Volumetric and Sedimentation Survey of LAKE O' THE PINES

November – December 2009 Survey

Prepared by:

The Texas Water Development Board

August 2011

Texas Water Development Board

Prepared for:

Northeast Texas Municipal Water District

With Support Provided by:

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

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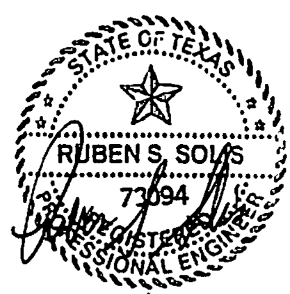

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Executive summary

In September 2009, 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 O' the Pines. 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 Northeast Texas Municipal Water District provided the remaining 50%. Surveying was performed using a multi-frequency (200 kHz, 50 kHz and 24 kHz), sub-bottom profiling depth sounder. In addition, sediment core samples were collected in select locations and correlated with the multi-frequency depth sounder signal returns to estimate sediment accumulation thicknesses and sedimentation rates.

Ferrells Bridge Dam and Lake O' the Pines are located on Cypress Creek, nine miles west of Jefferson in Marion County, Texas. The conservation pool elevation of Lake O' the Pines is 228.5 feet above mean sea level (NGVD29). TWDB collected bathymetric data for Lake O' the Pines between November 7, 2009 and December 14, 2009 while the daily average water surface elevations ranged between 243.04 feet and 237.93 feet above mean sea level.

The 2009 TWDB volumetric survey indicates that Lake O' the Pines has a total reservoir capacity of 241,363 acre-feet encompassing 17,638 acres at the conservation pool elevation (228.5 feet above mean sea level, NGVD29). Due to differences in the methodologies used to calculate areas and capacities from current and previous surveys of Lake O' the Pines, direct comparison between this survey and previous surveys is not recommended. Previous surveys include the original design estimate of 254,900 acre-feet in 1955 and a TWDB volumetric survey in 1998. The 1998 survey was re-evaluated using current processing procedures in order to compare the 2009 calculations.

The 2009 TWDB sedimentation survey indicates that Lake O' the Pines has accumulated 33,080 acre-feet of sediment since impoundment in 1957. Based on this calculated sediment volume, Lake O' the Pines has lost an average of 636 acre-feet of capacity per year. Sediment accumulation is well dispersed throughout the lake, although increased accumulation was found within the submerged rivers. TWDB recommends that a similar methodology be used to resurvey Lake O' the Pines in 10 years or after a major flood event.

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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. 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 September 2009, TWDB entered into agreement with U.S. Army Corps of Engineers, Fort Worth District, to perform a volumetric and sedimentation survey of Lake O' the Pines. 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 Northeast Texas Municipal Water District provided the remaining 50% (TWDB, 2009). This report describes the methods used to conduct the volumetric and sedimentation survey, including data collection and processing techniques, and provides the survey results. This report also serves as the final contract deliverable from TWDB to the U.S. Army Corps of Engineers, Fort Worth District and contains as deliverables: (1) elevation-capacity and elevation-area tables of the lake acceptable to the Texas Commission on Environmental Quality [Appendix A,B], (2) a bottom contour map [Figure 5], (3) a shaded relief plot of the lake bottom [Figure 3], and (4) an estimate of sediment accumulation and location [Figure 12].

Lake O' the Pines general information

Ferrells Bridge Dam is located on Cypress Creek, nine miles west of Jefferson in Marion County, Texas (TWDB, 1974). Lake O' the Pines inundates parts of Marion, Upshur, and Morris Counties (Figure 1). Lake O' the Pines is owned by the U.S. Government and operated by the U.S. Army Corps of Engineers, New Orleans District. The reservoir supplies water to the Northeast Texas Municipal Water District; provides flood protection to the city of Jefferson, Texas, Shreveport, Louisiana and the Red River; and provides recreational space (NETMWD, 2010, USACE, 2010). In 1953, the Northeast Texas Municipal Water District was created with the intent of locally sponsoring Lake O' the Pines and with a mission "to develop and deliver an adequate water supply to cities and industries in Northeast Texas" (NETMWD, 2010). Lake O' the Pines is the source of water "for eight cities and towns, numerous rural water districts, and several steel manufacturers and electricity generators" (Water Monitoring Solutions, Inc., 2010). Lake O' the Pines provides water for local timber and agricultural production as well as meeting irrigation needs (Water Monitoring Solutions, Inc., 2010). Construction on Ferrells Bridge Dam began on January 10, 1955. Deliberate impoundment of water began on August 21, 1957 and construction was completed on June 25, 1958 (USACE, 2010). Additional pertinent data about Ferrells Bridge Dam and Lake O' the Pines can be found in Table 1.

Water rights for Lake O' the Pines have been appropriated to the Northeast Texas Municipal Water District through Certificate of Adjudication and amendment Nos. 04-4590, 04-4590A, and 04-4590B. The complete certificates are on file in the Records Division of the Texas Commission on Environmental Quality.

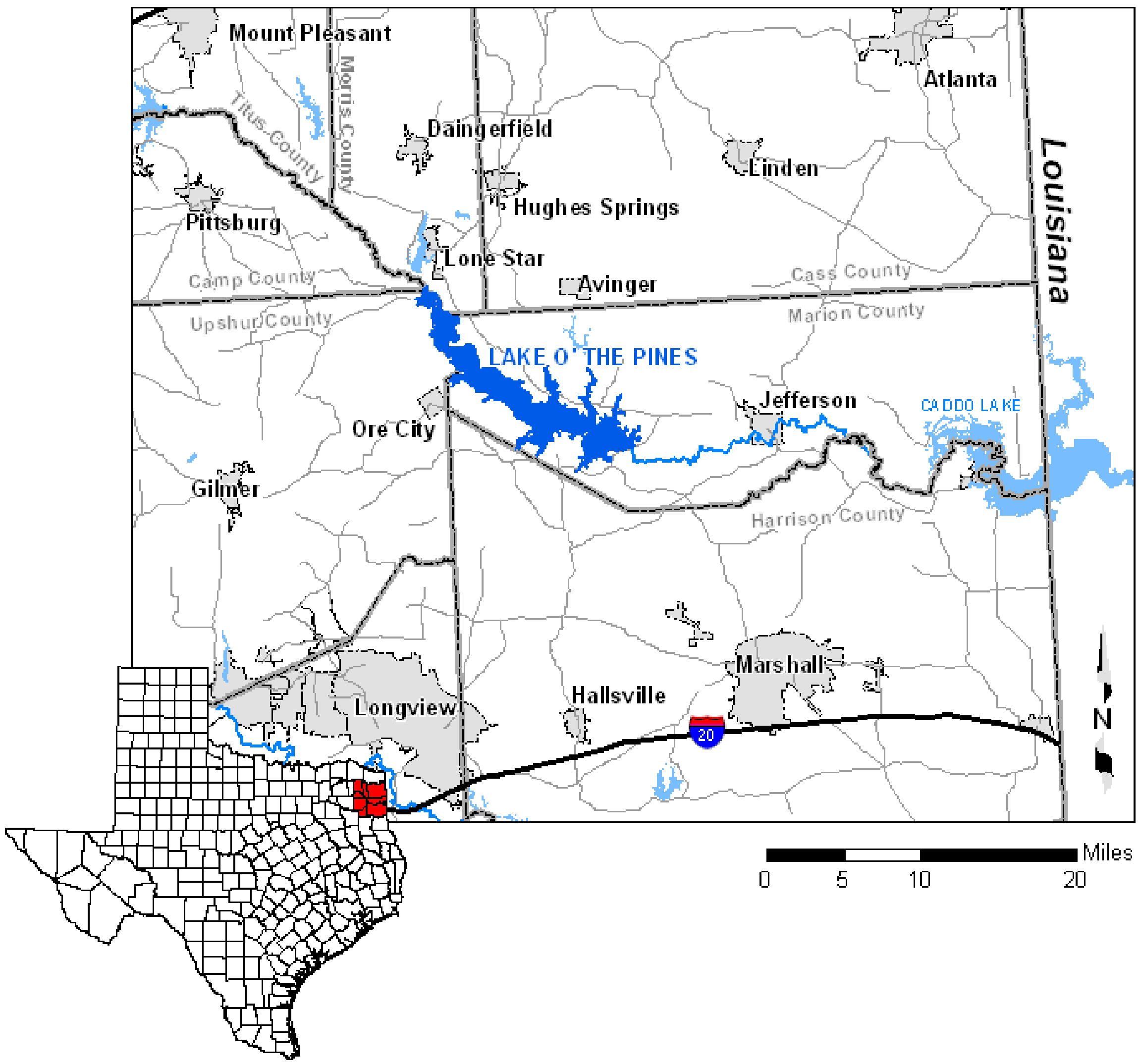


Figure 1: **Location Map – Lake O' the Pines**

Table 1:	Pertinent Data for Ferrells Bridge Dam and Lake O' the Pines		
Owner			
U.S. Army Corps of Engineers, New Orleans District			
Location of Dam			
River mile 81.2 on Cypress Creek, Marion County, 9 miles west of Jefferson, TX			
Drainage Area			
880 square miles			
Dam			
Type	Earth fill		
Length	10,600 feet		
Maximum height	97 feet		
Top width	30 feet		
Spillway			
Type	Concrete chute		
Length	200.0 feet		
Crest elevation	249.5 feet NGVD29[a]		
Outlet Works			
Type	2 conduits		
Size	10 feet diameter conduit		
Invert elevation	200.0 feet NGVD29[a]		
Control	Two 8 feet x 12.5 feet gates		
Reservoir Data (Based on 2009 TWDB volumetric survey)			
Feature	**Elevation (feet NGVD29[b])**	**Capacity (acre-feet)**	**Area (acres)**
Top of dam	277.0	N/A	N/A
Top of surcharge pool	269.9	1,856,000[a]	63,200[a]
Top of flood control pool	249.5	842,100[a]	38,200[a]
Top of seasonal pool	230.0	N/A	N/A
Top of conservation pool[c]	228.5	241,363	17,638
Bottom of conservation pool[d]	201.0	3,147	1,049
Invert of conduit	200.0	2,241	772
Streambed	180.0	N/A	N/A
Conservation storage	N/A	239,122	N/A

Source: (USACE, 2010), except where noted
[a] Source: (TWDB, 1974)
[b] NGVD29 = National Geodetic Vertical Datum 1929
[c] Originally named as top of water supply pool (TWDB, 1974)
[d] Originally named as top of conservation pool (TWDB, 1974)

Volumetric and sedimentation survey of Lake O' the Pines

Datum

The vertical datum used during this survey is that used by the United States Geological Survey (USGS) for the reservoir elevation gage *USGS 07345900 Lk O' the Pines nr Jefferson, TX* (USGS, 2010). The datum for this gage is reported as National Geodetic Vertical Datum 1929 (NGVD29) and all elevations reported herein are in feet above mean sea level (NGVD29), unless stated otherwise. 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 O' the Pines between November 7 and December 14, 2009. The daily average water surface elevations during data collection ranged between 243.04 feet and 237.93 feet. For data collection, TWDB used a Specialty Devices, Inc., 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 collection occurred while navigating 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 survey lines were those originally surveyed by TWDB during the 1998 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. During the 2009 survey, team members collected over 211,000 soundings over cross-sections totaling approximately 358 miles in length. Figure 2 shows where the soundings were collected during the 2009 TWDB survey.

