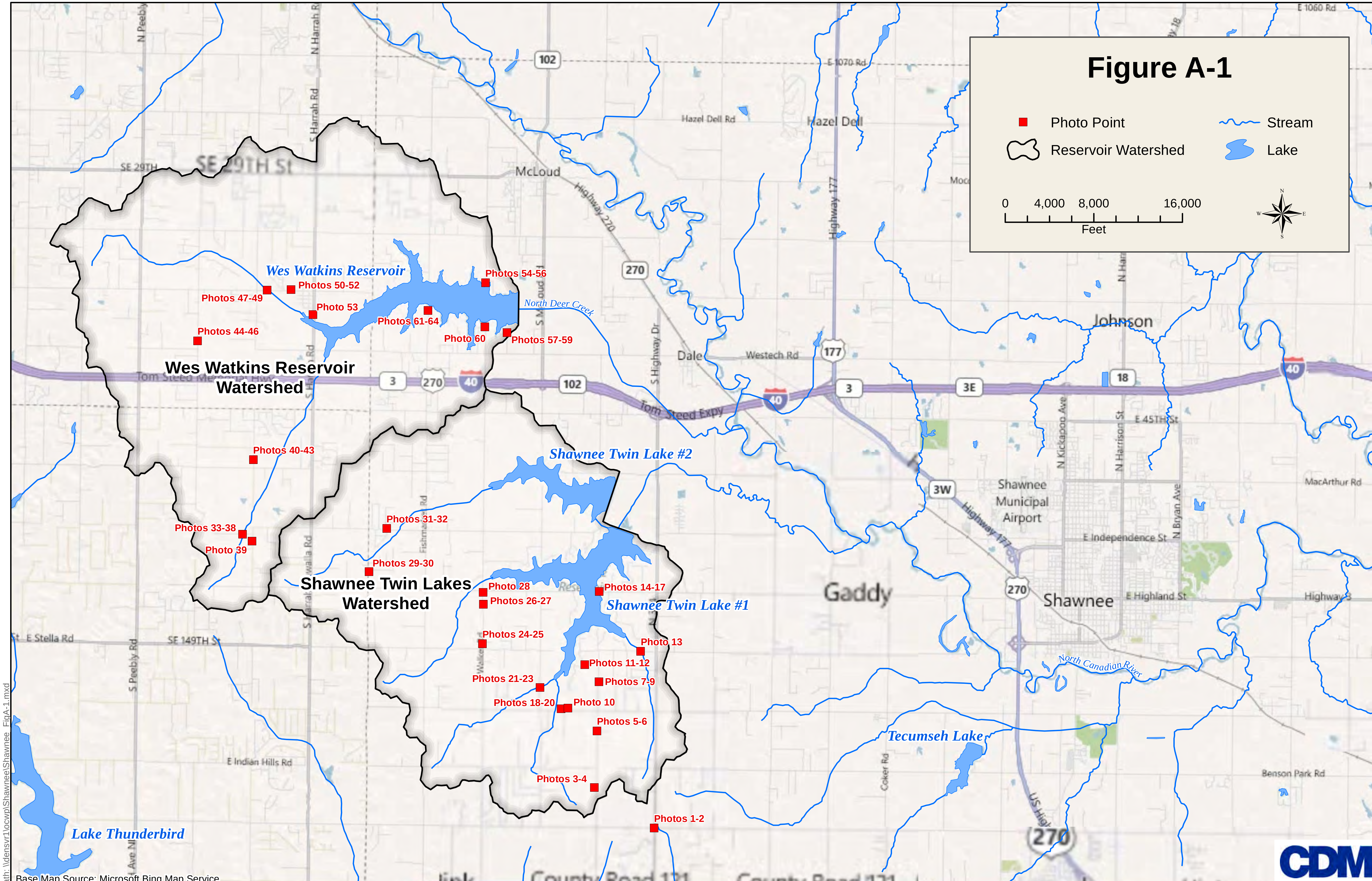
Photo 60: Taken along Timber.

Photo 61: Taken along Fishmarket.

Photo 62. Taken along Fishmarket.

Photo 63: Taken along Fishmarket.

Photo 64: Taken along Fishmarket.



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Appendix B
OCWP Approach for Statewide Reservoir Yield Analysis Technical Memorandum

State of Oklahoma
OWRB
WATER RESOURCES BOARD
the water agency

Oklahoma Comprehensive Water Plan
2011 Update

Approach for Statewide Reservoir Yield Analysis
Technical Memorandum

December 2009

Oklahoma Comprehensive Water Plan
OCWP

This study was funded through an agreement with the Oklahoma Water Resources Board under its authority to update the Oklahoma Comprehensive Water Plan, the state's long-range water planning strategy, due for submittal to the State Legislature in 2012. Results from this and other studies have been incorporated where appropriate in the OCWP's technical and policy considerations.
The general goal of the OCWP is to ensure reliable water supplies for all Oklahomans through integrated and coordinated water resources planning and to provide information so that water providers, policy-makers, and water users can make informed decisions concerning the use and management of Oklahoma's water resources.

Prepared by CDM under a cooperative agreement between the
United States Army Corps of Engineers and the Oklahoma Water Resources Board

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CDM

Technical Memorandum

To: *Kyle Arthur, OWRB*
Gene Lilly, USACE Tulsa District

From: *Tim Cox, CDM*
Kirk Westphal, CDM
Dan Reisinger, CDM

Date: *December 23, 2009*

Subject: *Approach for Statewide Reservoir Yield Analysis*

1.0 Purpose of this Memorandum

This memo will be used to clearly define a proposed approach for single-reservoir firm yield analysis in Oklahoma, as part of the 2011 update to the Oklahoma Comprehensive Water Plan (OCWP). Specifically, this document outlines the general analytical approach, demonstrates the approach by testing on two reservoirs, and discusses the ultimate utility of the information generated.

2.0 Purpose of the Test Case Yield Analysis

The purpose of the test case analysis was to substantiate an approach for reservoir firm yield analysis in Oklahoma that can be used across the state for determining reservoir yields. The approach blends common elements of standard practices employed by the United States Bureau of Reclamation (Reclamation), the United States Army Corps of Engineers (USACE), and Camp Dresser & McKee Inc. (CDM). The methodology discussed in this memorandum specifically focuses on a method for analysis of individual reservoirs, though by representing operational controls the approach could easily be extended to systems of multiple linked reservoirs.

Neither the definition of yield nor its basic mathematical derivation deviates from established practices. It is neither intended nor expected that this approach will be used to change prior estimates of firm yield, unless new data have become available or conditions have changed enough to warrant re-evaluation of existing yield values and associated water allocations. Rather, results of this approach were compared to prior estimates of reservoir yield for one of the two test cases in the Washita Basin (discussed below, and using the same data as were used in the original analyses) as a way to establish its credibility.

