Volumetric Survey of LAKE ARROWHEAD

September 2013 Survey

Texas Water Development Board

February 2014

Prepared for:

City of Wichita Falls, Texas

With Support Provided by:

U.S. Army Corps of Engineers, Fort Worth District

This report was prepared by staff of the Surface Water Resources Division:

Ruben S. Solis, Ph.D., P.E.
Jason J. Kemp, Team Lead
Holly Holmquist
Nathan Brock
Michael Vielleux, P.E.
Khan Iqbal
Bianca Whitaker

STATE OF TEXAS
RUBEN S. SOLIS
73094
REGISTERED PROFESSIONAL ENGINEER

4/22/2014

Published and distributed by the

Texas Water Development Board

P.O. Box 13231, Austin, TX 78711-3231

Executive summary

In December 2012, the Texas Water Development Board entered into agreement with the U.S. Army Corps of Engineers, Fort Worth District to perform a volumetric survey of Lake Arrowhead. The U.S. Army Corps of Engineers, Fort Worth District, provided 50% of the funding for this survey through their Planning Assistance to States Program, while the City of Wichita Falls provided the remaining 50%. Surveying was performed using a multi-frequency (200 kHz, 50 kHz, and 24 kHz), sub-bottom profiling depth sounder, although only the 200 kHz frequency was analyzed for this report.

Lake Arrowhead Dam and Lake Arrowhead are located on the Little Wichita River in Clay and Archer Counties, approximately 13 miles southeast of Wichita Falls, Texas. The conservation pool elevation of Lake Arrowhead is 926.00 feet above mean sea level (NGVD29). TWDB collected bathymetric data for Lake Arrowhead between June 27, 2013, and September 26, 2013. The daily average water surface elevation during the survey ranged between 910.40 and 912.01 feet above mean sea level.

The 2013 TWDB volumetric survey indicates that Lake Arrowhead has a total reservoir capacity of 230,359 acre-feet and encompasses 14,506 acres at conservation pool elevation (926.0 feet above mean sea level, NGVD29). Previous capacity estimates include the original design capacity of 262,100 acre-feet, and the volume obtained from a TWDB survey in 2001. The TWDB volumetric survey conducted in 2001 was re-evaluated using current processing procedures that resulted in an updated capacity estimate of 238,114 acre-feet.

TWDB recommends that a similar methodology be used to resurvey Lake Arrowhead in 10 years or after a major flood event. To further improve estimates of capacity loss, TWDB recommends a volumetric and sedimentation survey. Sedimentation surveys include additional analysis of the multi-frequency data for post-impoundment sediment by correlation with sediment core samples and a map identifying the spatial distribution of sediment throughout the reservoir.

Table of Contents

List of Tables

List of Figures

Appendices

Note: References to brand names throughout this report do not imply endorsement by the Texas Water Development Board

Introduction

The Hydrographic Survey Program of the Texas Water Development Board (TWDB) was authorized by the 72nd Texas State Legislature in 1991. Section 15.804 of the Texas Water Code authorizes TWDB to perform surveys to determine reservoir storage capacity, sedimentation levels, rates of sedimentation, and projected water supply availability.

In December 2012, the Texas Water Development Board entered into agreement with the U.S. Army Corps of Engineers, Fort Worth District to perform a volumetric and sedimentation survey of Lake Arrowhead (TWDB, 2012). The U.S. Army Corps of Engineers, Fort Worth District, provided 50% of the funding for this survey through their Planning Assistance to States Program, while the City of Wichita Falls provided the remaining 50%. This report describes the methods used to conduct the volumetric survey, including data collection and processing techniques. This report serves as the final contract deliverable from TWDB to the City of Wichita Falls and the U.S. Army Corps of Engineers, Fort Worth District, and contains as deliverables: (1) a shaded relief plot of the reservoir bottom [Figure 4], (2) a bottom contour map [Figure 6], and (3) an elevation-area-capacity table of the reservoir acceptable to the Texas Commission on Environmental Quality [Appendix A, B].

Lake Arrowhead general information

Lake Arrowhead Dam and Lake Arrowhead are located on the Little Wichita River in Clay and Archer Counties, approximately 13 miles southeast of Wichita Falls, Texas (Figure 1). The construction of Lake Arrowhead Dam began on May 17, 1965. Deliberate impoundment of water began in October 1966, and the dam was completed in December 1966 (TWDB, 1974). Lake Arrowhead is owned and operated by the City of Wichita Falls (TWDB, 1974).

Lake Arrowhead is a water supply reservoir, providing water primarily for municipal and industrial purposes to the City of Wichita Falls. Additional pertinent data about Lake Arrowhead Dam and Lake Arrowhead can be found in Table 1.

Water rights for Lake Arrowhead have been appropriated to the City of Wichita Falls through Certificate of Adjudication No. 02-5150 and Amendments to Certificate of Adjudication Nos. 02-5150A and 02-5150B. The complete certificates are on file in the Information Resources Division of the Texas Commission on Environmental Quality.

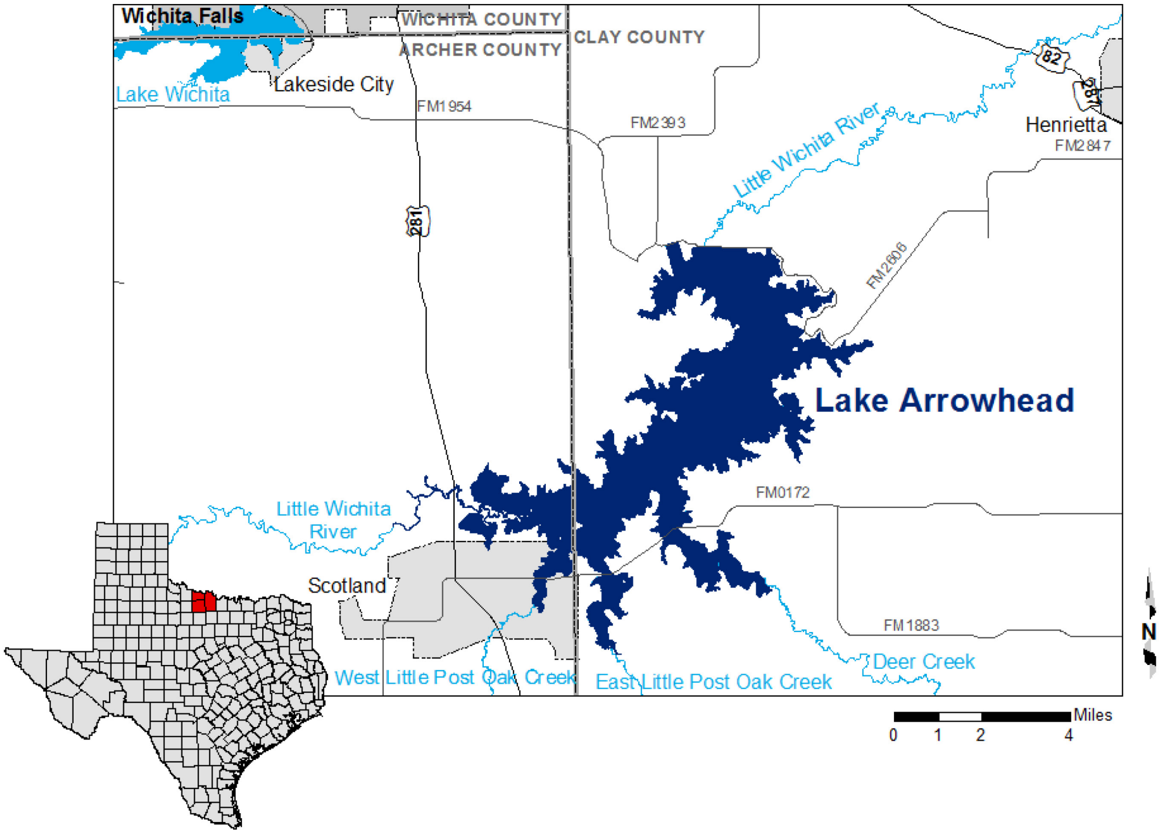


Figure 1. Location of Lake Arrowhead

Table 1. Pertinent data for Lake Arrowhead Dam and Lake Arrowhead

Owner	
City of Wichita Falls	
Engineer (Design)	
Homer A. Hunter, Dallas	
A.H. Wolverton, Austin	
Location of dam	
On the Little Wichita River in Clay County, 13 miles southeast of Wichita Falls, Texas	
Drainage area	
832 square miles (275 square miles of this is above Lake Kickapoo)	
Dam	
Type	Earthfill
Length (including spillway)	15,900 feet
Maximum height	62 feet
Top width	25 feet
Spillway	
Location	Left end of the dam
Type	Concrete ogee weir
Control	None
Crest elevation	926.00 feet above mean sea level
Crest length	1,581 feet
Outlet works	
Type	Cylindrical tower with two inlets at elevations 908.0 and 874.0 feet above mean sea level
Control	2 slide gates, each 5-feet diameter
Note: A third 5-foot diameter slide gate controls flow to a 60-inch diameter steel pipe installed inside the 8-foot diameter conduit with invert elevation 874.0 feet above mean sea level for municipal water supply	

