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

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.

Oklahoma Comprehensive Water Plan
OCWP

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

CDM

Technical Memorandum

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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.

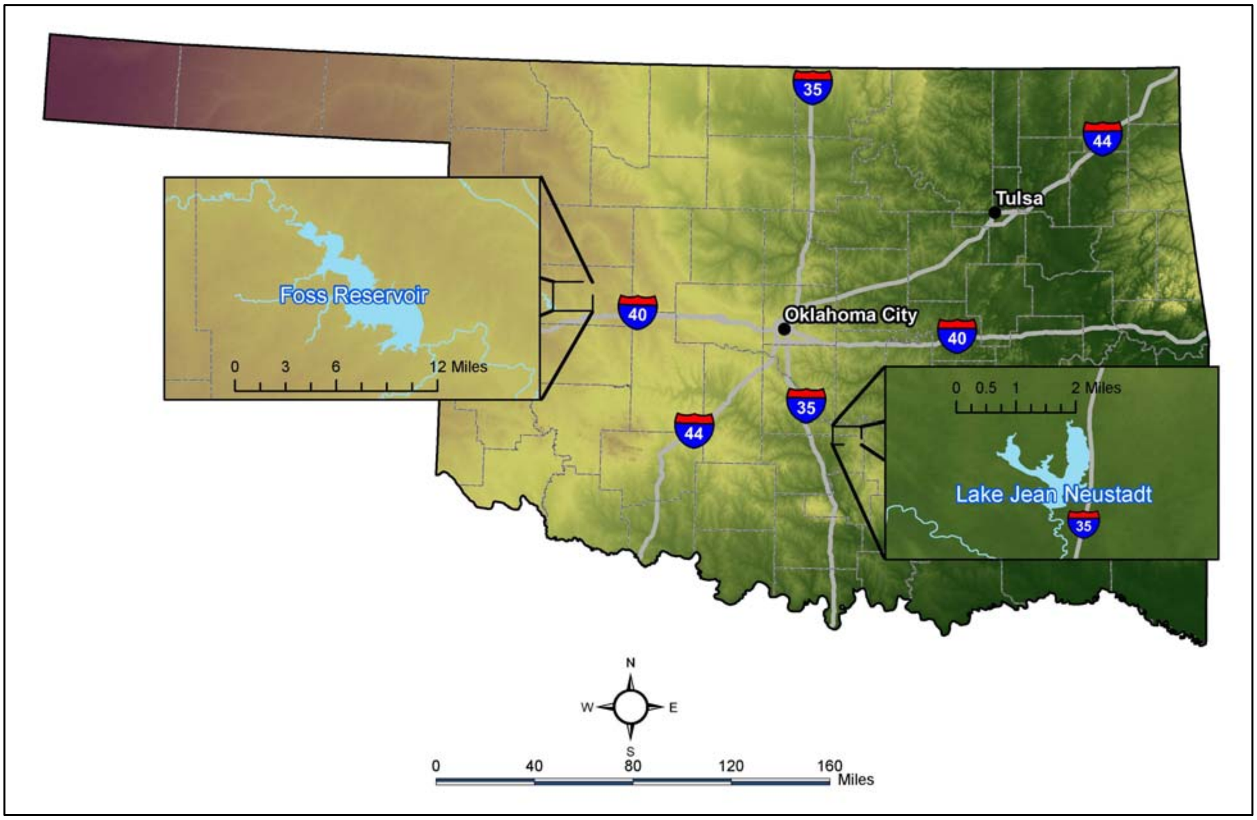


Figure 4-1 Location of Foss Reservoir and Lake Jean Neustadt

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.