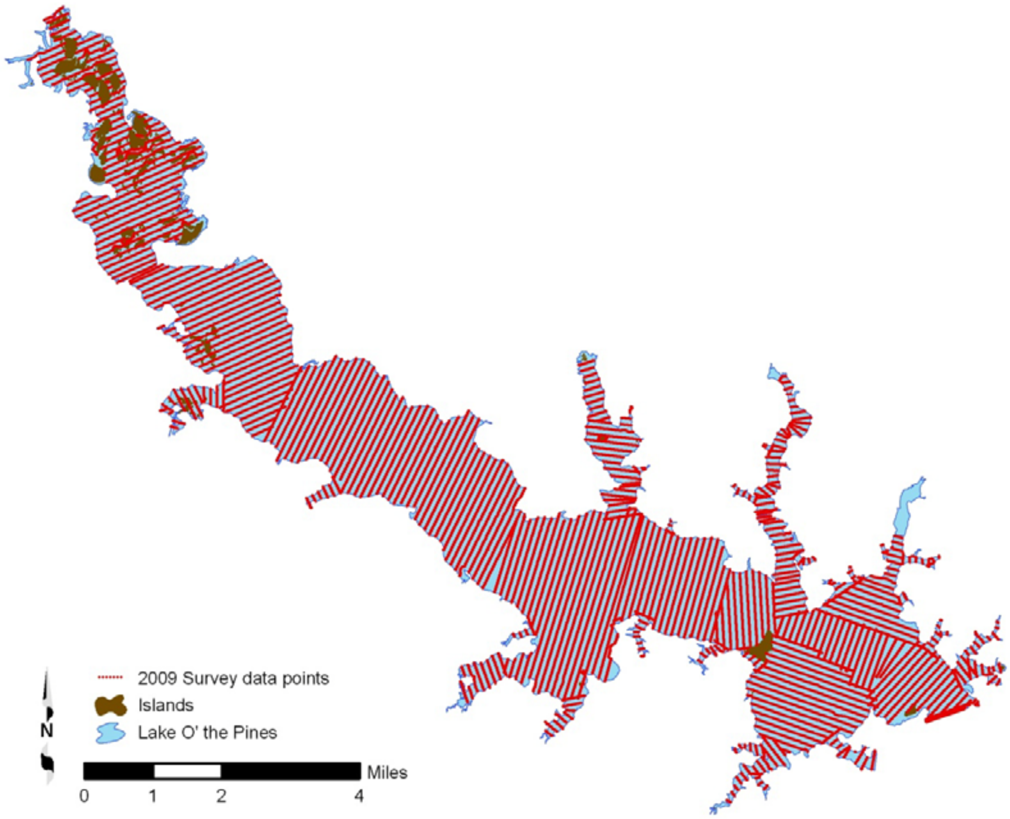


Figure 2: **Map of data collected during 2009 TWDB Survey**

Data processing

Model boundaries

The reservoir boundary was digitized from aerial photographs, also known as digital orthophoto quarter-quadrangle images (DOQQs), obtained from the Texas Natural Resources Information System (TNRIS), using Environmental Systems Research Institute's (ESRI) ArcGIS 9.3.1 software (TNRIS, 2009). The DOQQs that cover Lake O' the Pines are Harleton (NE and NW), Kellyville (SW), Lassater (NE, NW, SE and SW), Lone Star (SW) and Ore City (NE, NW and SE). The Harleton, Kellyville, Lassater and parts of the Ore City (NE and SE) DOQQs were photographed on January 15, 2009, while the water surface elevation of the lake measured 228.96 feet above mean sea level. Ore City (NE, NW and SE) and Lone Star (SW) were photographed on January 12, 2009, while the water surface elevation measured 229.15 feet above mean sea level. The Ore City (NE and SE) DOQQ's were photographed on January 12 and 15, 2009, due to a break in the county mosaic. According to the associated metadata, the 2009 DOQQS have a 0.5-meter vertical resolution and 3-5 meter horizontal accuracy. For this analysis, the boundary digitized at the land-water interface in the photographs is assumed to be a good approximation of the lake boundary at 229.0 feet above mean sea level. Therefore, the delineated boundary was given an elevation of 229.0 feet.

Triangulated Irregular Network model

Following completion of data collection, the raw data files collected by TWDB were edited using HydroEdit and DepthPic to remove data anomalies. HydroEdit is used to automate the editing of the 200 kHz frequency signal and identify the current reservoir bottom. DepthPic is used to display, interpret, and edit the multi-frequency data and to manually identify the reservoir-bottom surface at the time of initial impoundment (i.e. pre-impoundment surface). The water surface elevations at the times of each sounding were used to convert sounding depths to corresponding reservoir-bottom elevations. For processing outside of DepthPic, the sounding coordinates (X,Y,Z) were exported. Using the self-similar interpolation technique (described below), TWDB created additional interpolated bathymetric elevation data between surveyed cross sections. To better represent reservoir bathymetry in shallow regions, TWDB used a line extrapolation technique, described below (Furnans, 2006). The point files resulting from both the data interpolation and extrapolation were exported, and were used in conjunction with the sounding and boundary files to create a Triangulated Irregular Network (TIN) model with 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).

Area, Volume and Contour Calculations

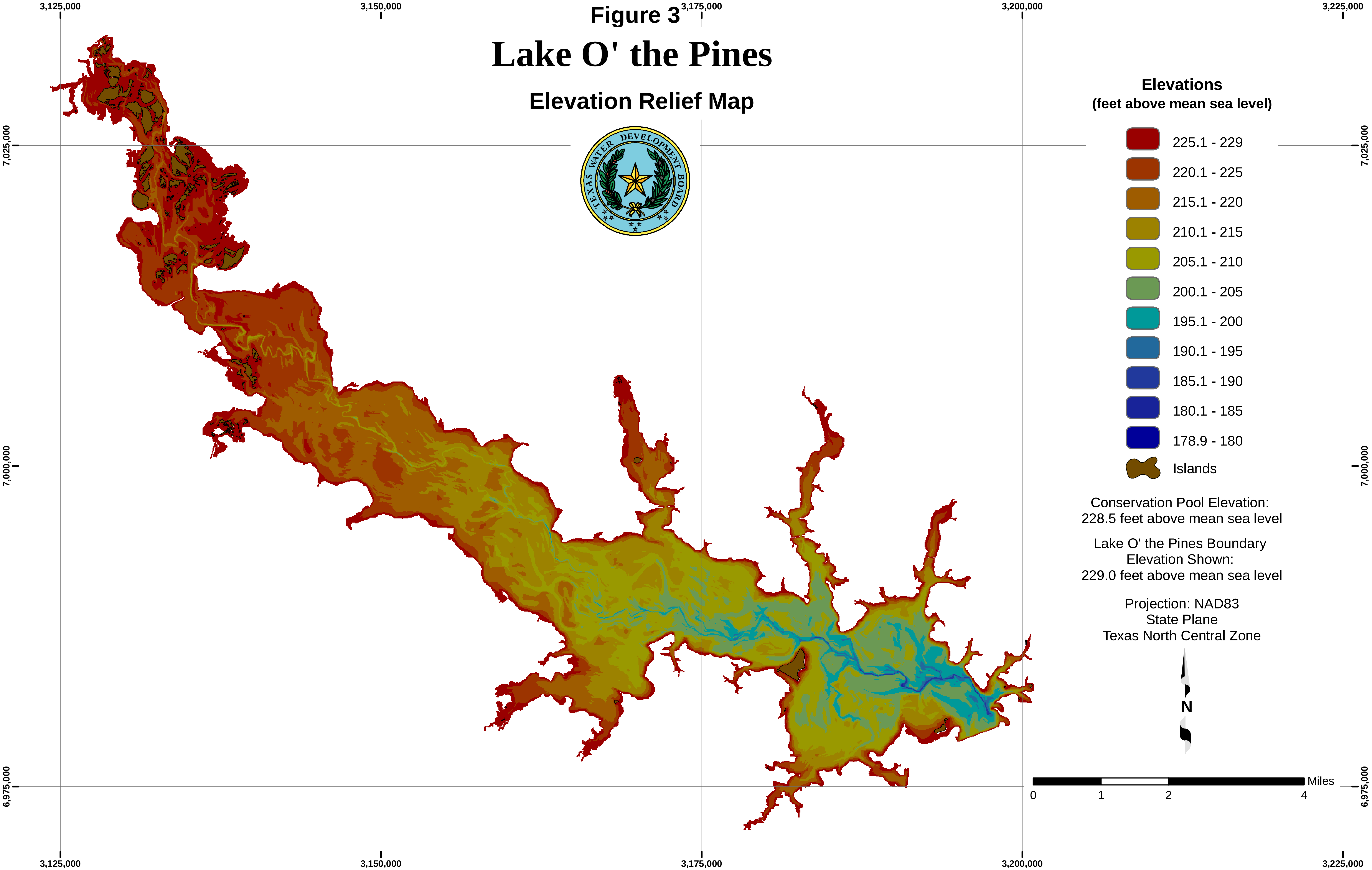
Using ArcInfo software, volumes and areas were calculated from the bathymetric TIN model for the entire reservoir at 0.1-foot intervals, from elevation 179.0 feet to elevation 229 feet. The elevation-capacity table and elevation-area table, updated for 2009, are presented in Appendices A and B, respectively. The area-capacity curves are presented in Appendix C.

The 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 3), representing the topography of the reservoir bottom, a depth range map (Figure 4), showing shaded depth ranges for Lake O' the Pines, and a 5-foot contour map (Figure 5 - attached).