Reservoir data (Based on 2013 TWDB survey)

Feature	**Elevation (feet** NGVD29[a]**)**	**Capacity (acre-feet)**	**Area (acres)**
Top of dam	944.00	N/A	N/A
Design flood stage	939.55	N/A	N/A
Conservation pool elevation	926.00	230,359	14,506
Low flow outlet/ Dead pool elevation	874.00	0	0
Usable conservation storage space[b]	-	230,359	-

Source: (TWDB, 1974)
[a] NGVD29 = National Geodetic Vertical Datum 1929
[b] Usable conservation storage space equals total capacity at conservation pool elevation minus dead pool capacity. Dead pool refers to water that cannot be drained by gravity through a dam's outlet works.

Volumetric survey of Lake Arrowhead

Datum

The vertical datum used during this survey is the National Geodetic Vertical Datum 1929 (NGVD29). This datum is also utilized by the United States Geological Survey (USGS) for the reservoir elevation gage *USGS 07314800 Lk Arrowhead nr Henrietta, TX* (USGS, 2013). Elevations herein are reported in feet relative to the NGVD29 datum. Volume and area calculations in this report are referenced to water levels provided by the USGS gage. The horizontal datum used for this report is North American Datum 1983

(NAD83), and the horizontal coordinate system is State Plane Texas North Central Zone (feet).

TWDB bathymetric data collection

TWDB collected bathymetric data for Lake Arrowhead on June 27, 2013, July 23-25, 2013, August 6-7, 2013, and September 26, 2013. The daily average water surface elevations during the survey measured 912.01, 911.49, 911.45, 911.43, 911.27, 911.22, and 910.40 feet above mean sea level (NGVD29), respectively. For data collection, TWDB used a Specialty Devices, Inc. (SDI), single-beam, multi-frequency (200 kHz, 50 kHz, and 24 kHz) sub-bottom profiling depth sounder integrated with differential global positioning system (DGPS) equipment. Data was collected along pre-planned survey lines oriented perpendicular to the assumed location of the original river channels and spaced approximately 500 feet apart. Many of the same survey lines were also used by TWDB during the 2001 survey. The depth sounder was calibrated daily using a velocity profiler to measure the speed of sound in the water column and a weighted tape or stadia rod for depth reading verification.

Due to continuous drought conditions in the region and low lake levels, TWDB also collected terrestrial elevation measurements in the upper reaches of Lake Arrowhead on September 11-12, 2013. The daily average water surface elevations during the survey measured 910.49 and 910.46 feet above mean sea level (NGVD29), respectively. For data collection, TWDB used a Trimble® R6 Global Navigation Satellite System (GNSS) survey system. This Real Time Kinematic with differential GPS (RTK-GPS) system utilizes a base station with multiple rovers collecting data both as continuous topography points (using ATV and bicycle mounts) and singular GPS points (walking with survey pole), depending on area access. Areas of data collection depended on physical accessibility, travel distance from access points, brush cover density, and soil moisture, and included dry upper reaches to near water's edge and creek bottoms. Figure 2 shows where data collection occurred during the 2013 TWDB survey.

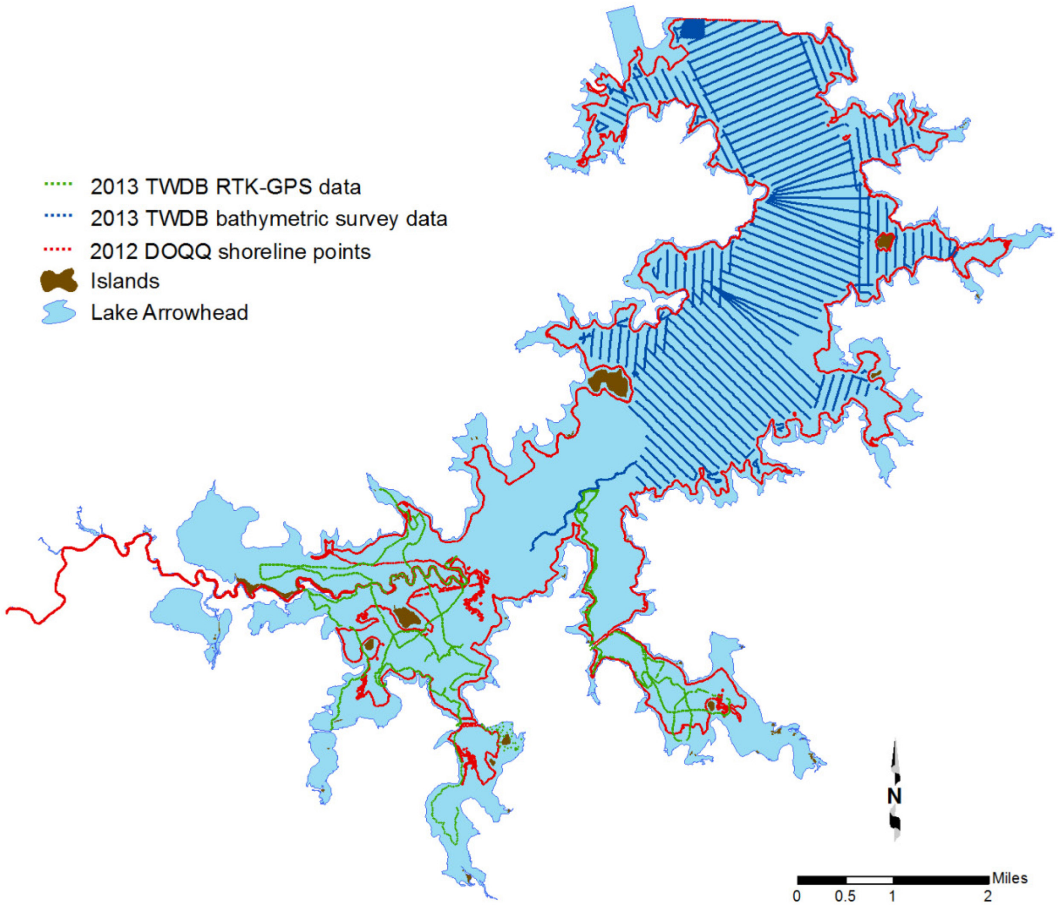


Figure 2. Data collected during 2013 TWDB Lake Arrowhead survey

Data processing

Model boundaries

The reservoir boundary was digitized using Environmental Systems Research Institute's ArcGIS software (ArcGIS) from aerial photographs, also known as digital orthophoto quarter-quadrangle images (DOQQs), obtained from the Texas Natural Resources Information System (TNRIS, 2013). The quarter-quadrangles that cover Lake Arrowhead are Archer City NE (NE, SE), Deer Creek (NW, NE, SW), Scotland (NW, NE, SW, SE), Jolly (SW), and Sloop Creek (SE). The DOQQs were photographed on July 19, 2010, while the daily average water surface elevation measured 924.87 feet (NGVD29). According to metadata associated with the 2010 DOQQs, the photographs have a resolution or ground sample distance of 1.0-meters and a horizontal accuracy within ± 6 meters to true ground (TNRIS, 2010, USDA, 2013). For this analysis, the boundary was digitized at the land-water interface in the 2010 photographs and assigned an elevation of 926.0 feet to facilitate calculating the area-capacity tables up to the conservation pool elevation.