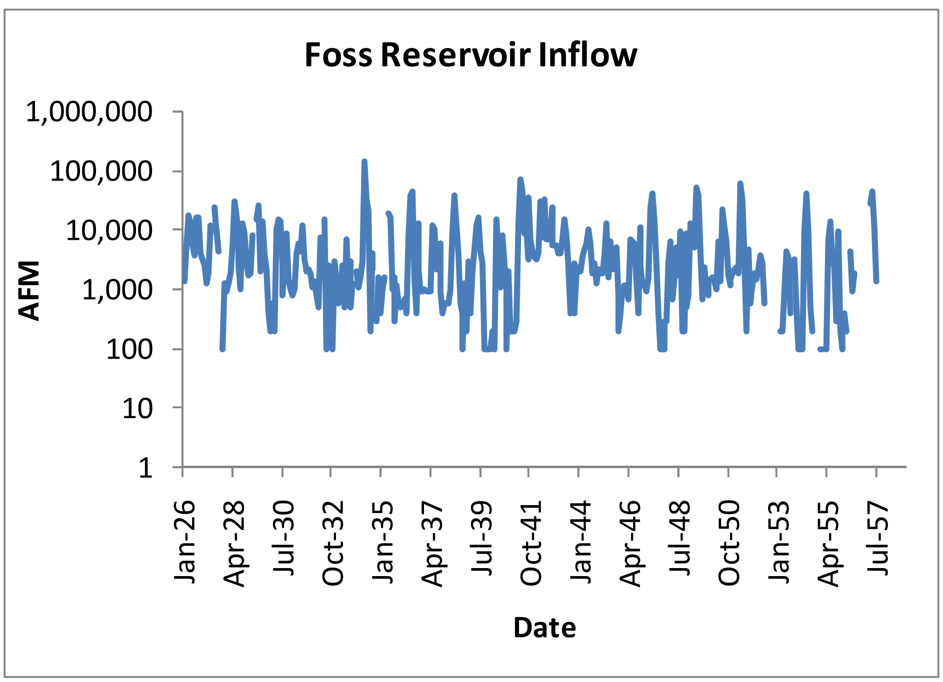


Figure 4-2 Foss Reservoir Modeled Inflow

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.

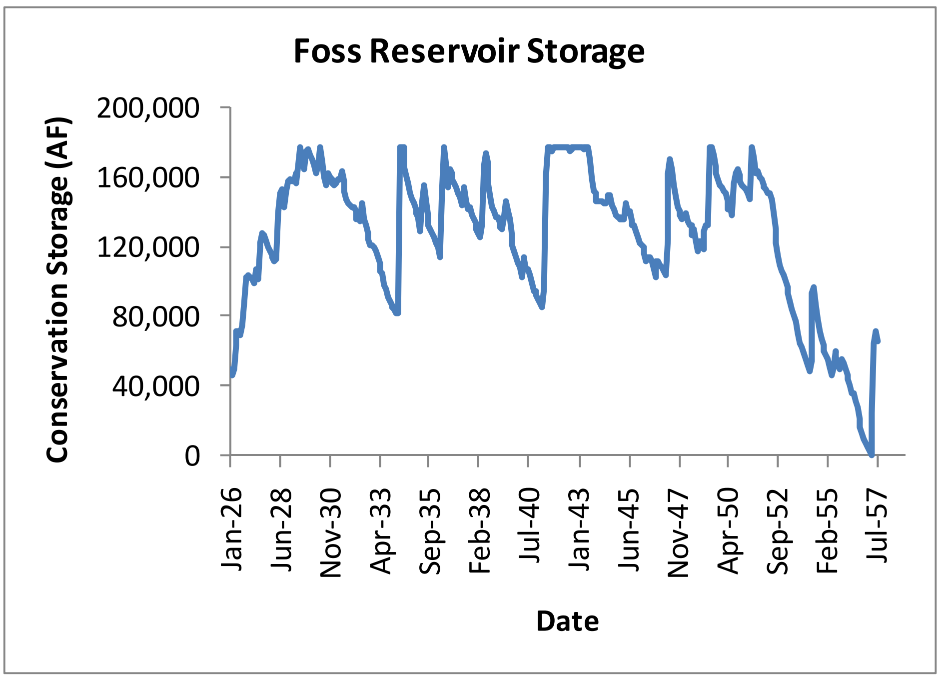


Figure 4-3 Foss Reservoir Modeled Storage Subject to Firm Yield Demand

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.