A primary objective of the yield analysis described here, then, was to validate the tool by reproducing published yield values using the same inputs. A second objective of the tests was to assess the sensitivity of yield estimates to alternative techniques for synthesizing streamflow records in ungaged basins (or in gaged basins during ungaged periods). Although beyond the scope of the current study, the tool demonstrated here can also be used in the future to better understand uncertainty in yield estimates by providing a simple platform with which to test the sensitivity of the estimates to reservoir characteristics that are difficult to quantify. Examples of uncertain characteristics include sedimentation rates, changing runoff patterns resulting from buildout, seepage patterns, hydrologic uncertainty, etc.

3.0 Proposed Approach for Statewide Firm Yield Analysis

Firm yield calculations may be performed for multiple reservoirs across the state as part of the 2011 update to the OCWP and/or subsequent OCWP implementation activities. For this work, firm yield is defined as the maximum annual demand that can be fully met with reservoir withdrawals throughout the period of analysis, including critical drought conditions. Firm yield is dependent on the amount of flow into the reservoir, the storage capacity of the reservoir, reservoir evaporation and other losses, reservoir operational constraints, and the seasonal pattern of water demands placed on the reservoir.

General Approach

As part of this initial study, CDM reviewed standard methodologies employed by both Reclamation and USACE so that the proposed approach, including the proposed tool itself, could match the standards of practice of both agencies with respect to reservoir firm yield analysis, especially for individual (non-linked) reservoirs. Additionally, the proposed approach provides for analysis of multi-reservoir systems without necessitating complex computer programs with specialized programming codes. Overall, the goal for this approach was to match the standards of practice of both Reclamation and USACE while providing a flexible and intuitive platform for both single-reservoir and multi-reservoir systems.

More specifically, the proposed approach is intended to enhance existing methods of reservoir yield analysis with the inclusion of:

- Improved hydrologic estimating techniques for estimating flow in ungaged basins, extending historical records, or filling data gaps
- Alternatives for reservoir evaporation calculations
- A simple and intuitive modeling interface
- Ability to link reservoirs into networks with operating rules while maintaining the basic simplicity of the tool

Collectively, Reclamation and USACE apply the following criteria to firm yield analysis for a single reservoir:

1. **Definition of Firm Yield:** Amount of water that can be withdrawn from a reservoir each year including the years of the critical drought of record without the reservoir (or its designated storage pool) going dry.

2. **Period of Record:** Must include the drought of record. (In Oklahoma, this is frequently identified in the 1950s, but in some locations, more severe droughts occurred in the 1930s and 1960s.) USACE uses the following historical time periods for firm yield analysis:

Major River Basin	*Duration*	*Years*
Arkansas River	69 years	1940-2008
Red River	71 years	1938-2008
Washita River	79 years	1924-2002
North Canadian River	56 years	1940-1995

3. **Timestep:** Monthly.

4. **Seasonal Demand Fluctuation:** Monthly percentages of annual demand computed from historical data.

5. **Inflows:** Gage data if available, or transposition from nearby gaged basins. For transposing flows from nearby gages, the drainage area of the gaged basin should be similar to that of the ungaged basin (i.e., drainage area ratios close to 1.0). (See discussion below for proposed alternatives for estimating ungaged flow).

6. **Sedimentation:** 100 years of sedimentation is generally used by Reclamation. For the USACE, the sedimentation period is set based on the project-specific planning horizon. In both cases, measured data from nearby similar reservoirs are used to develop sediment loading rates. These rates are then applied over the specified sedimentation period (e.g., 100 years) to estimate a total loss of available storage, which is then subtracted from the original available storage for subsequent firm yield analysis.

7. **Operational Flows:** Spills are computed as the total water above the top of the conservation pool at the end of each month so that the model never ends a month with water above the conservation pool. Other operational outflows (downstream releases, for example) can be included as necessary.

8. **Operating Logic:** Because this analysis is for a single reservoir, there is no need for the inclusion of operating decisions (priorities of sources, rules for water transfers, etc.).

9. **Pool Constraints:** The bottom of the "available water" is the lowest level at which municipal and industrial (M&I) withdrawals can physically be taken, or the bottom of the conservation pool (whichever is higher).

10. **Seepage:** Can be applied if deemed significant for the subject reservoir or dam.

11. **Reservoir Evaporation:** Evaporation is computed using the reservoir surface area corresponding to the beginning of each monthly timestep. Values can be derived using historical data or regional estimates for evaporation (and precipitation, if net evaporation is to be used).

12. **Tools:** Spreadsheet tools are commonly used for single-reservoir yield analysis.

Proposed Tool

The features described above, plus additional features, are currently available in CDM's Simplified Water Allocation Model (SWAM). This is a Microsoft Excel-based generalized water allocation modeling tool. SWAM is designed for simulating entire system networks of water supply and demand elements, but is also well-suited for calculating the firm yield of a single reservoir. Previous versions of SWAM were used by CDM to perform firm yield analyses in a variety of past studies and plans, such as Colorado reservoirs as part of the Colorado 2005 Statewide Water Supply Initiative (SWSI).

Further, as a fully networked water allocation model, SWAM also includes many features that may prove useful for extending these analyses to more complicated reservoirs or systems. For example, a downstream node could easily be added to the modeled reservoir system to simulate the impacts of downstream constraints (priority water rights of instream flow targets) on reservoir yield. Alternatively, the impacts of changing upstream diversions on estimated firm yields could be investigated with an upstream extension of the modeled system. These types of advanced analyses are beyond the scope of the approach outlined here but may feature in future studies.

Inflow and Other Model Parameters

There will be multiple alternatives for estimating and applying inflow timeseries (either streamflow or total net inflow) for the statewide yield analysis. The main options are listed below in descending order of preference. The order of preference is provided as general guidance only and is not intended to represent a rigorous decision tree for applying these methods. Ultimately, sound engineering judgment will need to be applied on a case by case basis when selecting a method for estimating reservoir inflows in the absence of measured site-specific data.

As part of the OCWP gap analysis, CDM has already developed synthetic flow records for selected major rivers that are either ungaged or that exhibited data gaps. Consequently, many inflow records needed for yield analysis can be obtained from the results of that analysis. The techniques listed below are available for gaps or records that may need additional work for yield analysis purposes.

- **United States Geological Survey (USGS) Stream Gages:** (For basins with USGS stream gages immediately upstream of reservoir) – USGS stream gages will be the primary source of reservoir inflow data for this analysis. Where upstream gages exist with adequate periods of record, monthly mean flow records will be used directly in the firm yield analysis. Appropriate consideration will be given to the use of gage data that have not yet been verified and are labeled as "provisional."

- **Net Inflow Estimates from Operating Logs:** (For reservoir with substantial monthly operating logs) – Where sufficient operational data are available for the drought of record and beyond, water balance calculations can provide reliable estimates of the net hydrologic flux into or out of a reservoir. Required data include monthly spills, releases/withdrawals, and changes in water surface elevation or storage. If those data are available, the water balance equation for each timestep can be solved for net inflow (defined below). Adjustments would be made to evaporation and seepage inputs to avoid double counting these phenomena.