Additional boundary information was obtained from aerial photographs taken on July 6, 2012, and July 12, 2012, while the daily average water surface elevation measured 916.42 and 916.27 feet, respectively. The 2012 boundary information was added to the lake model as points. According to metadata associated with the 2012 DOQQs, the photographs have a resolution or ground sample distance of 1.0-meters and a horizontal accuracy within ± 6 meters to true ground (TNRIS, 2012, USDA, 2013).

RTK-GPS post-processing

Data collected using the Trimble® GPS system was downloaded from each rover's data controller (by day) and post-processed using the Trimble® Business Center (Version 3.1) software. Post-processing entails confirming project settings (e.g. vertical and horizontal datum, horizontal coordinate system) and tying the base station coordinates to Continuously Operating Reference Stations (CORS) sites to improve the precision of the project data from each rover. CORS sites are maintained by the National Geodetic Survey (NGS), an office of the National Oceanographic and Atmospheric Administration's (NOAA) National Ocean Service (NGS, 2014a). To make the RTK-GPS data compatible with the bathymetric survey data, it was necessary to transform the data from vertical datum NAVD88 to NGVD29. Vertical coordinate transformations were done by applying a single vertical offset to all RTK-GPS data. The offset was determined by applying the National Oceanic and Atmospheric Administration National Geodetic Survey's VERTCON software (NGS, 2014b) to a single reference point in the vicinity of the survey, the reservoir elevation gage *USGS 07314800 Lk Arrowhead nr Henrietta, TX, of Latitude 33º45'51", Longitude 98º22'17" NAD27.* The resulting conversion factor of 0.203 feet was subtracted from all RTK-GPS data elevations to obtain the transformed vertical elevations.

Triangulated Irregular Network model

Following completion of data collection, the raw data files were edited to remove data anomalies. DepthPic©, software developed by SDI, Inc., was used to display, interpret, and edit the multi-frequency data by manually removing data anomalies in the current bottom surface and, in the case of a sedimentation survey, manually digitizing the reservoir-bottom surface at the time of initial impoundment (i.e. pre-impoundment surface). For processing outside of DepthPic©, an in-house software package, HydroTools, was used to identify the current reservoir-bottom surface, pre-impoundment surface, sediment thickness at each sounding location, if applicable, and to output the data into a single file. The water surface elevation at the time of each sounding was used to convert each sounding depth to a corresponding reservoir-bottom elevation. This survey point dataset was then preconditioned by inserting a uniform grid of artificial survey points between the actual survey lines. Bathymetric elevations at these artificial points are determined using an anisotropic spatial interpolation algorithm described in the next section. This technique creates a high resolution, uniform grid of interpolated bathymetric elevation points throughout a majority of the reservoir (McEwen et al., 2011a). Finally, the point file resulting from spatial interpolation was used in conjunction with sounding and boundary data to create volumetric and sediment Triangulated Irregular Network (TIN) models utilizing the 3D Analyst Extension of ArcGIS. The 3D Analyst algorithm uses Delaunay's criteria for triangulation to create a grid composed of triangles from non-uniformly spaced points, including the boundary vertices (ESRI, 1995).

Spatial interpolation of reservoir bathymetry

Isotropic spatial interpolation techniques such as the Delaunay triangulation used by the 3D Analyst extension of ArcGIS are, in many instances, unable to suitably interpolate bathymetries between survey lines common to reservoir surveys. Reservoirs and stream channels are anisotropic morphological features where bathymetry at any particular location is more similar to upstream and downstream locations than to transverse locations. Interpolation schemes that do not consider this anisotropy lead to the creation of several types of artifacts in the final representation of the reservoir bottom surface and hence to errors in volume. These include: artificially-curved contour lines extending into the reservoir where the reservoir walls are steep or the reservoir is relatively narrow; intermittent representation of submerged stream channel connectivity; and oscillations of contour lines in between survey lines. These artifacts reduce the accuracy of the resulting volumetric and sediment TIN models in areas between actual survey data.

To improve the accuracy of bathymetric representation between survey lines, TWDB developed various anisotropic spatial interpolation techniques. Generally, the directionality of interpolation at different locations of a reservoir can be determined from external data sources. A basic assumption is that the reservoir profile in the vicinity of a particular location has upstream and downstream similarity. In addition, the sinuosity and directionality of submerged stream channels can be determined by directly examining survey data or more robustly by examining scanned USGS 7.5 minute quadrangle maps (known as digital raster graphics or DRGs) and hypsography files (the vector format of USGS 7.5 minute quadrangle map contours), when available. Using the survey data, polygons are created to partition the reservoir into segments with centerlines defining directionality of interpolation within each segment. For surveys with similar spatial coverage, these interpolation definition files are in principle independent of the survey data and could be applied to past and future survey data of the same reservoir. In practice, however, minor revisions of the interpolation definition files may be needed to account for differences in spatial coverage and boundary conditions between surveys. Using the interpolation definition files and survey data, the current reservoir-bottom elevation, pre-impoundment elevation, and sediment thickness, when applicable, are calculated for each point in the high resolution uniform grid of artificial survey points. The reservoir boundary, artificial survey points grid, and survey data points are used to create the volumetric TIN model representing the reservoir bathymetry. Specific details of this interpolation technique can be found in the HydroTools manual (McEwen et al., 2011a) and in McEwen et al., 2011b.

In areas inaccessible to survey data collection such as small coves and shallow upstream areas of the reservoir, linear extrapolation is used for volumetric estimations. The linear extrapolation follows a linear definition file linking the survey points file to the lake boundary file (McEwen et al., 2011a). Without extrapolated data, the TIN Model builds flat triangles. A flat triangle is defined as a triangle where all three vertices are equal in elevation, generally the elevation of the reservoir boundary. Reducing flat triangles by applying linear extrapolation improves the elevation-capacity and elevation-area calculations. It is not always possible to remove all flat triangles, and linear extrapolation is only applied where adding bathymetry is deemed reasonable. For example, linear extrapolation was deemed reasonable and applied to Lake Arrowhead in the following situations: in small coves and throughout the main body of the reservoir using the USGS DRG channels, 2001 survey data, and aerial photographs taken on July 6 and July 12, 2012, as guidance.

Figure 3 illustrates typical results from application of the anisotropic interpolation and linear extrapolation techniques to Lake Arrowhead. The bathymetry shown in Figure 3C was used in computing reservoir capacity and area tables (Appendix A, B). In Figure 3A, deeper channels indicated by surveyed cross sections are not continuously represented in areas between survey cross sections. This is an artifact of the TIN generation routine rather than an accurate representation of the physical bathymetric surface. Inclusion of interpolation points, represented in Figure 3C, in creation of the volumetric TIN model directs Delaunay triangulation to better represent the lake bathymetry between survey cross-sections.