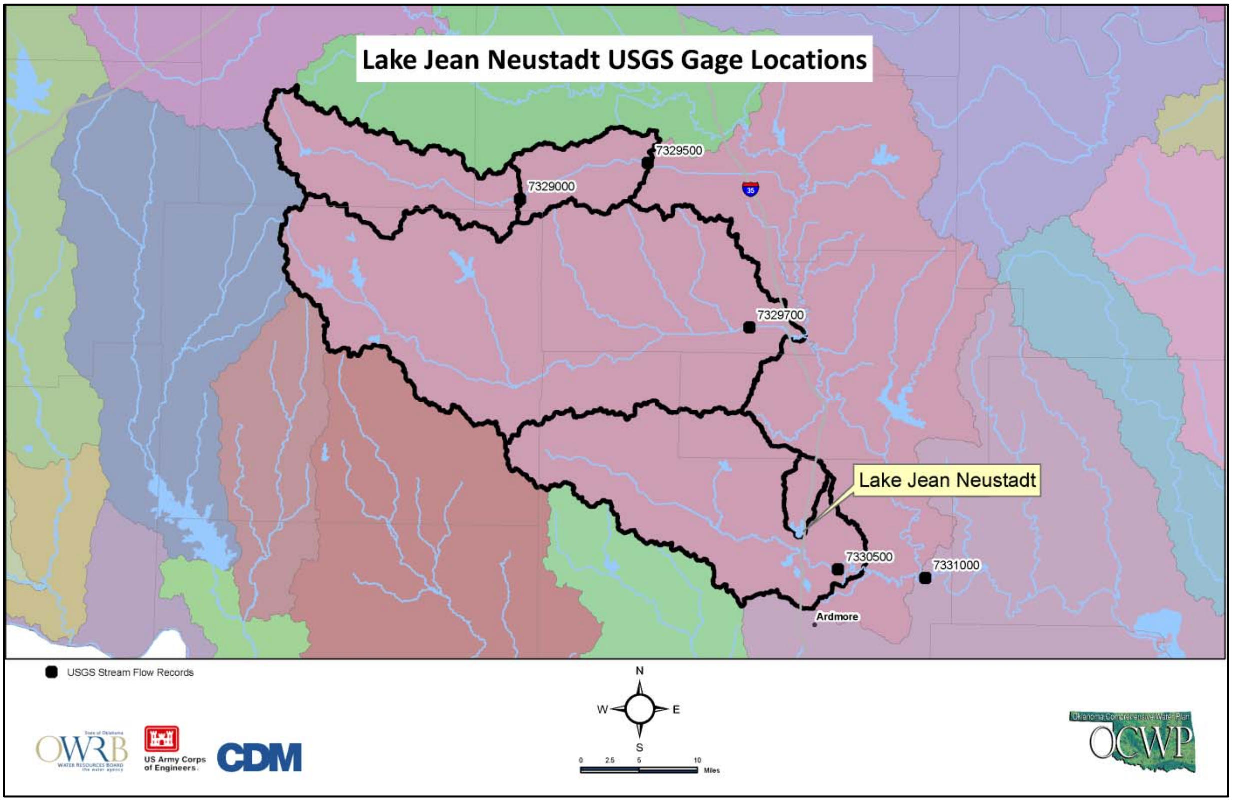
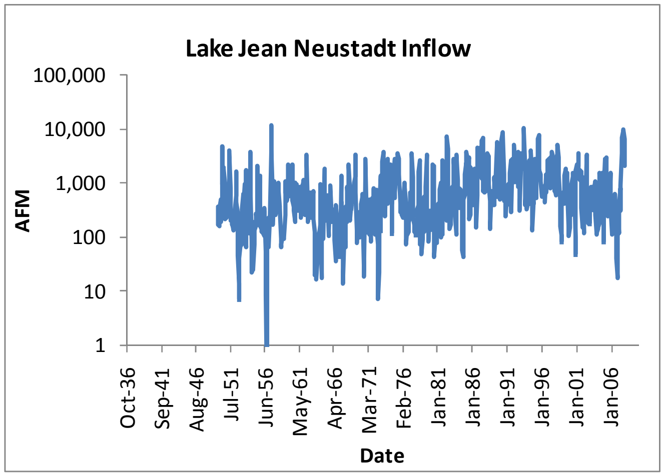