  Water balance for any timestep: $\Delta Storage = Q_{net} - Spill - Release$
  Where net inflow is defined: $Q_{net} = [Streamflow - Net\ Evap - Seepage]$

- **Statistical Record Extension:** (For basins with partial streamflow records upstream of reservoir) – Periods of missing streamflow data can be filled based on the flow in nearby measured streams using the Maintenance of Variance Extension (MOVE.2) statistical technique (Hirsch 1982). MOVE.2 is a statistical flow record extension technique that fills missing data in a streamflow record (y) based on the flow in a nearby reference stream gage (x) while preserving the statistics in basin y. The method has already been employed as part of the water availability analysis for the OCWP 2011 Update (Draft Physical Water Supply Availability Report 2009). The technique shown in the equation below uses the mean (m) and standard deviation (s) of the two streams.

$$y_i = m_y + \frac{S_y}{S_x} \bullet (x_i - m_x)$$

  The selection of an appropriate reference gage will be an important aspect of applying the MOVE.2 technique. Due to Oklahoma's strong east-west precipitation gradient, it is preferred that only nearby reference gages be used for any given reservoir. Additionally, reference basins will be selected so that basin size, land use, soils, and slope will match the characteristics of the basin whose record is to be extended as closely and as practically as possible (based in large part on data availability). Flow "mass curves" or flow-precipitation "double mass curves" (Wilson 1983) may be used to assess the appropriateness of reference gages for this application.

Also, if the statistics for the reference basin differ substantially between the periods for which the basin with data gaps has data and is missing data, a determination will be made as to whether to apply statistics for the entire record or just periods over which the statistics are relatively stable.

- **Streamflow Transposition by Area Ratios:** (For basins with no streamflow records) – For reservoirs where adequate upstream flow records are not available, a surrogate gage will be used to generate a new synthetic monthly timeseries of flows or to fill in gaps in an existing dataset. Basin area ratios will be applied to an appropriate surrogate gage to estimate monthly flows into the target reservoir. The surrogate gage will be selected based on proximity to the target reservoir and similarities (to the greatest extent practical based on data availability) in drainage basin land use, size, soils, and slope. In some cases, known diversions and water consumption may be added or subtracted from surrogate gage data to better replicate conditions of the target reservoir drainage basin. If partial flow records are available for the target reservoir, but not substantial enough to justify the use of the MOVE.2 technique described above, these will be used to validate the basin area ratio technique. This exercise will involve comparing actual monthly flows to gauged flows for the limited period of record. Based on this, simple adjustments to the ratios may be made to improve the accuracy of the method.

- **SCS Curve Number Approach for Runoff Flow:** (Used in combination with area ratio method) – In some cases the area ratio method may not provide satisfactory results, particularly if a surrogate gage with similar land use and hydrologic properties is not available. As an alternative to the area ratio method by itself, the Soil Conservation Service Curve Number (SCS CN) approach may be used to estimate the runoff fraction of the streamflow record using precipitation records (Bedient and Huber 1992). These calculations follow:

$$q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

where:

q = basin runoff flow (inches per day), P = basin precipitation (inches per day)

I_a = 0.2*S, S = 1000/CN – 10, and CN = calculated basin SCS curve number. The calculated flow rate depths, q, are then multiplied by the basin area to generate volumetric runoff flow rates, Q_r:

$$Q_r = q * A$$

where:

A = reservoir drainage basin area. Total basin flows are calculated as the sum of runoff flow and baseflow (Q_b):

$$Q_{tot} = Q_r + Q_b.$$

For this method, basin baseflows are calculated using the area ratio method described previously applied to surrogate gage baseflows. Hydrograph separation techniques will be applied to surrogate gage data to generate a timeseries of surrogate gage baseflows.

Reservoir design and construction plans, bathymetric surveys, or similar documents will be used to quantify reservoir physical parameters in the model. These parameters include total storage capacity, surface area-volume relationships, and inflow channel capacity. The best available information will be used to estimate annual reservoir seepage losses or gains (if any) and sedimentation rates. In some cases, simple water balance calculations may be performed using known reservoir inflows and outflows to quantify unknown flows. Sedimentation information will be used, if appropriate, to reduce the original storage capacity of the target reservoir for the firm yield analysis. When available, site-specific net pan evaporation rates measured over the full period of the analysis will be used directly in the firm yield model. When these data are not available, mean monthly evaporation rates will be obtained from pan evaporation data for nearby stations. In either case, pan correction coefficients will be applied as appropriate. Note that the use of net evaporation rates eliminates the need to include direct precipitation in the firm yield model.

4.0 Test Cases and Demonstration of Proposed Approach

Firm yields were calculated for Foss Reservoir and Lake Jean Neustadt in the Washita River watershed (Figure 4-1) to test the proposed approach described above. Foss Reservoir was built by the Reclamation in 1961. The reservoir is in-line with the Washita River and provides substantial water supply and flood protection, as well as recreation opportunities. The Foss Reservoir Master Conservancy District administers water supplies from the reservoir. Foss Reservoir was selected for this pilot study to allow for the comparison to previously-applied Reclamation methods and tools. To this end, CDM analyzed the preconstruction dataset provided by the Reclamation, which matches the data used by Reclamation in the original yield analysis. Because the dataset is complete and no backfilling is necessary to match the Reclamation dataset, this test focuses exclusively on the monthly reservoir calculations within the proposed tool as a way to validate the tool itself without introducing uncertainty in the input data.