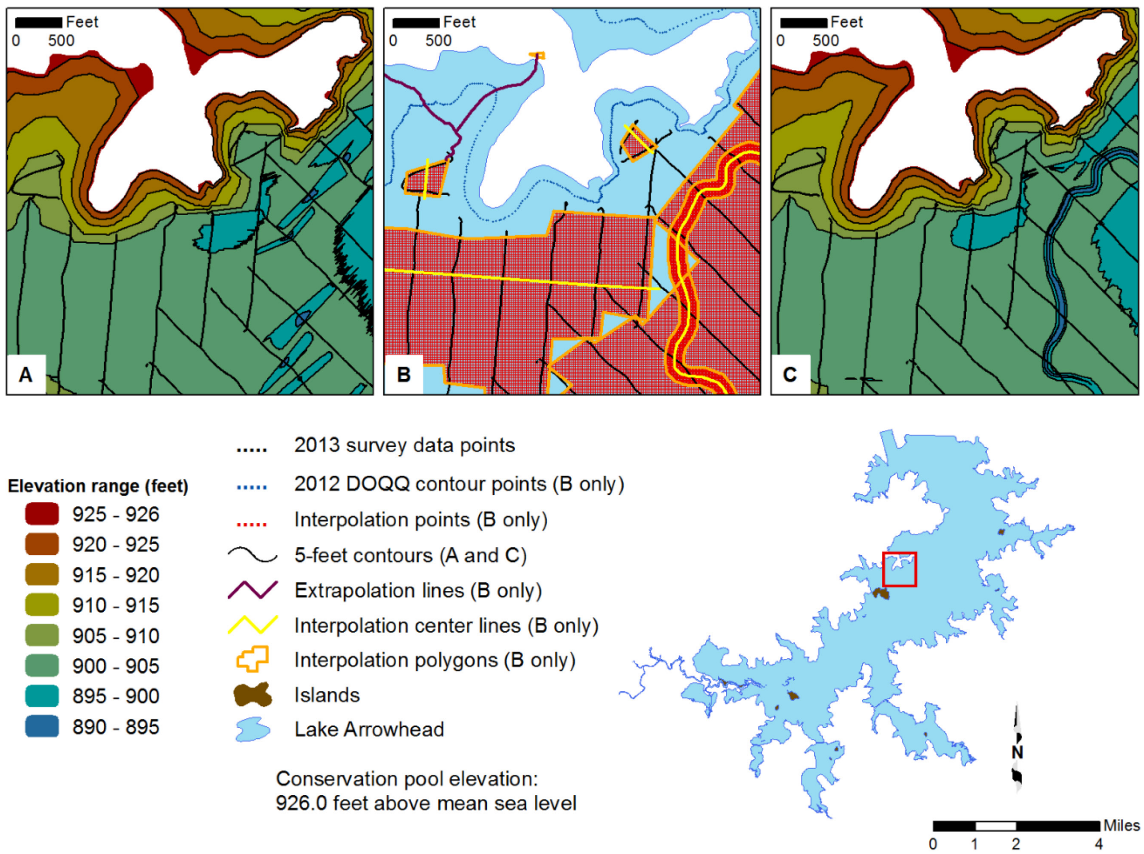


Figure 3. Anisotropic spatial interpolation and linear extrapolation of Lake Arrowhead sounding data - A) bathymetric contours without interpolated points, B) sounding points (black) and interpolated points (red), C) bathymetric contours with the interpolated points

Area, volume, and contour calculation

Using ArcInfo software and the volumetric TIN model, volumes and areas were calculated for the entire reservoir at 0.1 feet intervals, from 881.9 to 926.0 feet. The use of contour data from the 2012 DOQQs and RTK-GPS data helped provide otherwise unavailable topographic data in areas that were inaccessible by boat or too shallow for the instruments to work properly. However, the TIN models developed in these areas led to the creation of anomalous “flat triangles”, that is triangles whose three vertices all have the same elevation. The flat triangles in turn lead to anomalous calculations of surface area and volume at the boundary elevations, 916.27 feet, 916.42 feet, and 926.0 feet. To eliminate the effects of the flat triangles on area and volume calculations, areas between elevations 916.0 feet and 926.0 feet were linearly interpolated between the computed values, and volumes above elevation 916.0 were calculated based on the corrected areas. The elevation-capacity table and elevation-area table, updated for 2012, are presented in Appendices A and B, respectively. The capacity curve is presented in Appendix C, and the area curve is presented in Appendix D.

The volumetric TIN model was converted to a raster representation using a cell size of 2 feet by 2 feet. The raster data was then used to produce: an elevation relief map (Figure 4), representing the topography of the reservoir bottom; a depth range map (Figure 5), showing shaded depth ranges for Lake Arrowhead; and a 2-foot contour map (Figure 6 - attached).

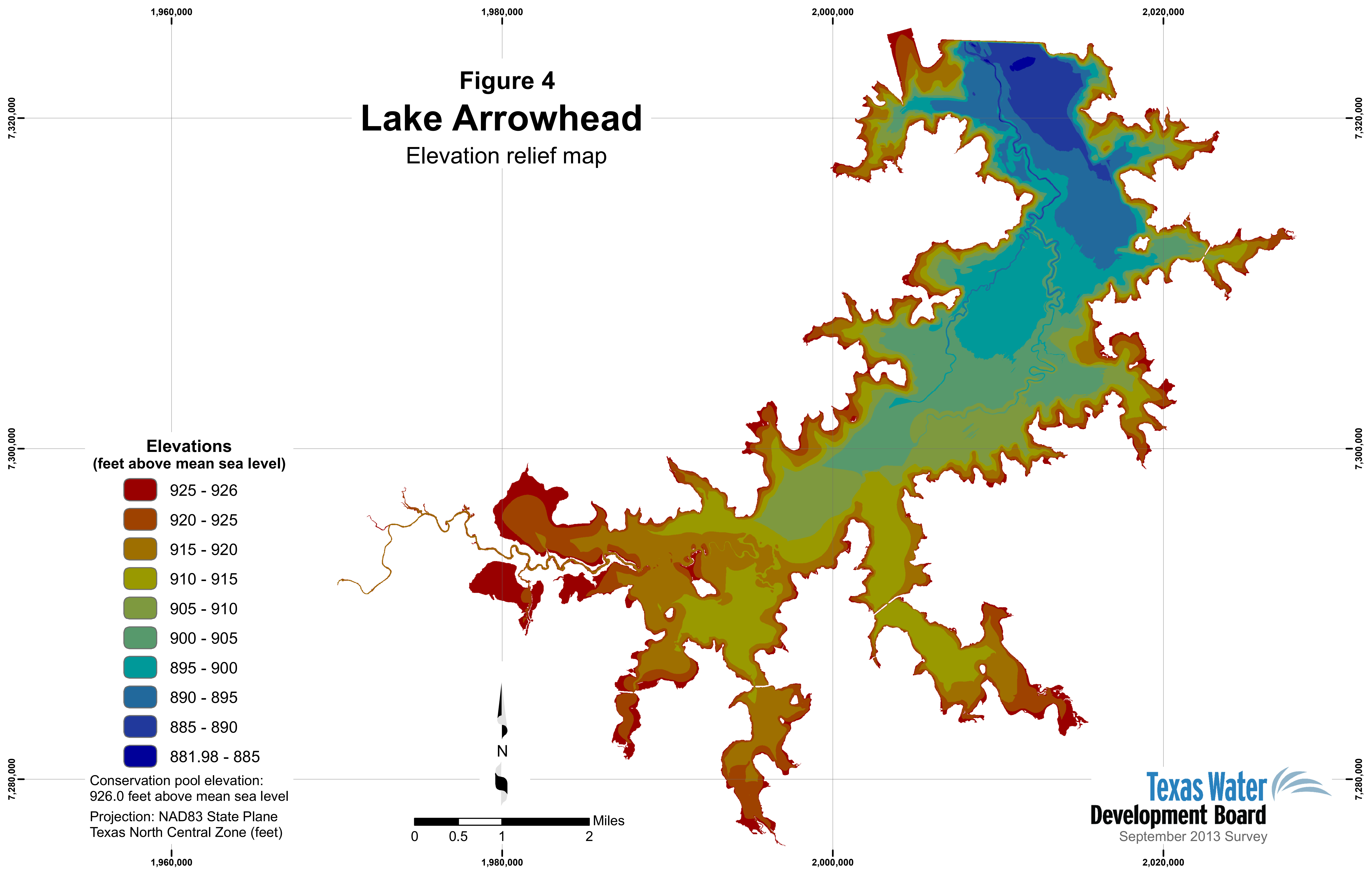


Figure 4
Lake Arrowhead
Elevation relief map
1,960,000
1,980,000
2,000,000
2,020,000
7,320,000
7,300,000
7,280,000
Elevations
(feet above mean sea level)
925 - 926
920 - 925
915 - 920
910 - 915
905 - 910
900 - 905
895 - 900
890 - 895
885 - 890
881.98 - 885
Conservation pool elevation:
926.0 feet above mean sea level
Projection: NAD83 State Plane
Texas North Central Zone (feet)
N
0
0.5
1
2
Miles
Texas Water
Development Board
September 2013 Survey