Figure 3

Lake O' the Pines

Elevation Relief Map



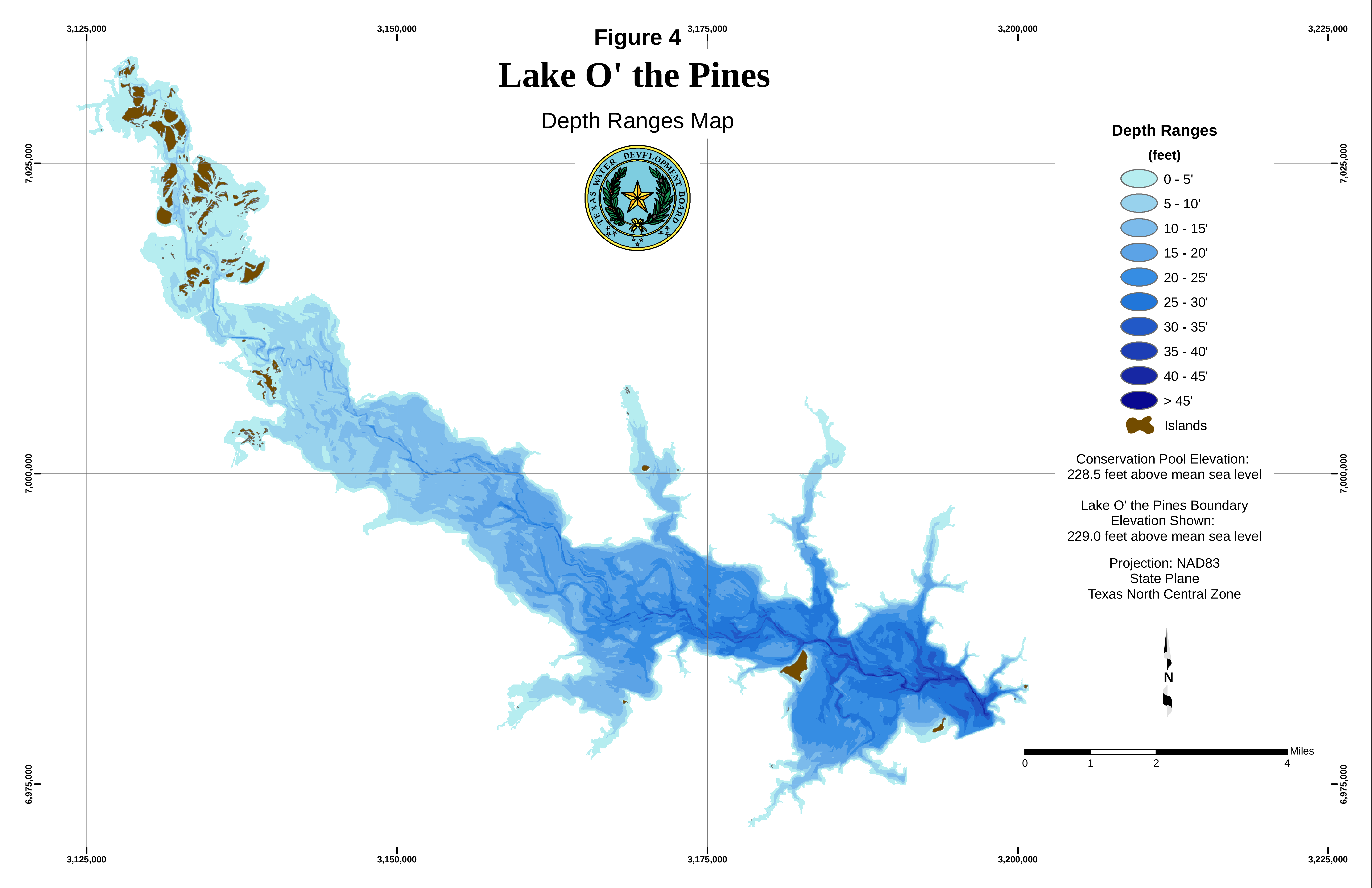


Figure 4
Lake O' the Pines
Depth Ranges Map
TEXAS WATER DEVELOPMENT BOARD
Depth Ranges
(feet)
0 - 5'
5 - 10'
10 - 15'
15 - 20'
20 - 25'
25 - 30'
30 - 35'
35 - 40'
40 - 45'
> 45'
Islands
Conservation Pool Elevation:
228.5 feet above mean sea level
Lake O' the Pines Boundary
Elevation Shown:
229.0 feet above mean sea level
Projection: NAD83
State Plane
Texas North Central Zone
N
Miles
0
1
2
4
3,125,000
3,150,000
3,175,000
3,200,000
3,225,000
7,025,000
7,000,000
6,975,000

Additional elevation-volume information was requested by the Northeast Texas Municipal Water District regarding water availability above conservation pool elevation. Volumes were estimated up to 235.0 feet above mean sea level using two methods. A complete explanation and results of this analysis are presented in Appendix D.

Self-similar interpolation

The 3D Analyst extension of ArcGIS utilizes the Delaunay method for triangulation. A limitation of the Delaunay method for triangulation when creating TIN models results in artificially-curved contour lines extending into the reservoir where the reservoir walls are steep and the reservoir is relatively narrow. These curved contours are likely a poor representation of the true reservoir bathymetry in these areas. Also, if the surveyed cross sections are not perpendicular to the centerline of the submerged river channel (the location of which is often unknown until after the survey), the TIN model is not likely to represent the true channel bathymetry well.

To ameliorate these problems, a self-similar interpolation routine developed by TWDB is used to interpolate the bathymetry between many survey lines. The self-similar interpolation technique increases the density of points input into the TIN model and directs the TIN interpolation to better represent the reservoir topography between cross sections (Furnans, 2006). In the case of Lake O' the Pines, the application of self-similar interpolation helped represent the lake morphology near the banks and improved the representation of the submerged river channel (Figure 6). In areas where obvious geomorphic features indicate a high-probability of cross-sectional shape changes (e.g. incoming tributaries, significant widening/narrowing of channel, etc.), the assumptions used in applying self-similar interpolation are not likely to be valid. Therefore, interpolation was not used in areas of Lake O' the Pines where a high probability of change between cross-sections exists. Figure 6 illustrates typical results from the self-similar interpolation routine for Lake O' the Pines. The bathymetry shown in Figure 6C was used in computing reservoir capacity and area tables (Appendix A, B).

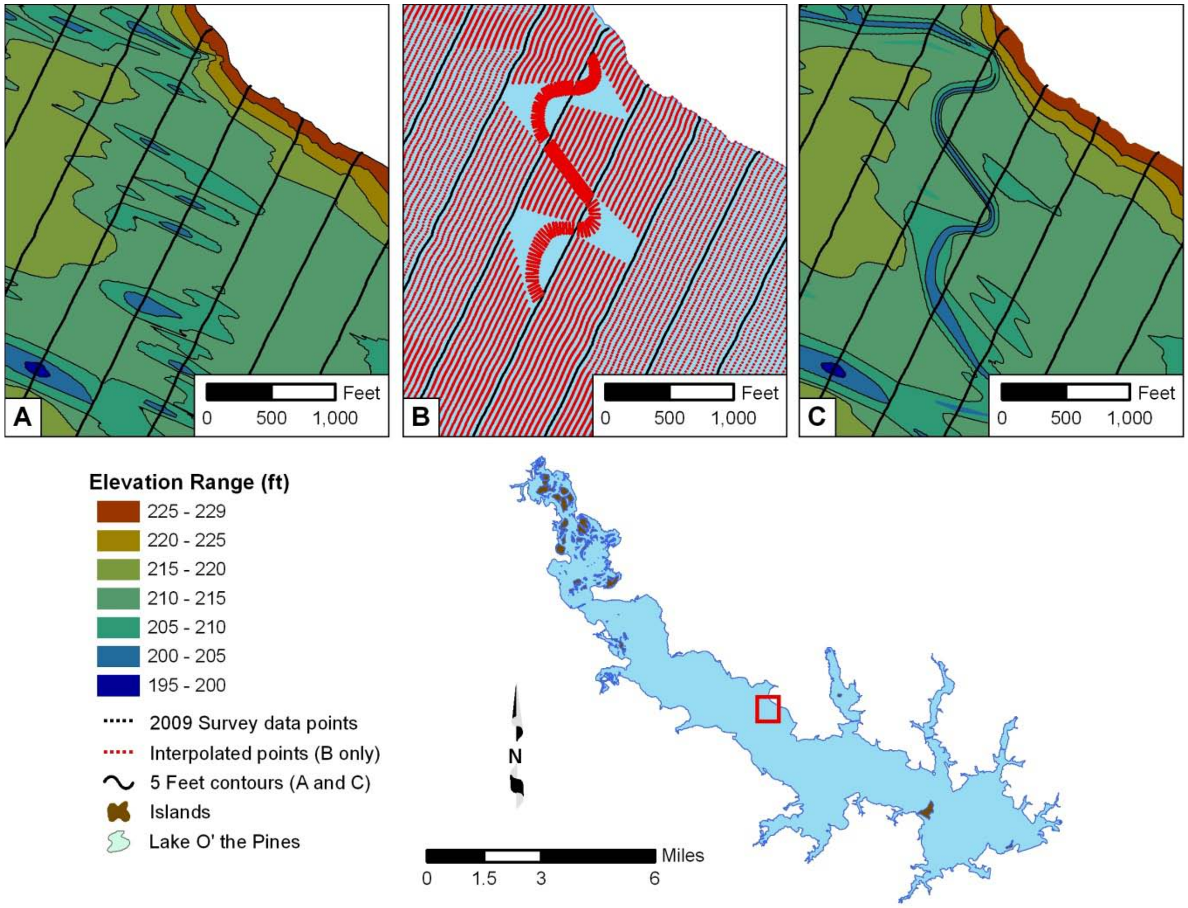


Figure 6: **Application of the self-similar interpolation technique to Lake O' the Pines sounding data – A) bathymetric contours without interpolated points, B) sounding points (black) and interpolated points (red) with reservoir boundary shown at elevation 229.0 feet, C) bathymetric contours made using survey and interpolated points.**

In Figure 6A the deeper channels indicated by the surveyed cross sections are not continuously represented in the 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 6B, in creation of the TIN model directs the Delauney method for triangulation to better represent the lake bathymetry between survey cross-sections.

Line extrapolation

In order to estimate the bathymetry within the small coves and other un-surveyed portions of Lake O' the Pines, TWDB applied a line extrapolation technique similar to the interpolation discussed above. TWDB uses line extrapolation to project bathymetries in small coves where water depths are too shallow to allow boat passage. Line extrapolation requires the user to define (1) a center line approximately bisecting the small cove, (2) the elevation at the beginning of the center line, (3) the number of cross sections along the center line and (4) the number of points between the center line and the cove boundary. The starting elevation of the center line is typically assumed equivalent to the elevation of the TIN model near the beginning of the center line or estimated based on the nearest surveyed depth.

Line extrapolation assumes a V-shaped profile for cross-sections within the extrapolation area, with the deepest section of the profile located along the center line. Elevations along the center line are linearly interpolated based on the distance along the line from the start (nearest the reservoir interior) to the end (where the center line crosses the reservoir boundary). The elevations at points along each extrapolated cross-section are linearly interpolated from an elevation on the center line (at the intersection with the cross-section) and the elevation at the extrapolation area boundary. Figure 7 illustrates line extrapolation as applied to Lake O' the Pines.

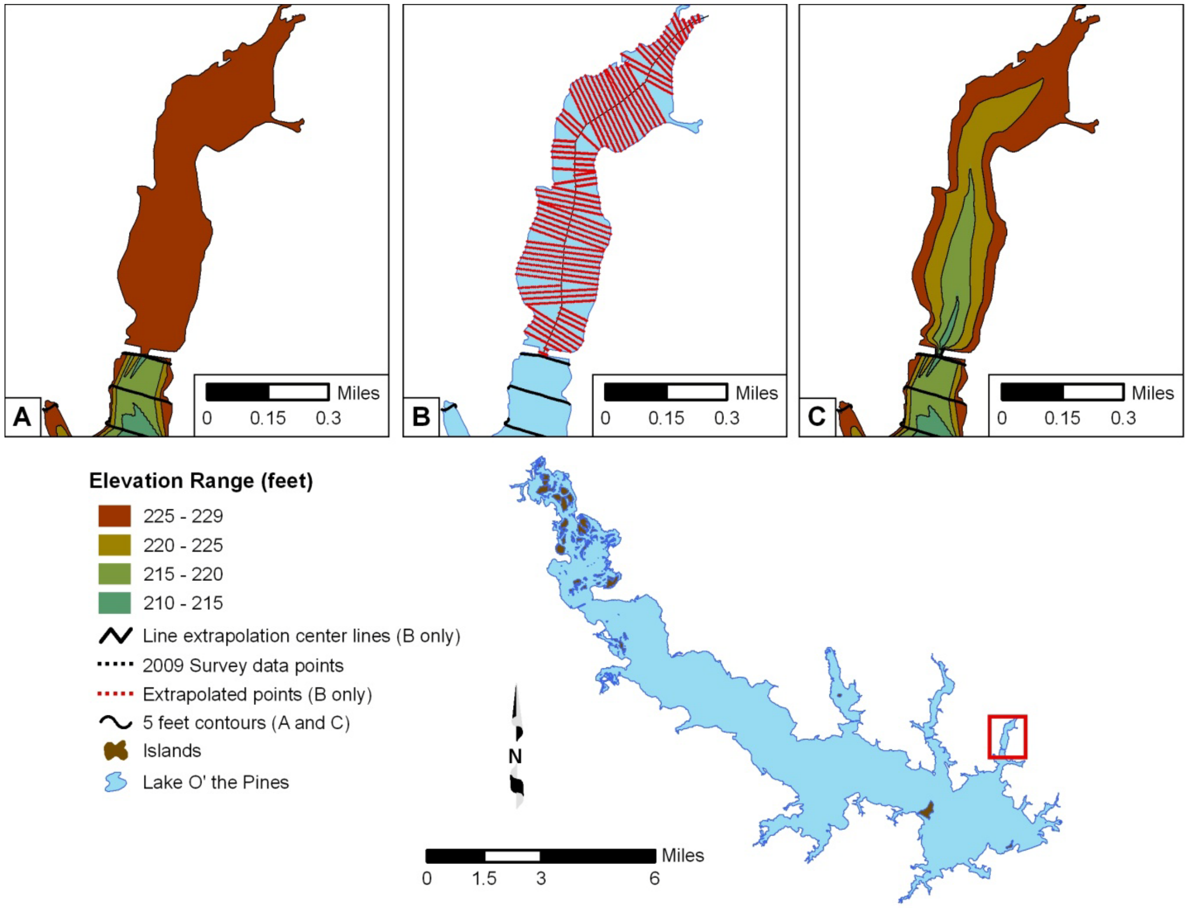


Figure 7: Application of the line extrapolation technique to Lake O' the Pines sounding data – A) bathymetric contours without extrapolated points, B) Sounding points (black) and extrapolated points (red) with reservoir boundary shown at elevation 229.0 feet and C) bathymetric contours with extrapolated points.