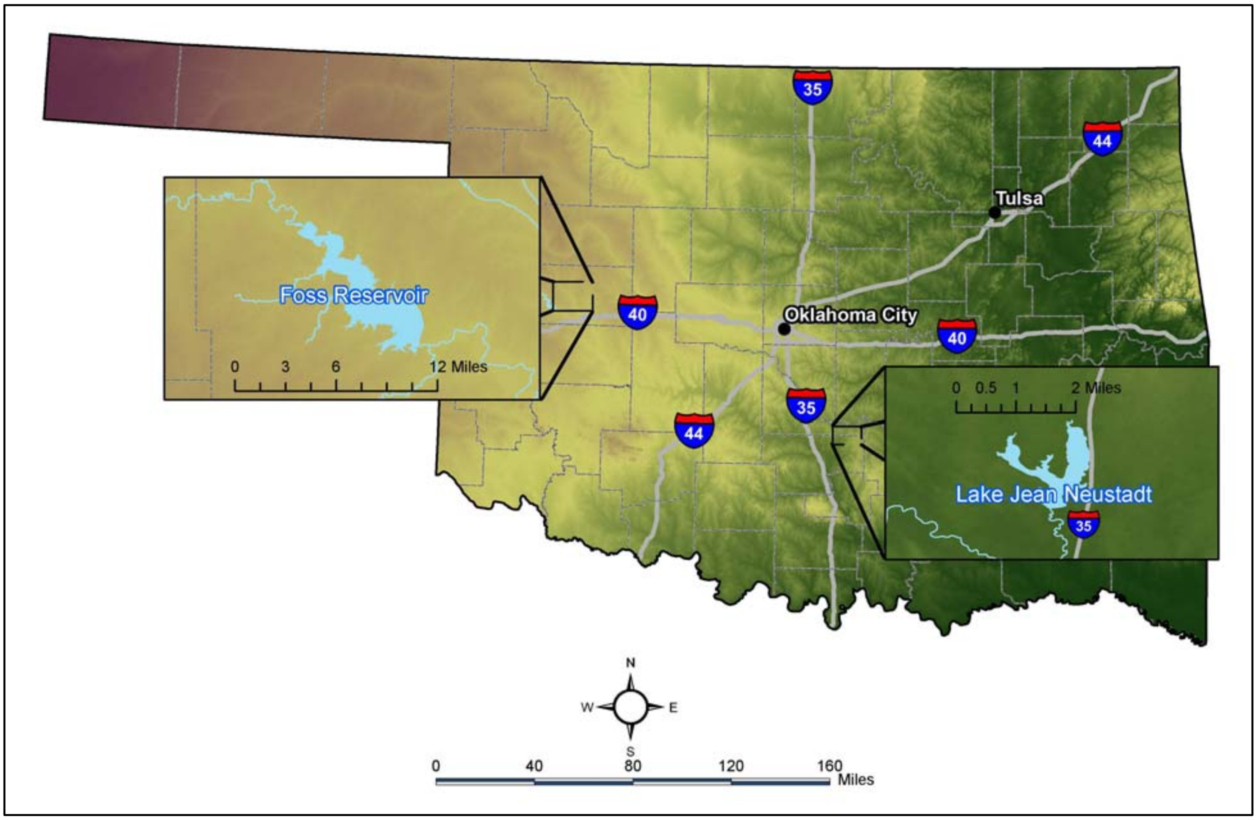


Figure 4-1 Location of Foss Reservoir and Lake Jean Neustadt

Lake Jean Neustadt, also known as Caddo Creek Watershed Site No. 13, is an intermediate sized municipal reservoir built in 1969 by the City of Ardmore and the Soil Conservation Service. The reservoir is used for recreation and backup water supply when water is not available from the Arbuckle Master Conservancy District. The 1967 design plans and 1999 intake tower repair discussions are available, which include information on the stage-storage relationship and inlet and outlet sizes and configurations. A bathymetric survey of the lake was conducted by the Oklahoma Water Resources Board in 2008, which was used in place of the 1967 design plans. The City of Ardmore's 2004 Comprehensive Water Resources plan estimated the reservoir's firm yield to be 2,150 acre-feet per year (AFY). A review of that plan and follow-up discussions with City of Ardmore staff did not identify the method used to estimate this firm yield value. This test reservoir was used primarily as a way to test and demonstrate the alternative ways of generating synthetic streamflow data.

4.1 Foss Reservoir

4.1.1 Input Data

Model input data for Foss Reservoir were obtained directly from the Reclamation spreadsheet tool previously used in the Reclamation's 1958 Definite Plan Report (DPR) to calculate that reservoir's firm yield. As described above, data were unchanged for the firm yield analysis using SWAM presented here. These data include pre-construction (1926 – 1957) monthly stream flows taken from gage records with adjustments made in previous studies to account for "retardation structures" and "land treatment measures" (Figure 4-2). Monthly evaporation rates for the period of record were previously estimated by the Reclamation using pan evaporation measurements and adjustments for precipitation. A detailed area-capacity table was available and used directly in SWAM. Per Reclamation documentation, this table reflects 73 years of anticipated sedimentation. The assumed total conservation pool (177,390 acre-feet [AF]) used in both the Reclamation analysis and the present analysis (using SWAM) is based on the top of pool elevation that existed at the time of the original study and is significantly greater than the actual conservation pool available today. Finally, site specific monthly water usage patterns were used directly in SWAM from the Reclamation study.

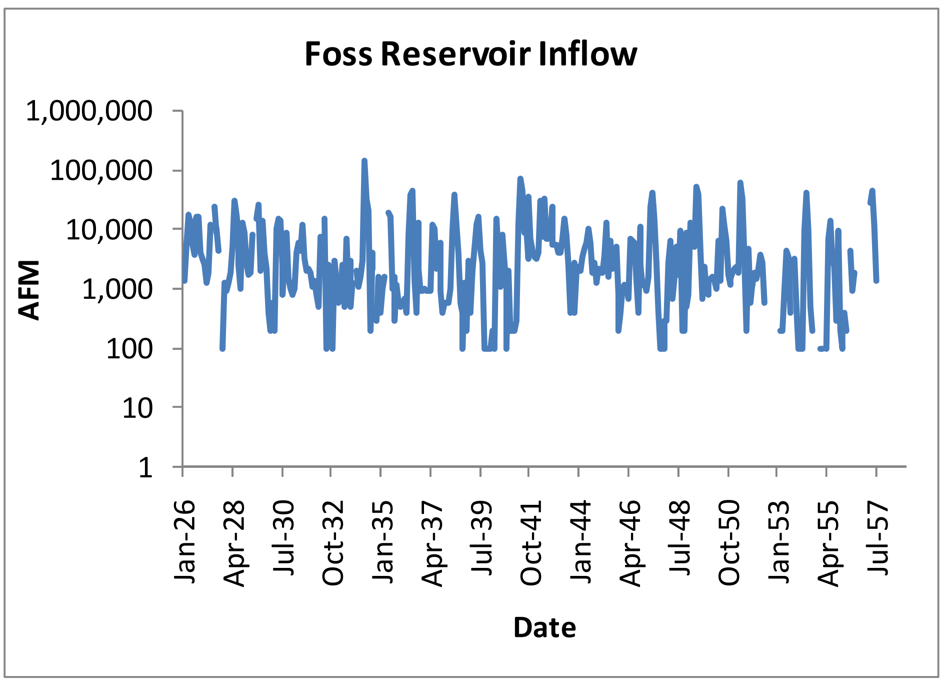


Figure 4-2 Foss Reservoir Modeled Inflow

4.1.2 Results

The Foss Reservoir firm yield calculated in this study exactly matches the value calculated during the previous Reclamation study: 31,200 AFY (Figure 4-3). This result effectively validates the modeling tool used here (SWAM) and confirms that SWAM and the Reclamation approach produce essentially the same result when using identical hydrologic records. Note, the firm yield for Foss Reservoir is currently 18,000 AF based on a study believed to be conducted in the 1970's. Reclamation is expected to publish an updated firm yield within the next year, which will replace the current firm yield of 18,000 AF.