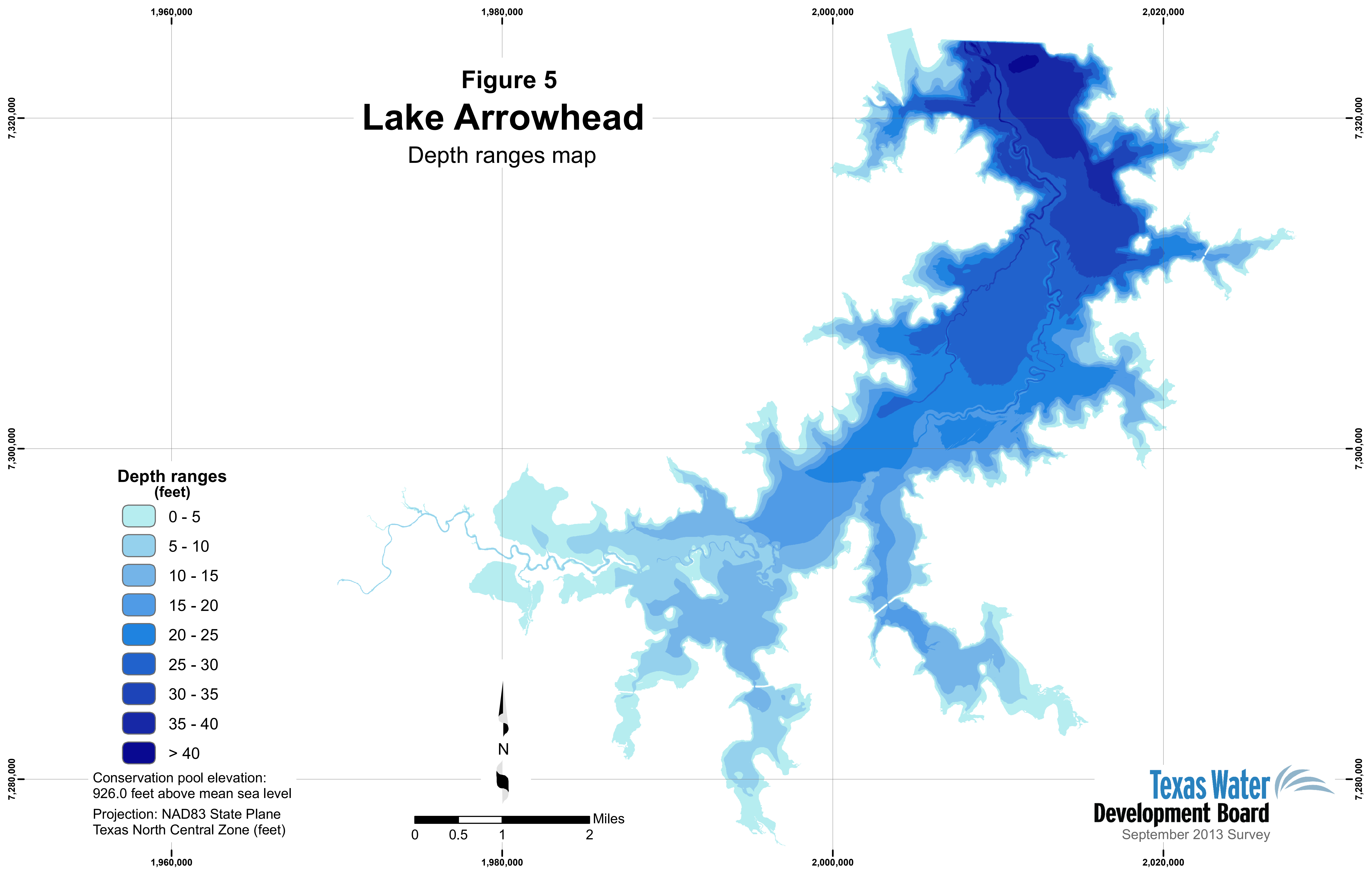


Figure 5
Lake Arrowhead
Depth ranges map
Depth ranges
(feet)
0 - 5
5 - 10
10 - 15
15 - 20
20 - 25
25 - 30
30 - 35
35 - 40
> 40
Conservation pool elevation:
926.0 feet above mean sea level
Projection: NAD83 State Plane
Texas North Central Zone (feet)
N
Miles
0
0.5
1
2
1,960,000
1,980,000
2,000,000
2,020,000
7,320,000
7,300,000
7,280,000
Texas Water
Development Board
September 2013 Survey

Survey results

Volumetric survey

The results of the 2013 TWDB volumetric survey indicate Lake Arrowhead has a total reservoir capacity of 230,359 acre-feet and encompasses 14,506 acres at conservation pool elevation (926.0 feet above mean sea level, NGVD29). Previous capacity estimates include the original design capacity of 262,100 acre-feet, and the volume obtained from a TWDB survey in 2001. Because of differences in past and present survey methodologies, direct comparison of volumetric surveys to estimate loss of capacity is difficult and can be unreliable.

To properly compare results of TWDB surveys, TWDB applied the 2013 data processing techniques to the data collected in 2001. Specifically, TWDB applied anisotropic spatial interpolation to the survey data collected in 2001 using the same interpolation definition file as was used for the 2013 survey with minor edits to account for differences in data coverage and boundary conditions. The 2001 survey boundary at conservation pool elevation was digitized from the digital USGS 7.5 minute quadrangle maps, or DRGs. The USGS quadrangle maps have a stated accuracy of ± ½ the contour interval (USBB, 1947). Additional boundary information was digitized from aerial photographs taken on January 23, 1995, while the water surface elevation of the reservoir measured 923.46 feet above mean sea level (TWDB, 2002). According to the associated metadata, the 1995-1996 DOQQs have a resolution of 1-meter, with a horizontal positional accuracy that meets the National Map Accuracy Standards (NMAS) for 1:12,000-scale products. Re-evaluation of the 2001 survey resulted in a 0.9 percent increase in the total capacity estimate (Table 2). Comparison of capacity estimates of Lake Arrowhead derived using differing methodologies are provided in Table 3 for sedimentation rate calculation.

Table 2. Current and previous survey capacity and surface area data

Survey	Surface area (acres)	Total capacity (acre-feet)
1969[a]	16,200	262,100
TWDB 2001[b]	14,969	235,997
TWDB 2001 (re-calculated)	14,978	238,114
TWDB 2013	14,506	230,359

[a] Source: (TWDB, 1974)
[b] Source: (TWDB, 2002)

Table 3. Capacity loss comparisons for Lake Arrowhead

Survey	Volume comparisons at conservation pool elevation (acre-feet)	
1969[a]	262,100	<>
TWDB 2001 (re-calculated)	<>	238,114
2013 volumetric survey	230,359	230,359
Volume difference (acre-feet)	31,741 (12.1%)	7,755 (3.3%)
Number of years	44	12
Capacity loss rate (acre-feet/year)	721	646

[a] Source: (TWDB, 1974). Note: Impoundment of Lake Arrowhead began in October 1966 and the dam was completed in December 1966.

Intake structure

Survey data was collected around the intake structure following planned survey lines oriented parallel to and perpendicular to the intake structure and dam in a 50-foot grid pattern extending approximately 500 feet to the east and west of the intake structure and 1,000 feet south of the dam. The structure is located at approximately Latitude 33º45’49.357” N and Longitude 98º22’12.429” W (NAD83) towards the west end of the dam. Figure 7 shows the elevation relief of the area in detail.

Recommendations

To improve estimates of sediment accumulation rates, TWDB recommends resurveying Lake Arrowhead in approximately 10 years or after a major flood event. To further improve estimates of capacity loss, TWDB recommends a volumetric and sedimentation survey. Sedimentation surveys include additional analysis of the multi-frequency data for post-impoundment sediment by correlation with sediment core samples and a map identifying the spatial distribution of sediment throughout the reservoir.