Figure 4-4 Lake Jean Neustadt USGS Gage Locations

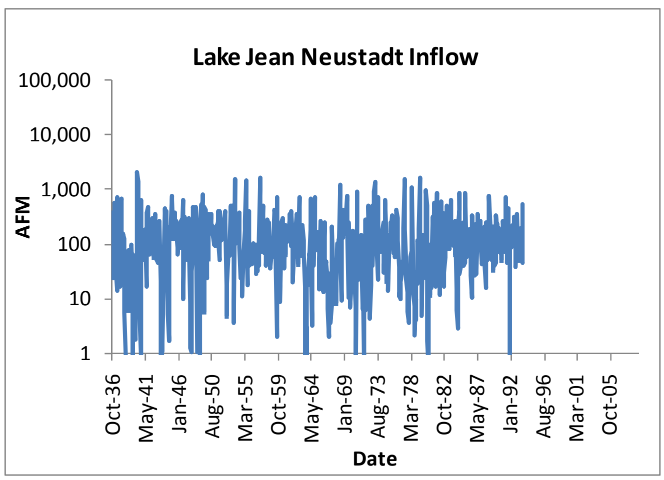
Table 4-1 USGS Streamflow Gages Used to Estimate Inflows to Lake Jean Neustadt

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

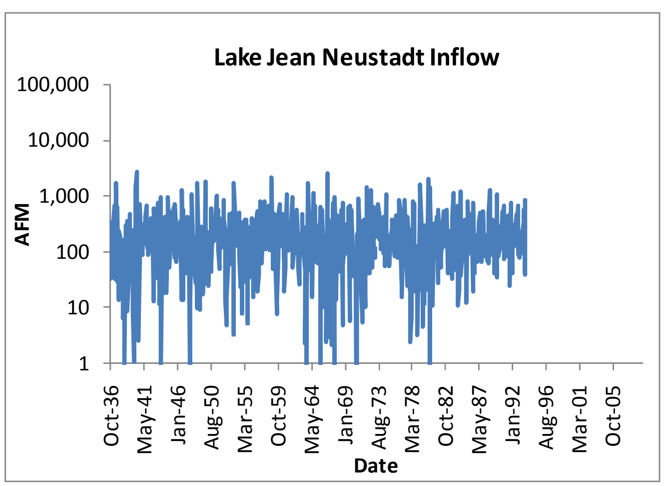
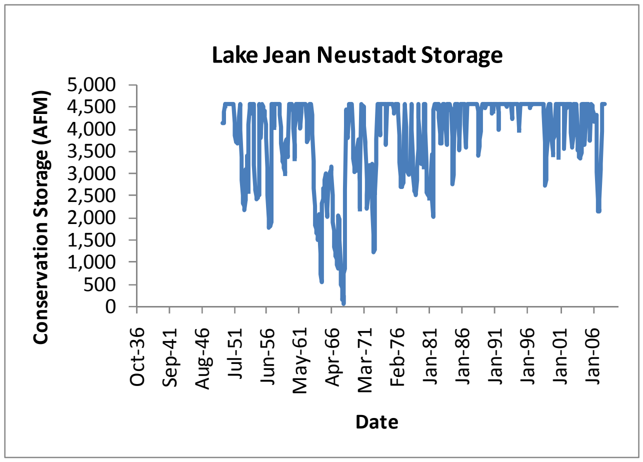
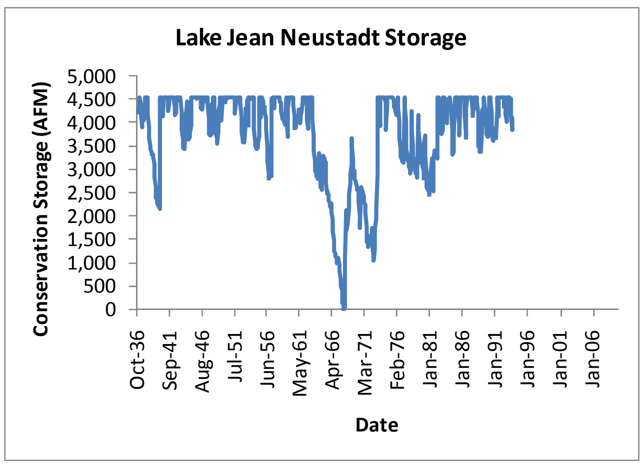