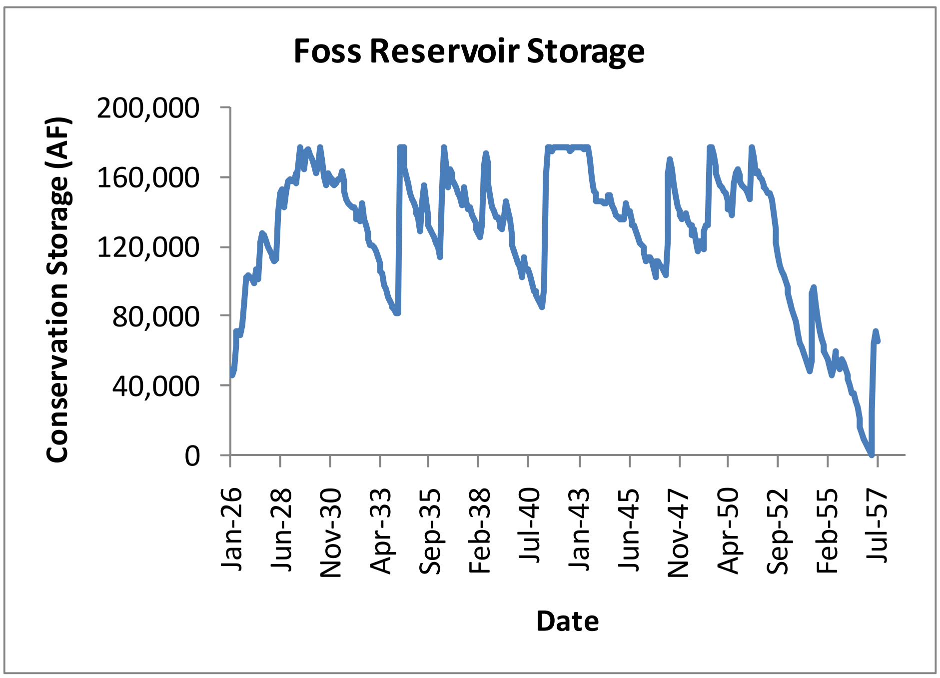


Figure 4-3 Foss Reservoir Modeled Storage Subject to Firm Yield Demand

4.2 Lake Jean Neustadt

4.2.1 Input Data

No gaged inflow data were available for Lake Jean Neustadt. Nor were there reservoir operational data available (e.g., volumes and outflows) with which to back-calculate inflows. Therefore, regional USGS flow gage records were used to construct multiple input data sets of estimated monthly inflows to Lake Jean Neustadt. Five different USGS gages, shown in Figure 4-4, were used in constructing three sets of inflow estimates by applying various combinations of the methods described in Section 3 (Figure 4-5). A summary of the gages used is presented in Table 4-1. Method 1 involved simple area-weighting of a 58-year continuous record from the downstream-most gage (Gage Number 07331000). Method 2 involved combining portions of records from gages 07330500 (preference 1), 07329700 (preference 2), and 07329500 (preference 3) and applying the simple area-weighting method to construct a 60 year continuous flow record for Lake Jean Neustadt. Method 3 involved applying the SCS Curve Number approach to the runoff portion of gage records from Method 2 (multiple gages) and combining with baseflow estimates using simple area-weighting applied to the same gage records. An effective SCS Curve Number for the reservoir drainage area was estimated based on the intersection of GIS layers of hydrologic soil type and land use.

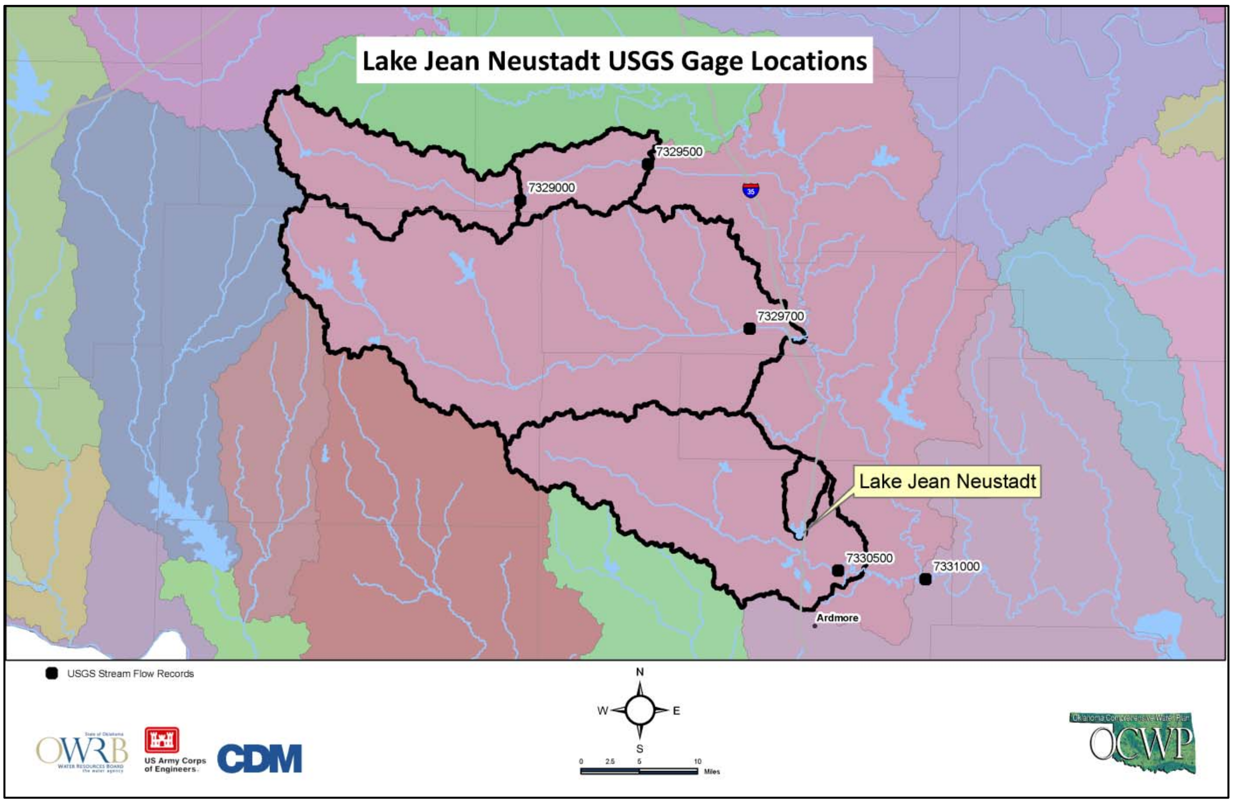
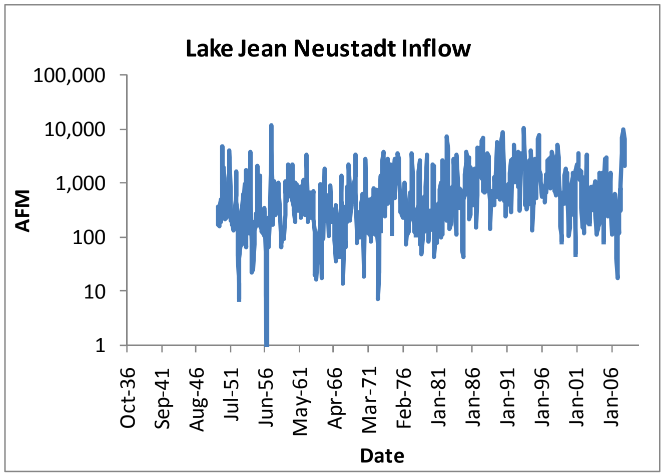