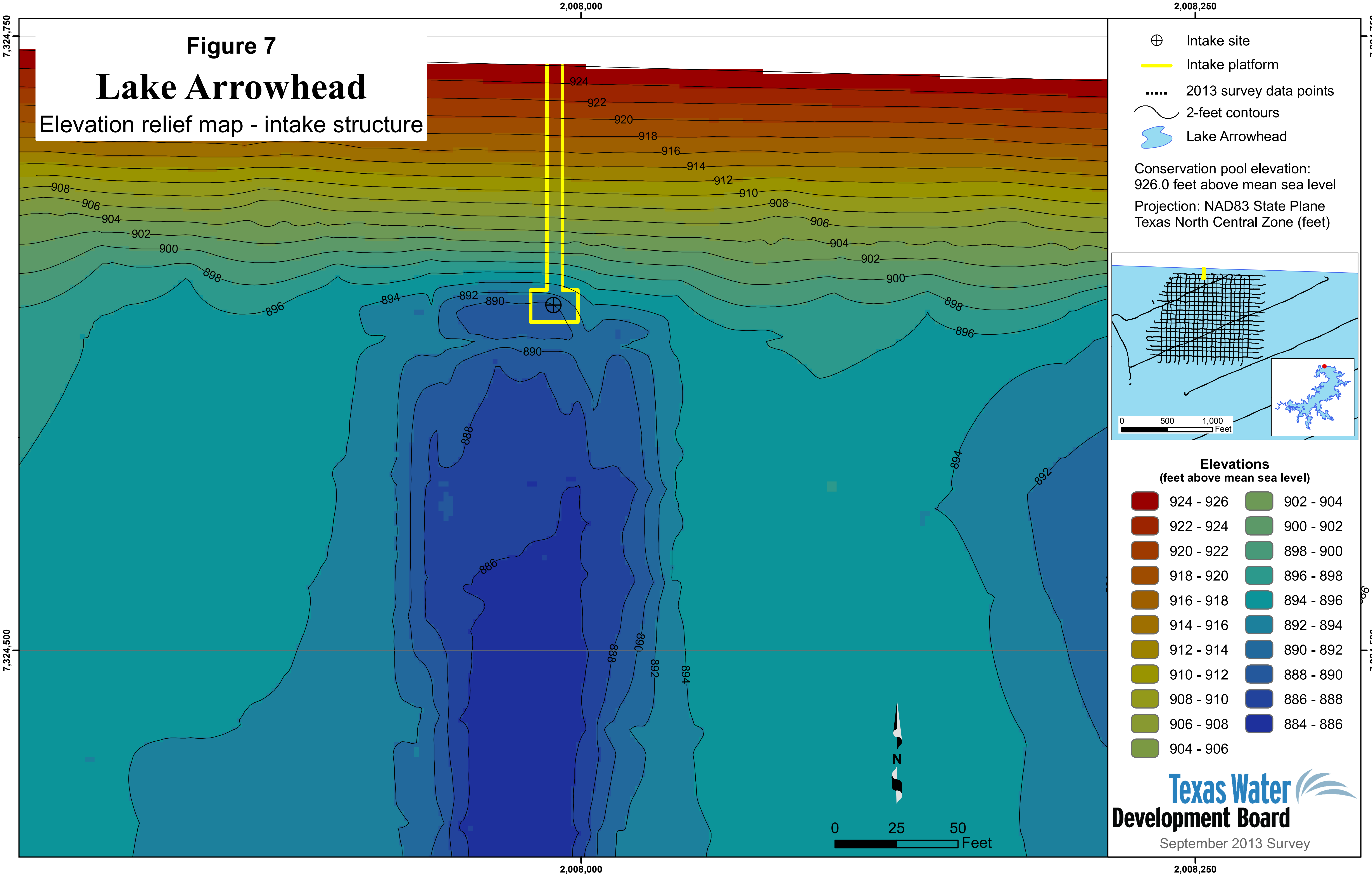


Figure 7

Lake Arrowhead

Elevation relief map - intake structure

TWDB contact information

More information about the Hydrographic Survey Program can be found at:

http://www.twdb.texas.gov/surfacewater/surveys/index.asp

Any questions regarding the TWDB Hydrographic Survey Program may be addressed to:

Jason J. Kemp
Team Lead, Hydrographic Survey Program
Phone: (512) 463-2456
Email: Jason.Kemp@twdb.texas.gov

Or

Ruben S. Solis, Ph.D., P.E.
Director, Surface Water Resources Division
Phone: (512) 936-0820
Email: Ruben.Solis@twdb.texas.gov

References

ESRI (Environmental Systems Research Institute), 1995, ARC/INFO Surface Modeling and Display, TIN Users Guide, ESRI, 380 New York Street, Redlands, CA 92373.

McEwen, T., Brock, N., Kemp, J., Pothina, D. & Weyant, H., 2011a, HydroTools User's Manual, Texas Water Development Board.

McEwen, T., Pothina, D. & Negusse, S., 2011b, Improving efficiency and repeatability of lake volume estimates using Python, submitted, Proceedings of the 10th Python for Scientific Computing Conference (SciPy 2011).

NGS (National Geodetic Survey), 2014a, Continuously Operating Reference Station (CORS) – National Geodetic Survey, http://geodesy.noaa.gov/CORS/, accessed December 2013.

NGS (National Geodetic Survey), 2014b, Orthometric Height Conversion, http://www.ngs.noaa.gov/cgi-bin/VERTCON/vert_con.prl, accessed January 2014.

TNRIS (Texas Natural Resources Information System), 2010, http://www.tnris.org/node/39, accessed September 2013.

TNRIS (Texas Natural Resources Information System), 2012, http://www.tnris.org/node/199, accessed September 2013.

TNRIS (Texas Natural Resources Information System), 2013, http://www.tnris.org/, accessed September 2013.

TWDB (Texas Water Development Board), 1974, *Lake Arrowhead Dam and Lake Arrowhead*, Report 126, Engineering Data on Dams and Reservoirs in Texas, Part I.

TWDB (Texas Water Development Board), February 2002, Volumetric Survey of Lake Arrowhead, http://www.twdb.texas.gov/hydro_survey/Arrowhead/2001-06/Arrowhead2001_FinalReport.pdf

TWDB (Texas Water Development Board), 2012, Contract No. 1348011556 with U.S. Army Corps of Engineers, Fort Worth District.

USBB (United States Bureau of the Budget), 1947, United States National Map Accuracy Standards, http://nationalmap.gov/standards/pdf/NMAS647.PDF.

USDA (US Department of Agriculture), 2013, *National Agricultural Imagery Program (NAIP) Information Sheet*, http://www.fsa.usda.gov/Internet/FSA_File/naip_info_sheet_2013.pdf.

USGS (United States Geological Survey), 2013, U.S. Geological Survey National Water Information System: Web Interface, USGS Real-Time Water Data for *USGS 07314800 Lk Arrowhead nr Henrietta, TX*, http://waterdata.usgs.gov/tx/nwis/uv/?site_no=07314800&PARAmeter_cd=00062,72020,00054, accessed October 2013.