Figure 4-5 Lake Jean Neustadt Modeled Inflow

a) Method 1: Area Weighting, Single Gage



b) Method 2: Area Weighting, Multiple Gages



c) Method 3: SCS CN + Area Weighting

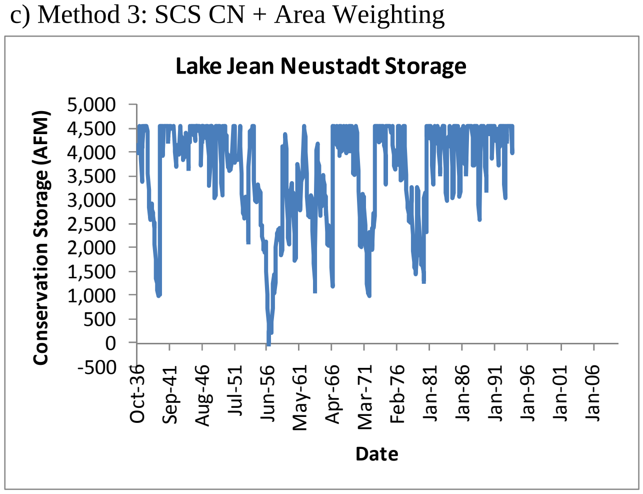


Figure 4-6 Lake Jean Neustadt Modeled Storage Subject to Firm Yield Demand

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.

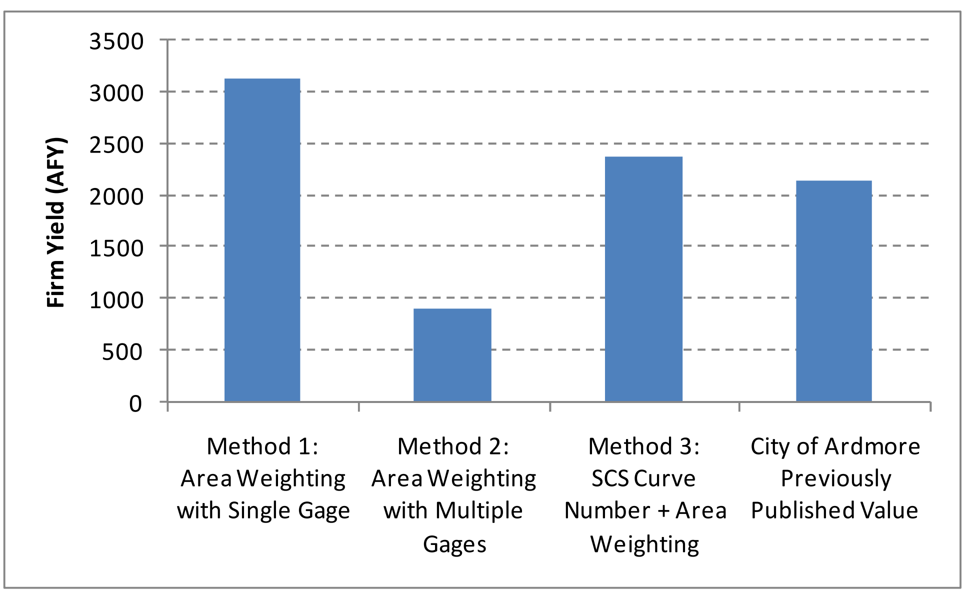


Figure 4-7 Summary of Calculated Firm Yields for Lake Jean Neustadt

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.