Figure 4-4 Lake Jean Neustadt USGS Gage Locations

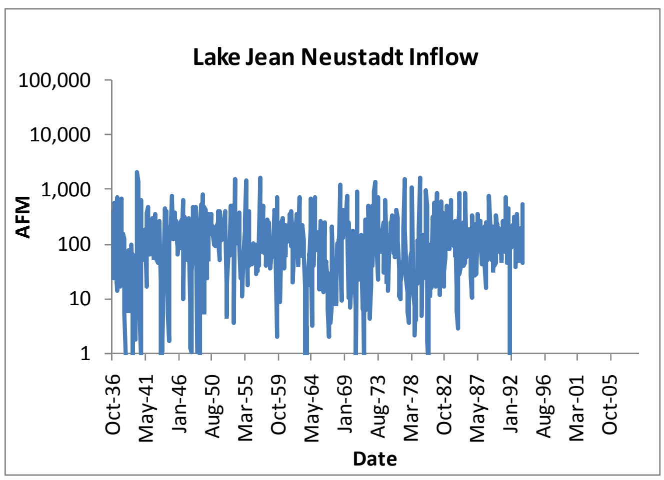
Table 4-1 USGS Streamflow Gages Used to Estimate Inflows to Lake Jean Neustadt

Streamflow Gage Name	USGS Gage Number	Tributary Area (Square Miles)	Period of Record	Location in Basin
Washita River near Dickson, OK	7331000	7202	10/1/1928 - 6/2/2008	At basin outlet
Caddo Creek near Ardmore, OK	7330500	298	10/1/1936 - 9/30/1950, 3/28/1996 -12/31/1997	Includes Lake Jean Neustadt
Wildhorse Creek near Hoover, OK	7329700	604	10/1/1969 - 9/30/1993, 7/1/2000 - 6/30/2002	In Lower Washita basin
Rush Creek near Maysville, OK	7329500	206	10/1/1954 - 9/30/1976	In Lower Washita basin

a) Method 1: Area Weighting, Single Gage



b) Method 2: Area Weighting, Multiple Gages



c) Method 3: SCS CN + Area Weighting

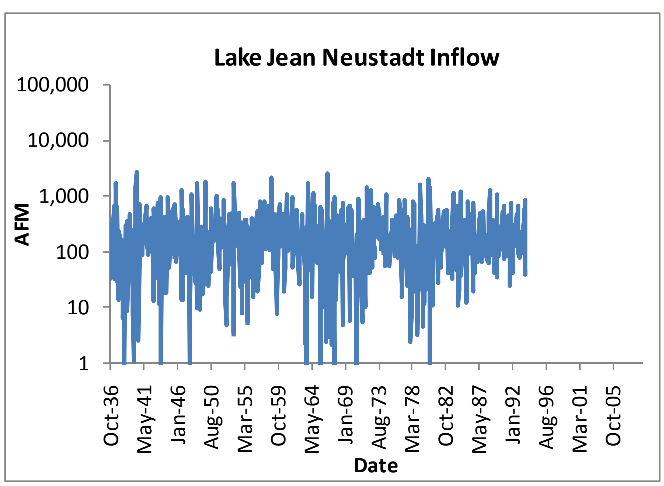
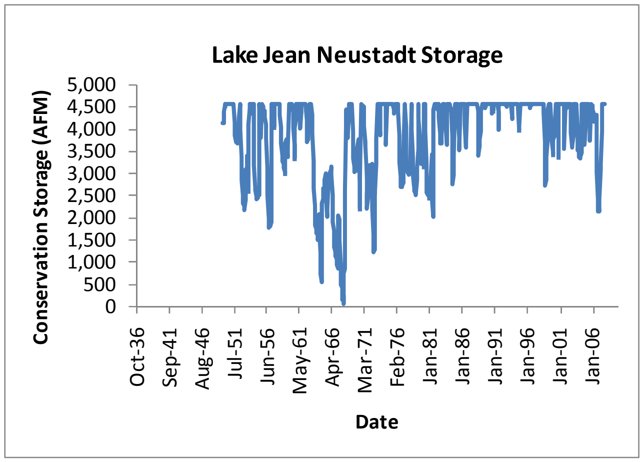
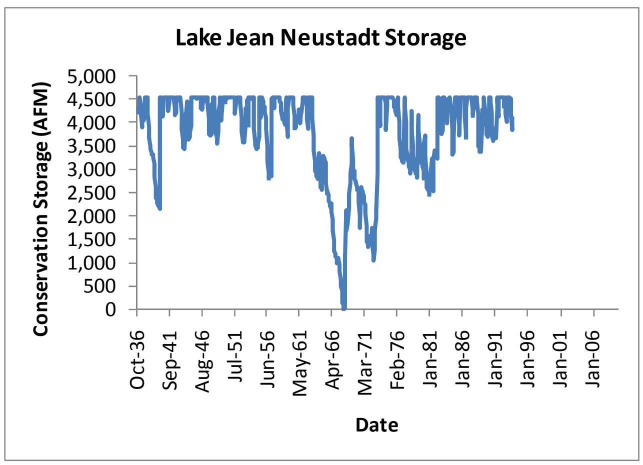


Figure 4-5 Lake Jean Neustadt Modeled Inflow

a) Method 1: Area Weighting, Single Gage



b) Method 2: Area Weighting, Multiple Gages



c) Method 3: SCS CN + Area Weighting

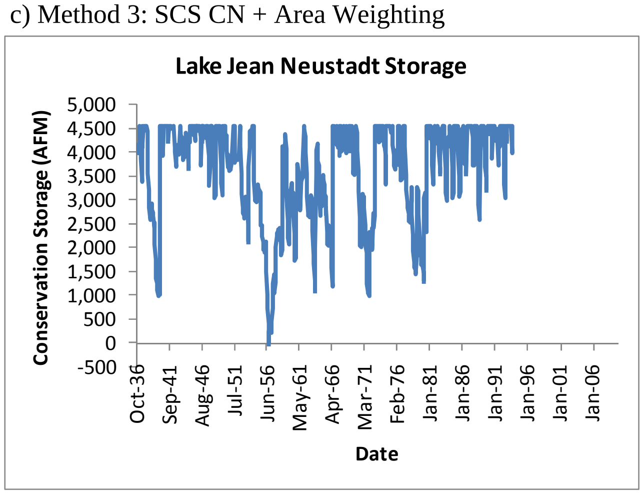


Figure 4-6 Lake Jean Neustadt Modeled Storage Subject to Firm Yield Demand

In the absence of site-specific information, reservoir evaporation rates (inches per month) were assumed equal to those measured over the extended period of record for Arbuckle Reservoir, described above. A detailed area-capacity table for Lake Jean Neustadt was available and an aggregated version of this table was used in SWAM for these analyses. A total municipal storage capacity of 4,542 AF was assumed for these analyses based on original reservoir design plans. In the absence of site-specific information, seasonal water usage patterns were set to the default M&I pattern available in SWAM.