Appendix A

Lake Arrowhead

RESERVOIR CAPACITY TABLE

TEXAS WATER DEVELOPMENT BOARD — September 2013 Survey

CAPACITY IN ACRE-FEET — Conservation Pool Elevation 926.0 feet NGVD29

ELEVATION INCREMENT IS ONE TENTH FOOT

ELEVATION in Feet	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
881	0	0	0	0	0	0	0	0	0	0
882	0	0	0	0	0	0	0	0	0	1
883	1	1	2	2	3	3	4	5	5	6
884	7	8	9	10	12	13	14	16	18	20
885	22	24	26	29	32	35	38	41	45	49
886	53	57	61	66	71	76	83	91	101	112
887	126	141	159	178	200	224	249	277	306	336
888	369	402	438	474	512	552	592	634	677	721
889	766	812	859	908	957	1,008	1,059	1,112	1,167	1,222
890	1,279	1,337	1,397	1,458	1,520	1,584	1,649	1,716	1,785	1,855
891	1,929	2,004	2,083	2,163	2,245	2,330	2,417	2,507	2,600	2,695
892	2,791	2,890	2,991	3,095	3,200	3,308	3,417	3,528	3,641	3,755
893	3,871	3,989	4,108	4,230	4,354	4,480	4,609	4,740	4,873	5,008
894	5,145	5,283	5,424	5,566	5,710	5,857	6,005	6,157	6,310	6,465
895	6,623	6,783	6,946	7,111	7,277	7,446	7,617	7,790	7,964	8,141
896	8,319	8,499	8,681	8,865	9,050	9,237	9,425	9,615	9,806	9,999
897	10,194	10,390	10,588	10,787	10,988	11,191	11,395	11,600	11,807	12,016
898	12,227	12,441	12,659	12,883	13,111	13,342	13,577	13,817	14,062	14,313
899	14,568	14,827	15,092	15,361	15,636	15,914	16,197	16,484	16,775	17,070
900	17,368	17,669	17,975	18,285	18,599	18,918	19,240	19,567	19,897	20,231
901	20,568	20,909	21,255	21,604	21,957	22,313	22,674	23,039	23,406	23,778
902	24,152	24,529	24,909	25,293	25,680	26,071	26,464	26,862	27,263	27,667
903	28,074	28,484	28,898	29,314	29,735	30,159	30,586	31,017	31,452	31,891
904	32,334	32,781	33,231	33,684	34,141	34,601	35,063	35,529	35,997	36,469
905	36,943	37,420	37,900	38,382	38,869	39,359	39,853	40,350	40,852	41,358
906	41,868	42,382	42,900	43,422	43,949	44,480	45,015	45,555	46,098	46,646
907	47,198	47,753	48,312	48,874	49,440	50,008	50,580	51,155	51,732	52,312
908	52,894	53,479	54,067	54,657	55,250	55,845	56,442	57,043	57,645	58,250
909	58,857	59,467	60,080	60,695	61,312	61,932	62,554	63,179	63,806	64,436
910	65,067	65,701	66,338	66,978	67,622	68,269	68,921	69,579	70,243	70,912
911	71,587	72,265	72,949	73,636	74,327	75,022	75,719	76,421	77,125	77,834
912	78,545	79,259	79,978	80,699	81,425	82,155	82,889	83,628	84,372	85,121
913	85,875	86,633	87,396	88,164	88,937	89,714	90,497	91,286	92,080	92,881
914	93,689	94,503	95,324	96,150	96,982	97,819	98,662	99,511	100,365	101,225
915	102,090	102,961	103,839	104,722	105,611	106,507	107,409	108,319	109,235	110,158
916	111,089	112,027	112,969	113,917	114,870	115,828	116,791	117,759	118,733	119,712
917	120,695	121,684	122,678	123,678	124,682	125,692	126,707	127,726	128,751	129,782
918	130,817	131,858	132,903	133,954	135,010	136,071	137,138	138,209	139,286	140,368
919	141,455	142,547	143,644	144,746	145,854	146,967	148,085	149,208	150,336	151,469
920	152,608	153,752	154,900	156,054	157,214	158,378	159,547	160,722	161,902	163,087
921	164,277	165,472	166,673	167,878	169,089	170,305	171,526	172,752	173,984	175,220
922	176,462	177,709	178,961	180,218	181,480	182,748	184,020	185,298	186,581	187,869
923	189,163	190,461	191,765	193,073	194,387	195,706	197,031	198,360	199,694	201,034
924	202,379	203,729	205,084	206,445	207,810	209,181	210,556	211,937	213,324	214,715
925	216,111	217,513	218,920	220,332	221,749	223,171	224,598	226,031	227,468	228,911
926	230,359									