As shown in Figure 7A, the bathymetric contours do not extend into the un-surveyed area and "flat" triangles are formed connecting the nodes of the reservoir boundary. This is an artifact of the TIN generation routine when data points are too far apart or are absent from portions of the reservoir. Inclusion of the extrapolated points (7C) corrects this and smoothes the bathymetric contours.

The inherent assumption underlying line extrapolation is a V-shaped cross section is a reasonable approximation of the actual unknown cross-section within the extrapolated area. TWDB has not yet been able to test this assumption, therefore can only assume that the results of the usage of line extrapolation are more accurate than those derived without line extrapolation. The use of a V-shaped extrapolated cross-section likely provides a conservative estimate of the water volume in un-surveyed areas, as most surveyed cross-sections within Lake O' the Pines had shapes more similar to U-profiles than to V-profiles. The V-profiles are thus conservative due to a greater implied volume of water for a U-profile when compared to a V-profile. Further information on line extrapolation is provided in the HydroEdit User's Manual (Furnans, 2006).

Analysis of sediment data from Lake O' the Pines

Sedimentation in Lake O' the Pines was determined by analyzing all three depth sounder frequencies in the DepthPic software. The 200 kHz signal was used to determine the current bathymetric surface of the lake, while the 50 kHz and 24 kHz frequencies were used to determine the reservoir bathymetric surface at the time of initial impoundment (i.e. pre-impoundment surface). Sediment core samples collected throughout the lake were correlated with the multi-frequency acoustic signals to verify the location of the pre-impoundment surface. The difference between the current surface and the pre-impoundment surface yields a sediment thickness value at each sounding location.

TWDB collected six sediment cores from Lake O' the Pines on March 18, 2010. Sediment core samples were collected at locations where sounding data had been previously collected (Figure 8). All sediment samples were collected with a customcoring boat and SDI VibraCore system. Sediment core samples were analyzed by TWDB and both the sediment thickness and the distance the core penetrated into the pre-impoundment boundary were recorded. Physical characteristics of the sediment core, including color, texture, relative water content, and presence of organics, were also recorded (Table 2).The pre-impoundment surface is identified within the sediment sample by one of the following methods: (1) a visual examination of the sediment core for organic materials, such as leaf litter, tree bark, twigs, intact roots, etc., concentrations of which tend to occur on or just below the pre-impoundment surface, (2) changes in texture from well sorted, relatively fine-grained sediment to poorly sorted mixtures of coarse and fine-grained materials and (3) variations in the physical properties of the sediment, particularly sediment water content and penetration resistance with depth (Van Metre et al, 2004).

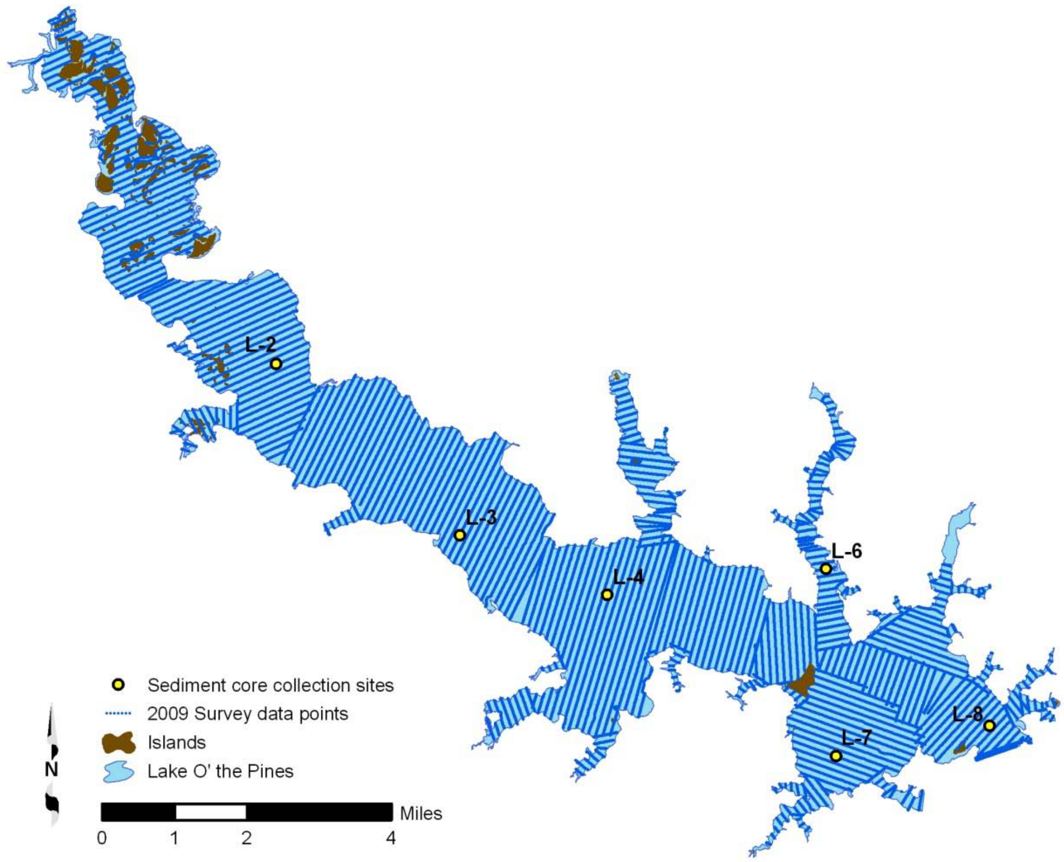


Figure 8: **Locations of sediment core samples relative to the 2009 TWDB survey data. Note: Samples L-1 and L-5 were unrecoverable due to field conditions and are not shown.**

Table 2: Sediment core sampling analysis data – Lake O' the Pines

Core	Easting[a] (feet)	Northing[a] (feet)	Total sediment/post-impoundment sediment	Core description	Munsell soil color
L-2	3143746.71	7007518.38	52"/35"	0-35" silty loam, high water content, little to no soil structure, bivalve shell at 31", root matter at 35"	2.5Y 3/1
				35-45" silty loam, high water content, increased soil structure, root matter found at 38" and 40"	5Y 5/1
				45-52" Fine sandy clay, decreased water content, increased soil structure, root matter found at 45"	2.5Y 5/1 (60%) 2.5Y 5/4 (40%)
L-3	3157166.54	6995088.85	32"/13"	0-13" Fine sandy silt (axle grease feel with fine sand interspersed), high water content	5GY 3/1
				13-27" Silty loam, decreased water content, increased soil structure	2.5Y 5/1 (80%) 2.5Y 5/3 (20%)
				27-32" Clay, decreased water content, increased soil structure, wood debris at 27"	N 5/ (gley) (80%) 5YR 3/4 (20%)
L-4	3167908.07	6990762.67	45"/21"	0-21" Fine sandy loam, high water content, dense soil with no structure	2.5Y 3/2
				21-38" Sandy loam, decreased water content, increased soil structure	2.5Y 5/2
				38-45" Sandy loam, decreased water content, increase soil structure	2.5Y 5/2 (60%) 2.5Y 5/3 (20%) 2.5Y 4/1 (20%)
L-6	3183843.74	6992622.81	28"/26"	0-26" Loam, high water content, no structure	2.5Y 3/2
				26-28" Loam, increased soil structure, no change in water content, organics at 26", root matter at 26-28"	5Y 3/2
L-7	3184581.35	6979005.94	46"/29"	0-29" Fine sandy loam, high water content, no structure, gelatinous feel	2.5Y 4/1
				29-37" Silty clay loam, increased soil structure, decreased water content	2.5Y 5/1
				37-46" Clay loam, increased soil structure, decreased water content, wood pieces at 37" and 40"	5Y 4/1 (80%) 2.5Y 2/1 (20%)
L-8	3195789.08	6981180.64	50"/42"	0-42" Loam, high water content, intermittent soil structure otherwise none, organics at 20 and 40"	5Y 4/2
				42-50" Clay loam, increased soil structure, decreased water content, root matter throughout	2.5Y 3/1 (65%) 2.5Y 4/3 (35%)

[a] Coordinates are based on NAD83 State Plane Texas North Central System (feet)

A photograph of sediment core L-4 is shown in Figure 9. The start of the tape measure indicates the assumed sediment level in the core tube before the water was poured from the core and the core was bisected for analysis. It was later determined that this was not the top of the sediment layer and the sediment between the top of the core tube and the beginning of the tape measure may have settled out of the water remaining in the core tube during transport. This section of the core tube to the left of the measuring tape in Figure 9 is likely the high porosity sediment which accumulates on the bottom of reservoirs (Van Metre et al, 2004). The 200 kHz frequency detects the top of this layer as the reservoir-bottom surface. Therefore, when comparing the image in Figure 9 to the description of the core in Table 2 the section of the core tube to the left of the measuring tape in Figure 9 has been accounted for and added into the descriptions. A detailed description of sediment core L-4 follows. The thicknesses in parentheses in Table 2 correspond to the measurements displayed in Figure 9.