4.2.2 Results

Calculated firm yields for Lake Jean Neustadt were 3,130, 900, and 2,385 AFY for Methods 1, 2, and 3, respectively (Figure 4-7). The previously calculated value, reported by the City of Ardmore's 2004 Comprehensive Water Resources Plan, is 2,150 AFY. Details of this previous calculation are not known. The range of values calculated here demonstrates the sensitivity of these calculations to inflow estimation techniques when site specific gage data are not available. Note that the critical periods with respect to the firm yields also varied across the three methods with the mid to late 1960s proving critical for Methods 1 and 2 while the mid 1950s were critical for Method 3. These differences are likely a function of both regional hydrologic differences and calculation uncertainty. In our opinion, for this particular application, the highest confidence of the three sets of results should be placed on Method 3. This method is the most rigorous and likely accurate of the three options given the lack of an appealing surrogate gage. For situations where a local gage of similar drainage area size and land use does exist, Method 1 (without the SCS CN calculations) would be recommended given the method's simplicity and the fact that, in such cases, the analysis would be supported by reliable empirical data.

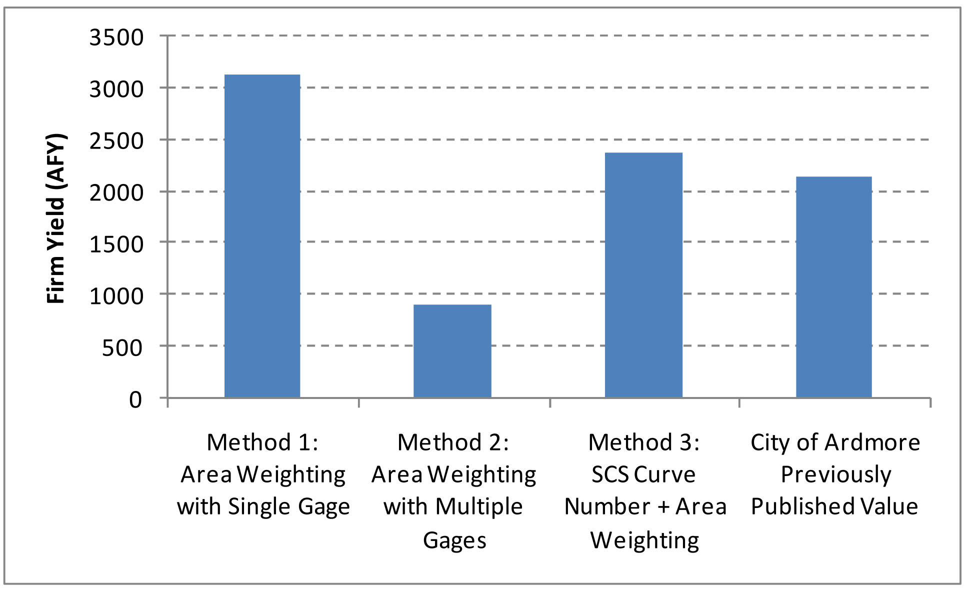


Figure 4-7 Summary of Calculated Firm Yields for Lake Jean Neustadt

5.0 Summary and Conclusions

Estimates of firm yields from individual reservoirs are critical to water supply planning at a local level. The discussion presented above is intended to provide a foundation for extending firm yield analyses to reservoirs across the state. Included in this memorandum are key definitions, a brief review of previously-applied firm yield methods, and a proposed approach for future analyses. The proposed tool, CDM's SWAM, is user-friendly and flexible and well-suited to these types of analyses, as demonstrated by the test case applications presented here.

The Foss Reservoir test case has verified the internal computations of SWAM by replicating a previous spreadsheet calculation by the USACE using the same data sets. The Lake Jean Neustadt test case has demonstrated the application of available options for estimating reservoir inflows when site-specific gaged flows are not available. The results of the latter test case show that, for ungaged basins, firm yield calculations can be highly sensitive to the inflow estimation technique. Care should therefore be taken when selecting the most appropriate method. For this particular case, a method involving area ratio transpositions from multiple regional flow gages combined with SCS Curve Number calculations of runoff flow is offered as the most accurate.

6.0 References

Bedient, P.B. and W.C. Huber. 1992. Hydrology and Floodplain Analysis, Second Edition. Addison-Wesley Publishing Company, Reading, MA.

Wilson, E.M. 1983. Engineering Hydrology, 3rd edition. Macmillan Press, London.

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Appendix C
Storage Tables

Appendix C
Storage Tables

Table C-1: Elevation and Storage for Twin Lakes [A]

Elevation (ft)	Storage (acre-feet)
1073.5	29,263
1073.0	28,452
1072.5	27,539
1072.0	26,627
1071.5	25,748
1071.0	24,868
1070.5	24,021
1070.0	23,173
1069.5	22,357
1069.0	21,541
1068.5	20,755
1068.0	19,968
1067.5	19,211
1067.0	18,454
1066.5	17,725
1066.0	16,995
1065.5	16,326
1065.0	15,656
1064.5	15,048
1064.0	14,440
1063.5	13,862
1063.0	13,283
1062.5	12,732
1062.0	12,180
1061.5	11,655
1061.0	11,131
1060.5	10,633
1060.0	10,136
1059.5	9,667
1059.0	9,197
1058.5	8,755
1058.0	8,312
1057.5	7,894
1057.0	7,476
1056.5	7,081
1056.0	6,687
1055.5	6,316
1055.0	5,945
1054.5	5,597
1054.0	5,249
1053.5	4,922
1053.0	4,596
1052.5	4,291
1052.0	3,987

Table C-1: Elevation and Storage for Twin Lakes [A]

Elevation (ft)	Storage (acre-feet)
1051.5	3,704
1051.0	3,421
1050.5	3,157
1050.0	2,893
1049.5	2,647
1049.0	2,401
1048.5	2,173
1048.0	1,944
1047.5	1,733
1047.0	1,521
1046.5	1,326
1046.0	1,130
1045.5	950
1045.0	769
1044.5	604
1044.0	438
1043.5	287
1043.0	136
1042.5	0

[A] The storage amount corresponds to the available volume above the lower intake elevation.