Note: Capacities above elevation 916.0 calculated from interpolated areas

Appendix B

Lake Arrowhead

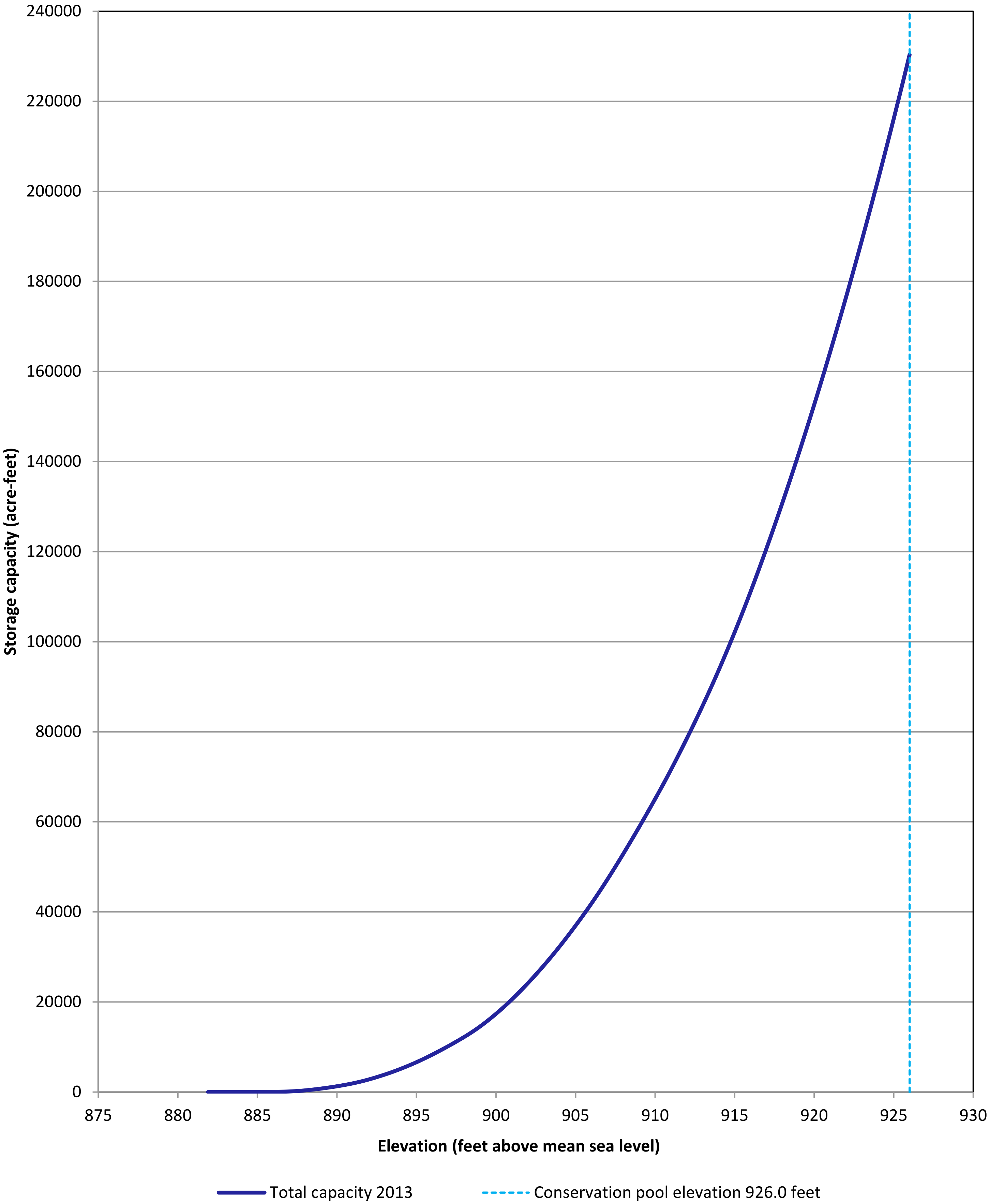
RESERVOIR AREA TABLE

TEXAS WATER DEVELOPMENT BOARD
AREA IN ACRES
ELEVATION INCREMENT IS ONE TENTH FOOT

September 2013 Survey
Conservation Pool Elevation 926.0 feet NGVD29

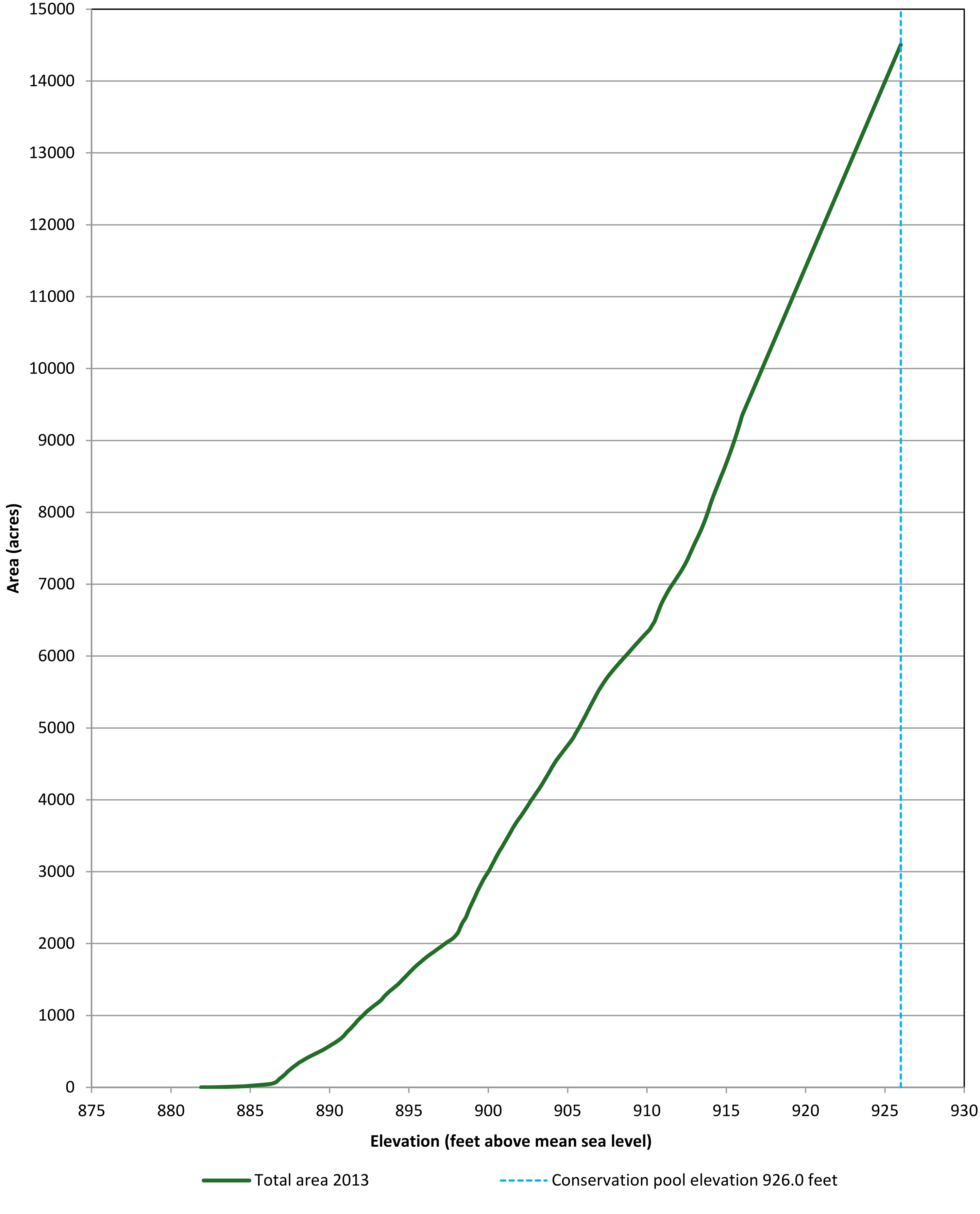
ELEVATION in Feet	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
881	0	0	0	0	0	0	0	0	0	0
882	0	0	0	0	0	1	1	1	2	2
883	3	4	4	5	6	6	7	8	8	9
884	10	11	11	12	13	14	15	16	18	20
885	22	24	25	27	29	31	33	34	36	38
886	40	43	45	48	53	61	70	87	109	128
887	145	164	183	207	228	246	264	282	298	314
888	332	347	360	373	386	399	412	423	434	445
889	456	467	478	489	500	511	523	536	549	562
890	575	590	603	616	630	645	661	676	697	718
891	746	770	793	813	836	862	885	912	937	958
892	979	1,000	1,023	1,045	1,065	1,083	1,100	1,119	1,136	1,153
893	1,169	1,185	1,203	1,226	1,253	1,278	1,300	1,321	1,341	1,358
894	1,376	1,395	1,413	1,431	1,453	1,476	1,499	1,521	1,544	1,567
895	1,591	1,613	1,635	1,658	1,679	1,699	1,718	1,736	1,755	1,774
896	1,793	1,810	1,827	1,844	1,859	1,875	1,890	1,906	1,923	1,938
897	1,953	1,970	1,987	2,003	2,018	2,033	2,046	2,061	2,079	2,100
898	2,126	2,156	2,205	2,257	2,299	2,333	2,370	2,426	2,480	2,529
899	2,574	2,620	2,670	2,720	2,764	2,809	2,850	2,891	2,929	2,963
900	2,997	3,036	3,079	3,120	3,162	3,205	3,245	3,285	3,320	3,355
901	3,396	3,433	3,472	3,509	3,548	3,588	3,626	3,662	3,695	3,728
902	3,757	3,787	3,821	3,853	3,887	3,921	3,957	3,992	4,023	4,054
903	4,087	4,120	4,152	4,186	4,220	4,258	4,295	4,331	4,369	4,408
904	4,447	4,484	4,519	4,553	4,582	4,611	4,640	4,669	4,698	4,727
905	4,756	4,784	4,814	4,844	4,880	4,921	4,959	4,997	5,036	5,079
906	5,119	5,160	5,203	5,247	5,290	5,332	5,373	5,415	5,456	5,498
907	5,536	5,570	5,605	5,638	5,671	5,702	5,731	5,759	5,786	5,813
908	5,838	5,864	5,890	5,914	5,939	5,963	5,988	6,013	6,037	6,061
909	6,087	6,112	6,137	6,162	6,186	6,210	6,235	6,259	6,283	6,306
910	6,329	6,352	6,380	6,418	6,452	6,492	6,552	6,610	6,667	6,722
911	6,768	6,809	6,851	6,892	6,929	6,964	6,997	7,030	7,062	7,096
912	7,130	7,164	7,200	7,238	7,277	7,319	7,365	7,414	7,464	7,514
913	7,561	7,608	7,654	7,701	7,750	7,801	7,856	7,916	7,977	8,041
914	8,112	8,175	8,234	8,291	8,347	8,402	8,459	8,514	8,569	8,624
915	8,683	8,742	8,802	8,863	8,926	8,990	9,057	9,126	9,197	9,271
916	9,348	9,400	9,451	9,503	9,554	9,606	9,657	9,709	9,761	9,812
917	9,864	9,915	9,967	10,019	10,070	10,122	10,173	10,225	10,276	10,328
918	10,380	10,431	10,483	10,534	10,586	10,637	10,689	10,741	10,792	10,844
919	10,895	10,947	10,999	11,050	11,102	11,153	11,205	11,256	11,308	11,360
920	11,411	11,463	11,514	11,566	11,618	11,669	11,721	11,772	11,824	11,875
921	11,927	11,979	12,030	12,082	12,133	12,185	12,236	12,288	12,340	12,391
922	12,443	12,494	12,546	12,598	12,649	12,701	12,752	12,804	12,855	12,907
923	12,959	13,010	13,062	13,113	13,165	13,216	13,268	13,320	13,371	13,423
924	13,474	13,526	13,578	13,629	13,681	13,732	13,784	13,835	13,887	13,939
925	13,990	14,042	14,093	14,145	14,197	14,248	14,300	14,351	14,403	14,454
926	14,506									

Note: Areas above elevation 916.0 feet interpolated



Lake Arrowhead
September 2013 Survey
Prepared by: TWDB

Appendix C: Capacity curve



Lake Arrowhead
September 2013 Survey
Prepared by: TWDB

Appendix D: Area curve

Figure 6

Contours
(feet above mean sea level)

924
922
920
918
916
914
912
910
908
906
904
902
900
898
896
894
892
890
888
886
884

Lake Arrowhead

Islands

Conservation pool elevation: 926.0 feet

Projection: NAD83
State Plane Texas
North Central Zone (feet)

This map is the product of a survey conducted by the Texas Water Development Board's Hydrographic Survey Program to determine the capacity of Lake Arrowhead. The Texas Water Development Board makes no representations nor assumes any liability.