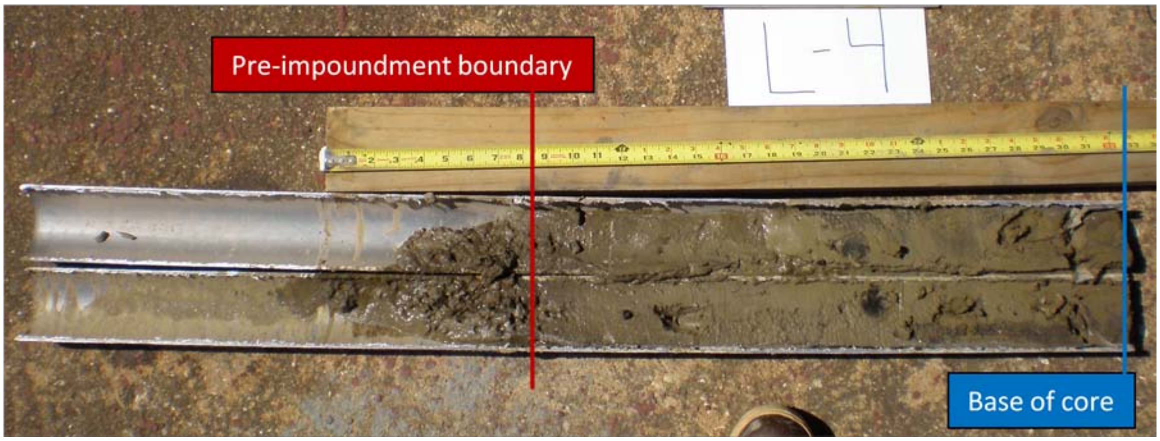


Figure 9: Sediment Core L-4 from Lake O' the Pines

Sediment core sample L-4 consisted of 45 (32) inches of sediment. The upper sediment layer (horizon), from 0 – 21 (8) inches, had high water content, consisted of fine sandy-loam soil with no soil structure and was a 2.5Y 3/2 color on the Munsell soil color chart. The second horizon, beginning at 21 (8) inches and extending to 38 (25) inches below the surface, consisted of a 2.5 Y 5/2 Munsell soil color, sandy loam texture, a decrease in soil moisture and an increase in soil structure from the horizon above. The third horizon consisted of 80% 2.5Y 5/2 Munsell color soil and 20% 2.5Y 5/3 mottling, sandy loam texture, a decrease in soil moisture and an increase in soil structure from the horizon above. The base of the sample is at 45 (32) inches and denoted by the blue line in Figure 9.

The pre-impoundment boundary (red line in Figure 9) was evident within this sediment core sample at 21 (8) inches and is identified by the change in soil color, texture, moisture, porosity and structure. Identification of the pre-impoundment surface for the remaining sediment cores followed a similar procedure.

Figures 10 and 11 illustrate how a sediment core sample is correlated with the sounding data to verify post-impoundment sediment in the acoustic signal. Within DepthPic, the current surface is automatically determined based on the signal returns from the 200 kHz transducer and verified by TWDB staff, while the pre-impoundment surface must be determined visually. The pre-impoundment surface is first identified along cross-sections for which sediment core samples have been collected. When analyzing data from cross-sections where sediment core samples were not collected, it is assumed that the pre-impoundment layer can be identified based on similarity to acoustic patterns seen where sediment core sample data was available. To improve the validity of this assumption, sediment core samples are collected at regularly spaced intervals within the lake, or at locations where interpretation of the DepthPic display would be difficult without site-specific sediment data. For this reason, all sounding data is collected and reviewed before sediment core sites are selected and collected. For shallow areas of the lake where soundings have not been collected, sediment thicknesses are assumed negligible. This assumption may lead to an underestimation of the calculated sediment volume when compared to the physical sediment volume present within the lake. In Lake O' the Pines, the physical characteristics associated with the pre-/post-impoundment barrier of the sediment samples matched well with the bottom of the 50 kHz frequency, which was used to digitize the pre-impoundment surface throughout the data.

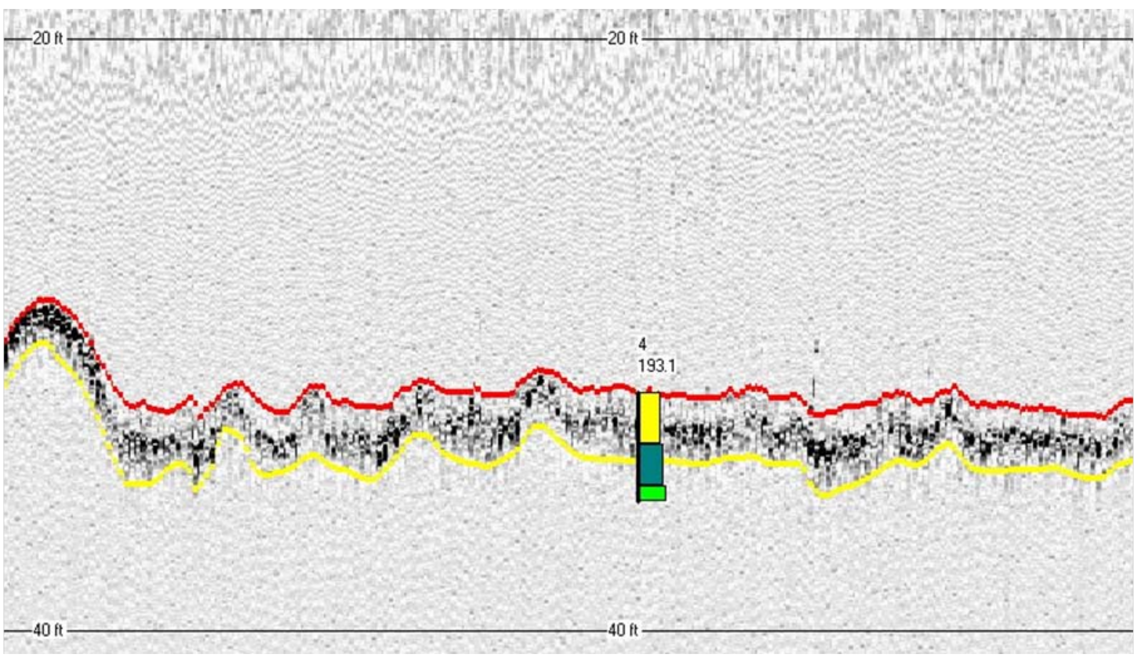


Figure 10: **Cross-section of data collected during 2009 survey, displayed in DepthPic (50 kHz frequency), correlated with sediment core sample L-4 and showing the current surface in red and pre-impoundment surface in yellow.**

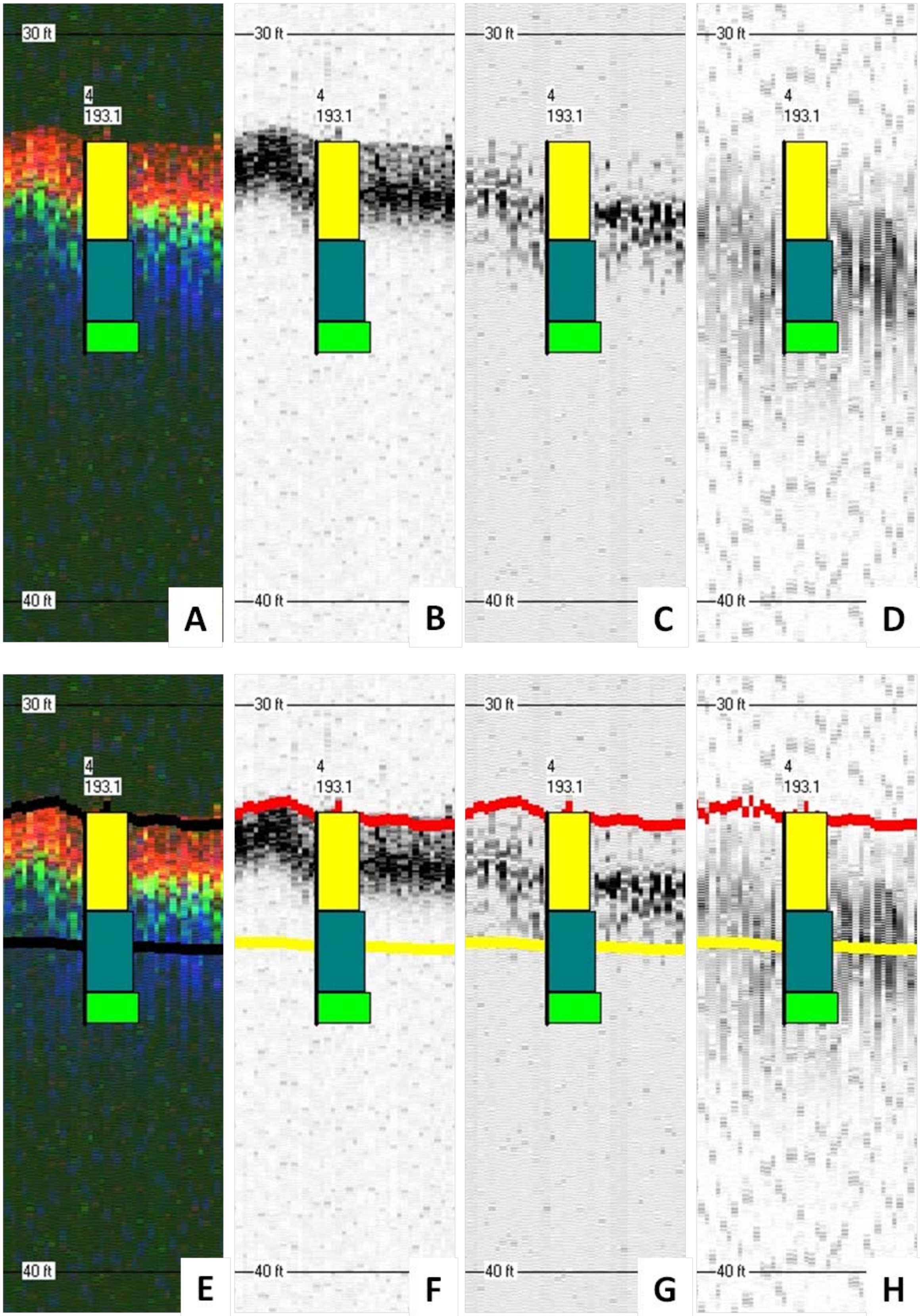


Figure 11: A,E) Close up of combined acoustic signal returns shown in Figure 10 correlated with sediment core sample L-4; B,F) 200 kHz frequency; C,G) 50 kHz frequency; D,H) 24 kHz frequency.

In figure 11A-D, the bathymetric surfaces are not shown. In figure 11E, the current bathymetric surface is represented as the top black line and the pre-impoundment surface is represented by the bottom black line. In figures 11F-H, the red line represents the current surface and the yellow line represents the pre-impoundment surface. The sediment core sample is represented in DepthPic as colored boxes, where yellow represents post-impoundment sediment, identified as the 21 inches of fine sandy loam with high water content described in Table 2; the blue box represents the more structured sandy loam soil from 21 inches to 38 inches and the green box represents the more dense sandy loam soil found from 38 inches to the base of the core at 45 inches.

After manually digitizing the pre-impoundment surface from all cross-sections, a sediment thickness TIN model is created following standard GIS techniques (Furnans, 2007). Sediment thicknesses were interpolated for locations between surveyed cross-sections using the TWDB self-similar interpolation technique (Furnans, 2006). For the purposes of the TIN model creation, TWDB assumed sediment thickness at the model boundary was zero feet (defined as the 229.0 feet elevation contour). This TIN model was converted to a raster representation using a cell size of 5 feet by 5 feet and used to produce a sediment thickness map (Figure 12) representing sediment accumulation throughout Lake O' the Pines.