Table C-2: Elevation and Storage for Wes Watkins [A]

Elevation (ft)	Storage (acre-feet)
1074.0	13,993
1073.5	13,481
1073.0	12,970
1072.5	12,458
1072.0	11,947
1071.5	11,488
1071.0	11,030
1070.5	10,572
1070.0	10,114
1069.5	9,655
1069.0	9,197
1068.5	8,739
1068.0	8,281
1067.5	7,919
1067.0	7,557
1066.5	7,195
1066.0	6,833
1065.5	6,471
1065.0	6,109
1064.5	5,747
1064.0	5,385
1063.5	5,092
1063.0	4,800
1062.5	4,507
1062.0	4,215
1061.5	3,929
1061.0	3,643
1060.5	3,385
1060.0	3,126
1059.5	2,926
1059.0	2,725
1058.5	2,525
1058.0	2,324

Table C-2: Elevation and Storage for Wes Watkins [A]

Elevation (ft)	Storage (acre-feet)
1057.5	2,141
1057.0	1,958
1056.5	1,801
1056.0	1,644
1055.5	1,529
1055.0	1,414
1054.5	1,299
1054.0	1,185
1053.5	1,070
1053.0	955
1052.5	840
1052.0	726
1051.5	658
1051.0	590
1050.5	522
1050.0	454
1049.5	386
1049.0	318
1048.5	250
1048.0	182
1047.5	143
1047.0	105
1046.5	66
1046.0	28
1045.5	19
1045.0	11
1044.5	3
1044.4	0

[A] The storage amount corresponds to the available volume above the lower intake elevation.

Table C-3: Storage and Percent of Total System Storage

Total System Storage (acre-feet)	Percent of total system storage (combined Twin Lakes and Wes Watkins)
43,256	100%
38,930	90%
34,605	80%
30,279	70%
25,954	60%
21,628	50%
17,302	40%
12,977	30%
8,651	20%
4,326	10%

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Appendix D
Raw Water Transmission Capacity Tables

Appendix D
Raw Water Transmission Capacity Tables

The City of Shawnee provided the attached raw water transmission pipe capacity tables. With confirmation from the City, the minimum raw water storage elevation rows were used since the raw water storage tank has been bypassed. These tables were used to assess the minimum elevation at the reservoirs needed for the raw water to flow by gravity to the treatment plant.

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TABLE 5

GRAVITY FLOW FROM NORTH DEER CREEK RESERVOIR TO THE SHAWNEE WATER TREATMENT PLANT

MANNINGS EQUATION

	RESERVOIR ELEVATION	RAW WATER STORAGE ELEVATION	RAW WATER LINE LENGTH (FEET)	HYDRAULIC GRADE (FT./100FT.)	PIPE DIAMETER (INCHES)	DEPTH OF FLOW (INCHES)	COEFFICIENT OF FRICTION "N"	FLOW (MGD)	VELOCITY (FPS)
FLOOD POOL TO MAXIMUM RAW WATER ELEVATION	1081.80	1037.36	66,100	0.000672	31.25	31.25	0.012	8.44	2.45
NORMAL POOL TO MAXIMUM RAW WATER ELEVATION	1074.00	1037.36	66,100	0.000554	31.25	31.25	0.012	7.67	2.23
DOWN 5 FEET TO MAXIMUM RAW WATER ELEVATION	1069.00	1037.36	66,100	0.000479	31.25	31.25	0.012	7.13	2.07
DOWN 10 FEET TO MAXIMUM RAW WATER ELEVATION	1064.00	1037.36	66,100	0.000403	31.25	31.25	0.012	6.54	1.90
RECREATION POOL TO MAXIMUM RAW WATER ELEVATION	1061.20	1037.36	66,100	0.000361	31.25	31.25	0.012	6.19	1.80
FLOOD POOL TO MINIMUM RAW WATER ELEVATION	1081.80	1027.00	66,100	0.000829	31.25	31.25	0.012	9.38	2.72
NORMAL POOL TO MINIMUM RAW WATER ELEVATION	1074.00	1027.00	66,100	0.000711	31.25	31.25	0.012	8.69	2.52
DOWN 5 FEET TO MINIMUM RAW WATER ELEVATION	1069.00	1027.00	66,100	0.000635	31.25	31.25	0.012	8.21	2.38
DOWN 10 FEET TO MINIMUM RAW WATER ELEVATION	1064.00	1027.00	66,100	0.000560	31.25	31.25	0.012	7.71	2.24
RECREATION POOL TO MINIMUM RAW WATER ELEVATION	1061.20	1027.00	66,100	0.000517	31.25	31.25	0.012	7.41	2.15

TABLE 4

GRAVITY FLOW FROM SHAWNEE TWIN RESERVOIRS TO THE SHAWNEE WATER TREATMENT PLANT

MANNINGS EQUATION

	RESERVOIR ELEVATION	RAW WATER STORAGE ELEVATION	RAW WATER LINE LENGTH (FEET)	HYDRAULIC GRADE (FT./100FT.)	PIPE DIAMETER (INCHES)	DEPTH OF FLOW (INCHES)	COEFFICIENT OF FRICTION "N"	FLOW (MGD)	VELOCITY (FPS)
FLOOD POOL TO MAXIMUM RAW WATER ELEVATION	1073.50	1037.36	47,700	0.000758	31.25	31.25	0.012	8.97	2.60
NORMAL POOL TO MAXIMUM RAW WATER ELEVATION	1067.00	1037.36	47,700	0.000621	31.25	31.25	0.012	8.12	2.36
DOWN 5 FEET TO MAXIMUM RAW WATER ELEVATION	1062.00	1037.36	47,700	0.000517	31.25	31.25	0.012	7.41	2.15
DOWN 10 FEET TO MAXIMUM RAW WATER ELEVATION	1057.00	1037.36	47,700	0.000412	31.25	31.25	0.012	6.61	1.92
DOWN 15 FEET TO MAXIMUM RAW WATER ELEVATION	1052.00	1037.36	47,700	0.000307	31.25	31.25	0.012	5.71	1.66
DOWN 20 FEET TO MAXIMUM RAW WATER ELEVATION	1047.00	1037.36	47,700	0.000202	31.25	31.25	0.012	4.63	1.34
LOW ELEVATION TO MAXIMUM RAW WATER ELEVATION	1043.50	1037.36	47,700	0.000129	31.25	31.25	0.012	3.70	1.07
FLOOD POOL TO MINIMUM RAW WATER ELEVATION	1073.50	1027.00	47,700	0.000975	31.25	31.25	0.012	10.17	2.95
NORMAL POOL TO MINIMUM RAW WATER ELEVATION	1067.00	1027.00	47,700	0.000839	31.25	31.25	0.012	9.44	2.74
DOWN 5 FEET TO MINIMUM RAW WATER ELEVATION	1062.00	1027.00	47,700	0.000734	31.25	31.25	0.012	8.83	2.57
DOWN 10 FEET TO MINIMUM RAW WATER ELEVATION	1057.00	1027.00	47,700	0.000629	31.25	31.25	0.012	8.17	2.37
DOWN 15 FEET TO MINIMUM RAW WATER ELEVATION	1052.00	1027.00	47,700	0.000524	31.25	31.25	0.012	7.46	2.17
DOWN 20 FEET TO MINIMUM RAW WATER ELEVATION	1047.00	1027.00	47,700	0.000419	31.25	31.25	0.012	6.67	1.97
LOW ELEVATION TO MINIMUM RAW WATER ELEVATION	1043.50	1027.00	47,700	0.000346	31.25	31.25	0.012	6.06	1.76