Survey results

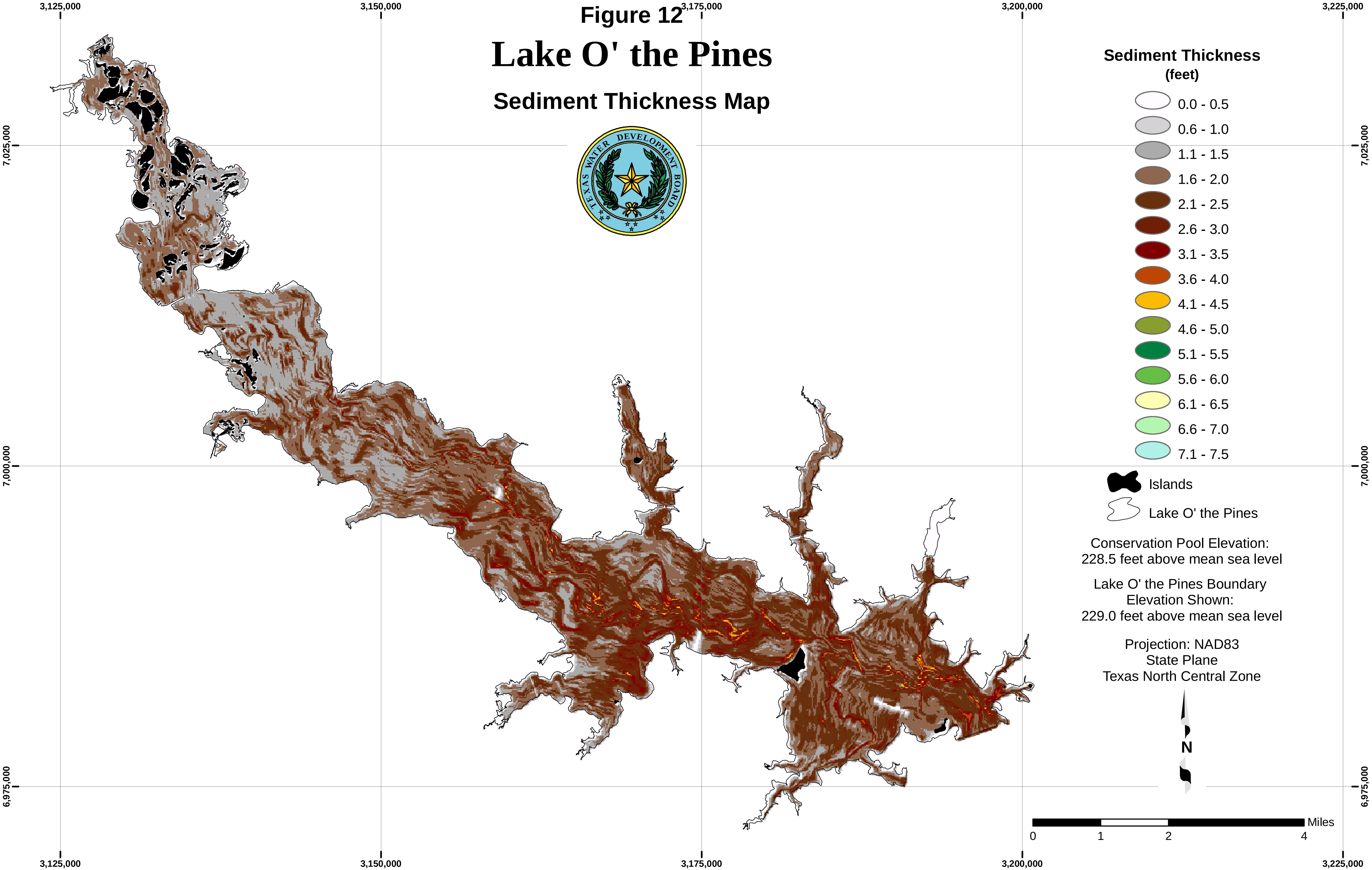
Volumetric survey

The results of the 2009 TWDB volumetric survey indicate Lake O' the Pines has a total reservoir capacity of 241,363 acre-feet and encompasses 17,638 acres at conservation pool elevation (228.5 feet). In approximately 1955, the exact date is unknown, the U.S. Army Corps of Engineers estimated Lake O' the Pines when constructed would have a total capacity of 254,900 acre-feet and encompass 18,700 acres at conservation pool elevation (USACE, 2010). Differences in past and present survey methodologies make direct comparison of volumetric surveys difficult and potentially unreliable. TWDB does not recommend directly comparing results from TWDB volumetric surveys to other volumetric surveys unless data from each survey was collected and processed using similar techniques.

Figure 12

Lake O' the Pines

Sediment Thickness Map



To properly compare results from TWDB surveys of Lake O' the Pines, TWDB applied the 2009 data processing techniques to the survey data collected in 1998. Specifically, TWDB applied the self-similar interpolation and line extrapolation techniques to the 1998 survey dataset (Furnans, 2006). A revised TIN model was created using the original 1998 survey boundary. The 1998 survey boundary was created from 7.5 minute USGS quadrangle maps, which have a stated vertical accuracy of ± 1/2 the contour interval (USBB, 1947). As presented in Table 3, revision of the 1998 survey using current TWDB data processing methods resulted in a 4,002 acre-feet (1.6%) increase in reservoir capacity. Such an increase is typical for lakes of similar size and shape as Lake O' the Pines and is due to the improved representation of the lake bathymetry between adjacent cross sections obtained with interpolation (see Figure 6, Figure 7 and sections entitled Self-similar interpolation and Line extrapolation).

Table 3: Current and previous survey capacity and surface area data

Survey	Surface area (acres)	Capacity (acre-feet)
TWDB 1974	18,700	254,900
TWDB 1998	16,919	241,081
TWDB 1998 revised	16,851	245,083
TWDB 2009	17,638	241,363

Sedimentation survey

The 2009 TWDB sedimentation survey indicates that Lake O' the Pines has accumulated 33,080 acre-feet of sediment since impoundment in 1957. Sediment accumulation is well dispersed throughout the lake, although increased accumulation was found within the submerged river channels. The maximum sediment thickness observed in Lake O' the Pines was 7.2 feet.

Theoretically, comparing lake volumes from multiple lake surveys allows for calculation of capacity loss rates. If all lost capacity is due to sediment accumulation, then comparisons of lake volumetric surveys would yield sediment accumulation rates. In practice, however, the differences in methodologies used in each lake survey may yield greater differences in computed lake volumes than the true volume differences. In addition, because volumetric surveys are not exact, small losses or gains in sediment may be masked by the imprecision of the computed volumes. For this reason, TWDB prefers to estimate sediment accumulation rates through sedimentation surveys, which directly measure the sediment layer thicknesses throughout the reservoir. The sediment accumulation rates derived from such surveys reflect the average rate of sediment accrual since the time of impoundment.

For informational purposes only, a capacity loss rate, i.e. sedimentation rate, was calculated based on the difference between the current volumetric survey and the original design estimate; the current capacity estimation and the 2009 pre-impoundment capacity estimation; as well as the current volumetric capacity estimation and the revised 1998 volumetric capacity estimation (Table 4). Based on the 2009 estimated sediment volume and assuming a constant sediment accumulation rate, Lake O' the Pines loses approximately 636 acre-feet of capacity per year. Comparison 3 in Table 4 compares the current volumetric survey to the 1998 revised volumetric survey. This comparison suggests the current rate of sedimentation in Lake O' the Pines is approximately 338 acre-feet per year. Comparison of capacity estimates of Lake O' the Pines derived using differing methodologies are provided in Table 4 for sedimentation rate calculation, however direct measurement of sediment accumulation and subsequent calculation of sedimentation rates is recommended.

Table 4: Capacity loss comparisons for Lake O' the Pines

Survey	Volume comparisons @ CPE (acre-feet)		
	Comparison 1	**Comparison 2**	**Comparison 3**
Original U.S. Army Corps estimate [a]	254,900	< >	< >
TWDB pre-impoundment estimate based on 2009 survey	< >	274,443[b]	< >
1998 volumetric survey (revised)	< >	< >	245,083
2009 volumetric survey	241,363	241,363	241,363
Volume difference (acre-feet)	13,537 (5.3%)	33,080 (12.1%)	3,720 (1.5%)
Number of years	52[a]	52[a]	11
Approximate capacity loss rate (acre-feet/year)	260	636	338

[a] Impoundment began on August 21, 1957.
[b] 2009 TWDB surveyed capacity of 241,363 acre-feet plus 2009 TWDB surveyed sediment volume of 33,080 acre-feet.

Recommendations

To improve estimates of sediment accumulation rates, TWDB recommends resurveying Lake O' the Pines in approximately 10 years or after a major flood event. To further improve estimates of sediment accumulation, TWDB recommends another sedimentation survey. A re-survey would allow a more accurate quantification of the average sediment accumulation rate for Lake O' the Pines.

TWDB contact information

More information about the Hydrographic Survey Program can be found at: http://www.twdb.state.tx.us/assistance/lakesurveys/volumetricindex.asp

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

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Appendix A

Lake O' the Pines

RESERVOIR CAPACITY TABLE

TEXAS WATER DEVELOPMENT BOARD
CAPACITY IN ACRE-FEET
ELEVATION INCREMENT IS ONE TENTH FOOT

November - December 2009 Survey
Conservation Pool Elevation 228.5 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
178	0	0	0	0	0	0	0	0	0	0
179	0	0	0	0	0	0	0	0	0	0
180	0	0	0	0	0	0	0	0	0	0
181	0	0	0	1	1	1	1	1	1	1
182	1	1	1	1	1	2	2	2	2	2
183	2	2	3	3	3	3	3	4	4	4
184	4	5	5	5	6	6	6	7	7	8
185	8	9	9	10	10	11	12	13	13	14
186	15	16	17	18	19	20	21	22	24	25
187	26	28	29	31	32	34	35	37	39	41
188	43	44	46	48	51	53	55	57	59	62
189	64	66	69	71	74	77	79	82	85	88
190	91	94	97	100	103	106	110	113	117	120
191	124	128	132	136	140	144	148	152	157	161
192	166	171	176	181	186	192	197	203	209	215
193	221	228	234	241	248	256	264	272	280	289
194	298	307	317	327	337	348	359	371	383	395
195	408	422	436	450	465	481	497	514	531	549
196	568	587	607	627	649	671	694	718	742	768
197	794	822	850	880	910	942	976	1,010	1,046	1,083
198	1,121	1,161	1,202	1,244	1,288	1,334	1,381	1,430	1,480	1,533
199	1,587	1,642	1,700	1,760	1,821	1,885	1,952	2,020	2,091	2,165
200	2,241	2,320	2,400	2,484	2,570	2,659	2,751	2,845	2,943	3,043
201	3,147	3,253	3,362	3,475	3,590	3,709	3,832	3,958	4,087	4,220
202	4,356	4,496	4,639	4,785	4,935	5,087	5,244	5,403	5,566	5,732
203	5,902	6,076	6,254	6,436	6,621	6,811	7,005	7,202	7,405	7,611
204	7,822	8,037	8,257	8,482	8,711	8,946	9,185	9,430	9,679	9,934
205	10,194	10,461	10,733	11,011	11,296	11,587	11,884	12,188	12,498	12,815
206	13,140	13,470	13,808	14,152	14,503	14,860	15,224	15,593	15,969	16,351
207	16,738	17,132	17,531	17,936	18,348	18,765	19,188	19,618	20,053	20,495
208	20,942	21,396	21,855	22,320	22,790	23,266	23,748	24,235	24,727	25,225
209	25,730	26,240	26,756	27,277	27,805	28,338	28,877	29,421	29,972	30,528
210	31,091	31,659	32,232	32,811	33,395	33,985	34,580	35,181	35,787	36,400
211	37,018	37,643	38,274	38,910	39,553	40,202	40,857	41,518	42,185	42,858
212	43,537	44,221	44,910	45,606	46,306	47,012	47,723	48,440	49,163	49,891
213	50,625	51,364	52,109	52,860	53,616	54,378	55,146	55,918	56,696	57,479
214	58,268	59,063	59,863	60,668	61,479	62,295	63,117	63,944	64,777	65,615
215	66,460	67,310	68,166	69,028	69,895	70,768	71,648	72,533	73,424	74,321
216	75,225	76,136	77,052	77,975	78,904	79,839	80,780	81,727	82,680	83,639
217	84,604	85,576	86,555	87,539	88,530	89,528	90,531	91,541	92,557	93,580
218	94,609	95,645	96,688	97,738	98,796	99,860	100,932	102,011	103,098	104,191
219	105,291	106,398	107,513	108,635	109,764	110,900	112,043	113,192	114,348	115,511
220	116,680	117,855	119,037	120,225	121,419	122,619	123,826	125,039	126,259	127,484
221	128,717	129,957	131,204	132,458	133,719	134,987	136,263	137,546	138,836	140,134
222	141,438	142,749	144,067	145,392	146,723	148,062	149,407	150,759	152,118	153,484
223	154,857	156,237	157,624	159,018	160,419	161,828	163,243	164,666	166,097	167,534
224	168,980	170,432	171,891	173,358	174,831	176,312	177,800	179,294	180,797	182,306
225	183,824	185,349	186,882	188,423	189,971	191,527	193,090	194,660	196,236	197,819
226	199,409	201,006	202,609	204,219	205,836	207,459	209,090	210,726	212,371	214,021
227	215,679	217,344	219,015	220,693	222,378	224,070	225,769	227,474	229,186	230,905
228	232,631	234,364	236,103	237,849	239,602	241,363	243,130	244,903	246,683	248,470
229	250,263									

Appendix B

Lake O' the Pines

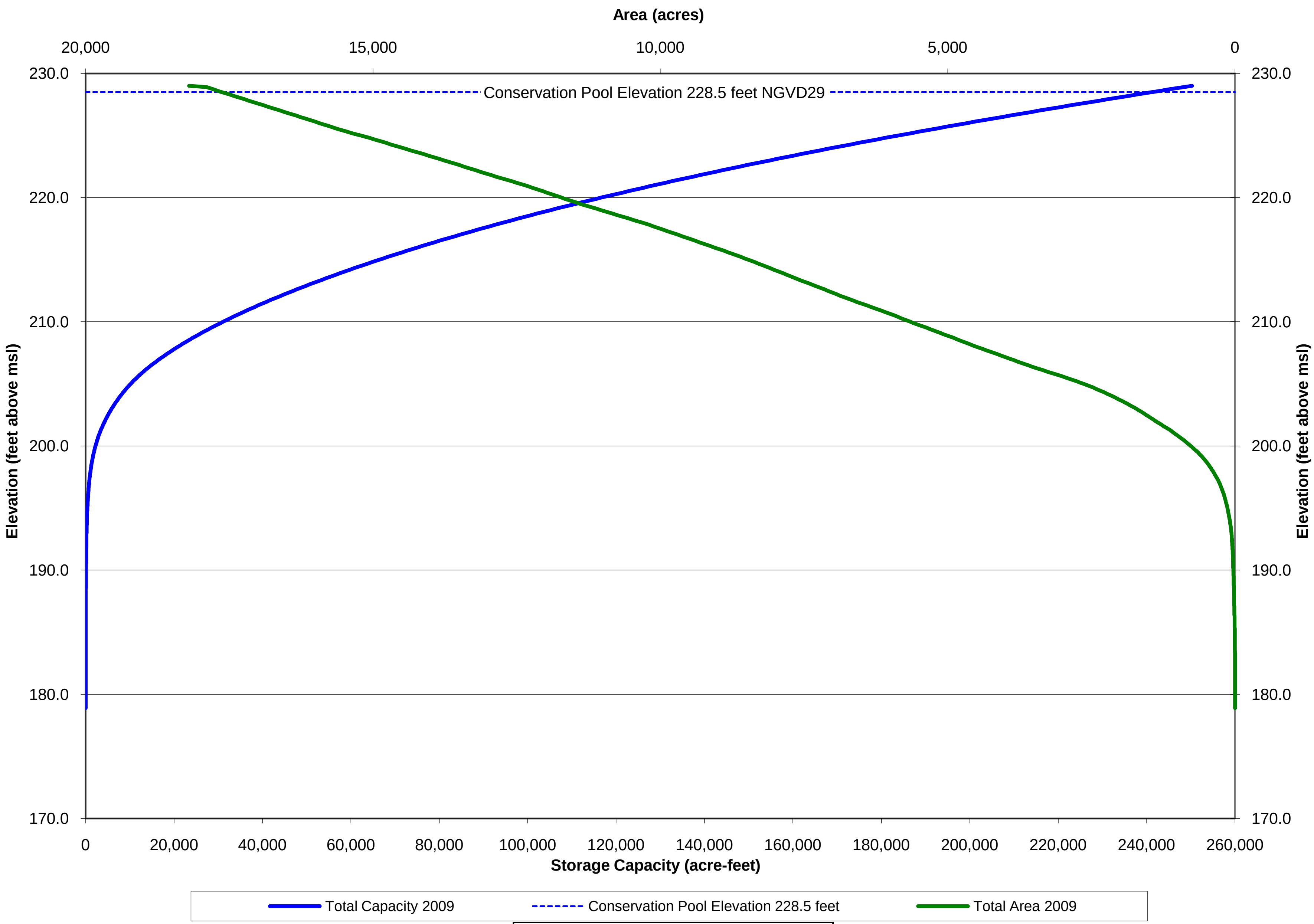
RESERVOIR AREA TABLE

TEXAS WATER DEVELOPMENT BOARD — November - December 2009 Survey

AREA IN ACRES — Conservation Pool Elevation 228.5 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
178	0	0	0	0	0	0	0	0	0	0
179	0	0	0	0	0	0	0	0	0	0
180	0	0	0	0	0	0	0	0	0	0
181	0	0	0	1	1	1	1	1	1	1
182	1	1	1	1	1	1	1	1	1	2
183	2	2	2	2	2	2	2	2	2	3
184	3	3	3	3	3	4	4	4	5	5
185	5	5	6	6	6	7	7	8	8	8
186	9	9	10	10	11	11	12	12	13	13
187	14	14	15	15	16	16	17	18	18	19
188	19	19	20	20	21	21	22	22	23	23
189	24	24	25	26	26	27	27	28	29	29
190	30	30	31	32	33	33	34	35	35	36
191	37	38	39	40	41	42	43	44	45	46
192	48	49	50	52	53	55	56	58	60	62
193	64	66	68	71	73	76	79	82	85	88
194	91	95	98	102	106	110	114	118	123	127
195	132	137	142	148	154	159	165	171	177	182
196	188	195	202	209	217	226	234	242	251	260
197	270	279	290	301	313	326	338	351	363	375
198	389	403	418	433	449	465	480	497	514	531
199	548	567	586	606	628	651	675	699	724	748
200	772	797	822	848	875	902	931	960	990	1,020
201	1,049	1,078	1,107	1,139	1,173	1,207	1,243	1,278	1,312	1,347
202	1,380	1,413	1,446	1,478	1,510	1,544	1,578	1,612	1,646	1,682
203	1,720	1,758	1,797	1,836	1,875	1,916	1,958	2,000	2,044	2,087
204	2,131	2,176	2,223	2,270	2,319	2,368	2,419	2,470	2,523	2,576
205	2,631	2,692	2,754	2,816	2,878	2,940	3,004	3,070	3,138	3,207
206	3,275	3,343	3,410	3,475	3,540	3,603	3,666	3,727	3,787	3,846
207	3,906	3,964	4,022	4,082	4,143	4,202	4,264	4,325	4,386	4,447
208	4,505	4,563	4,621	4,677	4,732	4,787	4,842	4,896	4,953	5,013
209	5,072	5,131	5,188	5,244	5,302	5,359	5,417	5,477	5,536	5,595
210	5,652	5,707	5,762	5,816	5,870	5,922	5,978	6,036	6,095	6,156
211	6,217	6,276	6,336	6,396	6,458	6,520	6,582	6,641	6,700	6,757
212	6,814	6,869	6,924	6,978	7,032	7,086	7,141	7,197	7,253	7,310
213	7,366	7,423	7,479	7,535	7,591	7,647	7,701	7,753	7,806	7,860
214	7,916	7,972	8,028	8,082	8,136	8,189	8,245	8,301	8,356	8,413
215	8,472	8,531	8,589	8,646	8,703	8,762	8,822	8,882	8,943	9,007
216	9,071	9,134	9,197	9,259	9,319	9,379	9,439	9,499	9,561	9,625
217	9,688	9,751	9,815	9,879	9,942	10,005	10,067	10,130	10,193	10,258
218	10,326	10,396	10,466	10,536	10,609	10,682	10,755	10,828	10,897	10,967
219	11,039	11,111	11,183	11,255	11,325	11,393	11,461	11,527	11,594	11,659
220	11,722	11,785	11,847	11,909	11,972	12,036	12,099	12,163	12,227	12,294
221	12,363	12,433	12,503	12,575	12,648	12,722	12,795	12,866	12,937	13,007
222	13,076	13,145	13,214	13,284	13,353	13,419	13,486	13,553	13,623	13,693
223	13,764	13,836	13,907	13,977	14,047	14,119	14,192	14,266	14,342	14,416
224	14,488	14,558	14,630	14,701	14,770	14,840	14,912	14,985	15,059	15,135
225	15,212	15,291	15,373	15,448	15,522	15,593	15,662	15,731	15,798	15,867
226	15,934	16,000	16,066	16,133	16,200	16,267	16,336	16,405	16,474	16,543
227	16,613	16,679	16,747	16,815	16,884	16,952	17,021	17,089	17,157	17,225
228	17,292	17,359	17,427	17,497	17,567	17,638	17,704	17,768	17,832	17,896
229	18,201									



Lake O' the Pines
November - December 2009 Survey
Prepared by: TWDB

Appendix C: Area and Capacity Curves

Appendix D

Introduction

Per request from the Northeast Texas Municipal Water District, TWDB was asked to estimate the elevation corresponding to an additional 50,000 acre-feet of water above the seasonal pool elevation of 230 feet above mean sea level. Lake O' the Pines operates at the seasonal pool elevation from approximately May through September. TWDB used two approaches to estimate the elevation: (1) creation of a TIN model using United States Geological Survey elevation data in the area surrounding Lake O' the Pines and (2) extrapolation using a polynomial regression based on 2009 TWDB volumetric survey data. The daily average water surface elevations during the survey ranged between 237.93 and 243.04 feet.

Although the daily average water surface elevations during the survey ranged between 237.93 and 243.04 feet, TWDB was unable to perform a volumetric calculation for water surface elevations above 229 feet as described in the Lake O' the Pines survey because (1) mature trees surrounding Lake O' the Pines limited data collection outside of the lake boundary at 229 feet and (2) aerial photography of Lake O' the Pines, used to create a boundary, for water surface elevations above 229.7 feet was unavailable.

Methodology

TWDB estimated the elevation corresponding to 50,000 acre-feet of water above the seasonal pool elevation of 230 feet above mean sea level using a TIN model calculation and a polynomial extrapolation calculation.

TIN model calculation

To supplement the TWDB survey data and create a TIN model extending above the 229 feet boundary elevation, United States Geological Survey 1/3 arc second (32.8 feet or 10 meters) digital elevation data from the National Elevation Dataset was used for the area surrounding Lake O' the Pines (USGS, 2011). The elevation data is available in the form of a raster image known as a digital elevation model (DEM). TWDB used ArcGIS to extract 0.5-foot contours from the DEM for elevations above the current bathymetric survey boundary (229 feet) to 235 feet. With the additional contour data, a TIN model was created for Lake O' the Pines using the TWDB 2009 survey data points, 2009 TWDB survey interpolation points, the 229 feet boundary, and DEM-derived contours from 229 to 235 feet using standard GIS techniques. For instances where the current bathymetric survey boundary conflicted with the contours, the 2009 TWDB survey boundary was used. The elevation-volume calculations for this new TIN model were conducted according to the procedures outlined in the Area, Volume and Contour Calculations section on page 7 of this report. The resulting elevation/volume calculations up to 229 feet rely on the TWDB survey data and are identical to those found in Appendix A. Volume calculation between 229 feet and 235 feet are based on the extended TIN model that is based on the USGS DEM data.

Polynomial extrapolation calculation

The polynomial trend line data extrapolation uses the 2009 volumetric survey data to predict the seasonal pool elevation (230 feet) capacity as well as the elevation where an additional 50,000 acre-feet is achieved. The volumetric data used to develop the regression line was limited to data between 225 and 229 feet. Volumes at elevations above 225 feet vary smoothly. Figure 1A shows the area-volume-elevation curves derived from the 2009 volumetric survey of Lake O' the Pines.

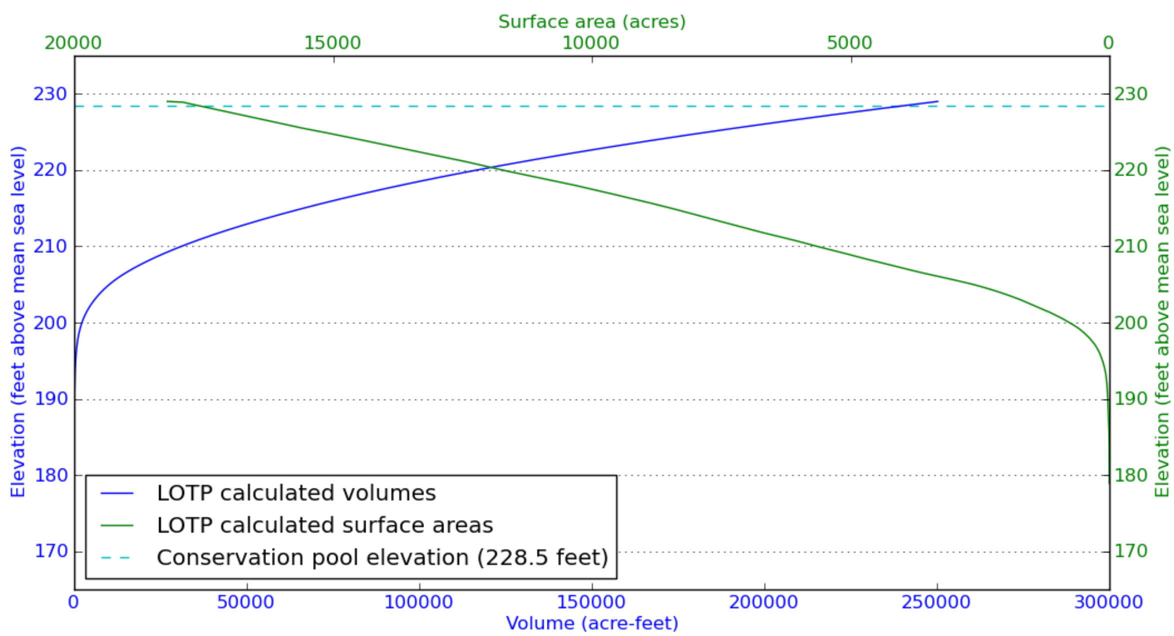


Figure 1A: Elevation-area-volume curves for 2009 volumetric survey of Lake O' the Pines

Figure 2A shows the Lake O' the Pines volumetric calculation data points for every 0.1 feet change in elevation. The shaded region in Figure 2A depicts the data points (blue) used to create the polynomial data extrapolation equation. Using the data between 225 feet and 229 feet, the best-fit polynomial equation was found to be:

with an $R^2 = 0.999$. A perfect correlation is represented by an R^2 value of 1.0. The *x* term in the polynomial equation represents volume in acre-feet and the resulting predicted elevation is in feet above mean sea level. Use of this equation to extrapolate significantly beyond 250,000 acre-feet is not recommended.

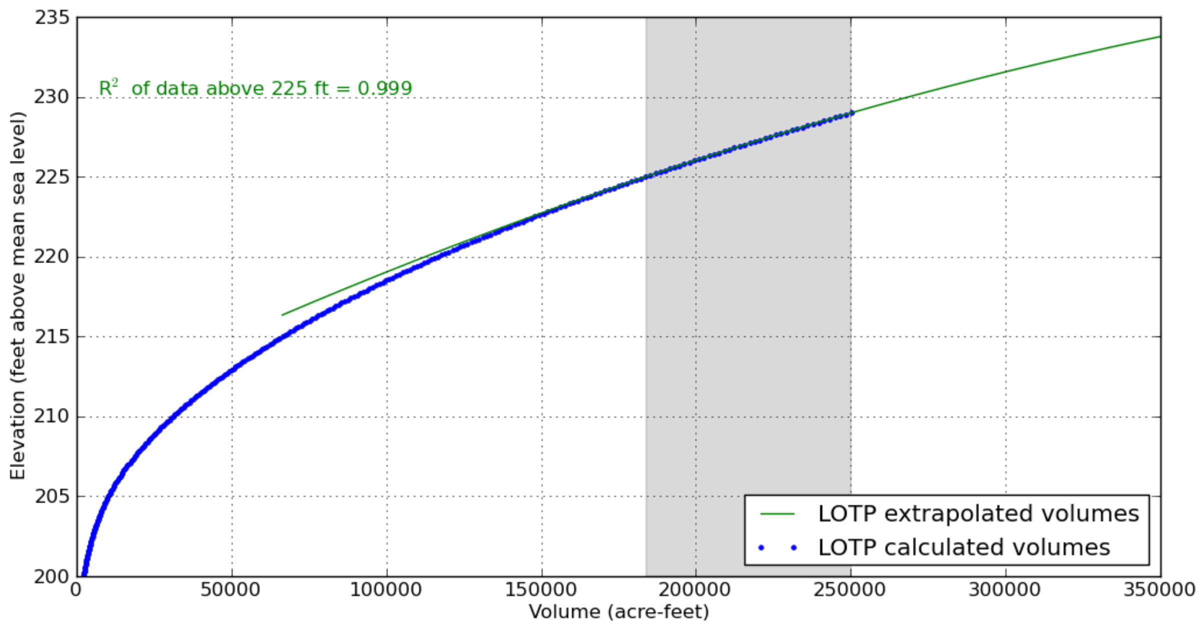


Figure 2A: **Lake O' the Pines elevation-volume polynomial extrapolation. Extrapolation based on data between 225 and 229 feet above mean sea level (grey region).**

Results

TIN model calculation

The results of the TIN model volumetric calculation provide an approximate volume of 269,700 at the seasonal pool elevation of 230 feet above mean sea level. An additional 50,000 acre-feet of water, a total of 319,700 acre-feet, above the seasonal pool elevation is found to occur at 232.42 feet above mean sea level.

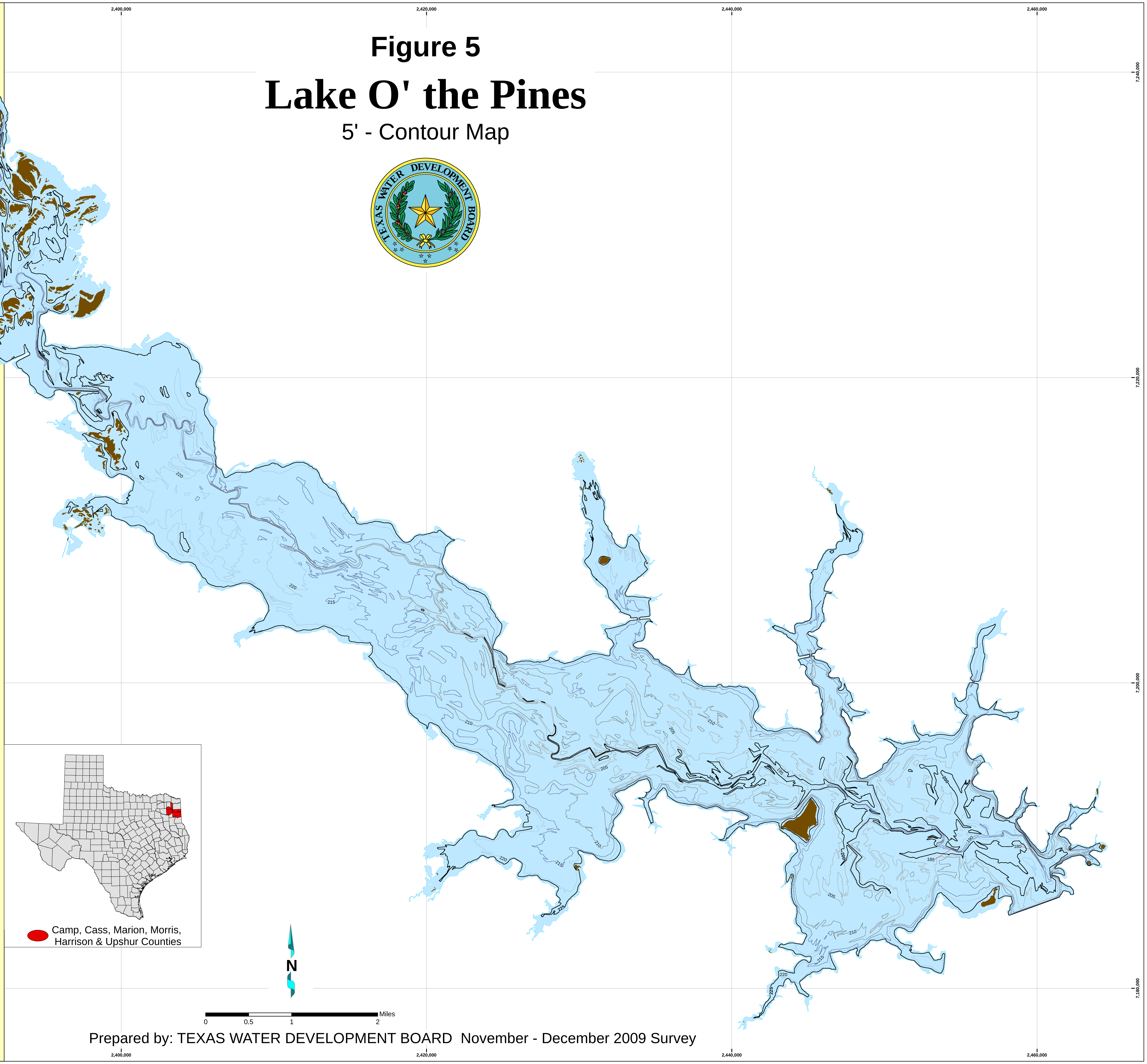
Polynomial extrapolation calculation

The results of the polynomial extrapolation calculation provide an approximate volume of 268,900 at the seasonal pool elevation of 230 feet above mean sea level. An additional 50,000 acre-feet of water, a total of 318,900 acre-feet, is found to occur at 232.44 feet above mean sea level based on extrapolation.

Figure 5

Lake O' the Pines

5' - Contour Map



CONTOURS

(feet above mean sea level)

225

220

215

210

205

200

195

190

185

180

Islands

Lake O' the Pines

Conservation Pool Elevation:
228.5 feet above mean sea level

Lake O' the Pines Boundary
Elevation Shown:
229.0 feet above mean sea level

Projection: NAD83
State Plane
Texas North Central Zone

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 O' the Pines. The Texas Water Development Board makes no representations nor assumes any liability.

Prepared by: TEXAS WATER DEVELOPMENT BOARD November - December 2009 Survey