Volumetric and Sedimentation Survey of WACO LAKE

May 2011 Survey

Texas Water Development Board

October 2012

Texas Water Development Board

Prepared for:

City of Waco

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Executive summary

In May, 2011, the Texas Water Development Board entered into agreement with the City of Waco, to perform a volumetric and sedimentation survey of Waco Lake. 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.

Waco Dam and Waco Lake are located on the Bosque River in McLennon County, within the city limits of Waco, Texas. The conservation pool elevation of Waco Lake is 462.0 feet above mean sea level (NGVD29). TWDB collected bathymetric data for Waco Lake between May 5, 2011, and May 23, 2011. Additional data was collected on June 30, 2011. The daily average water surface elevations during May ranged between 460.37 and 460.58 feet above mean sea level (NGVD29). The daily average water surface elevation on June 30, 2011 was 459.0 feet above mean sea level (NGVD29).

The 2011 TWDB volumetric survey indicates that Waco Lake has a total reservoir capacity of 189,773 acre-feet and encompasses 8,190 acres at conservation pool elevation (462.0 feet above mean sea level, NGVD29). Information provided by the U.S. Army Corps of Engineers indicates Waco Lake was estimated to have a new storage capacity of 199,227 acre-feet and inundate 8,437 acres after the conservation pool elevation was increased from 455.0 feet to 462.0 feet in 2003. Capacity estimates before conservation pool was raised include the original 1962 U.S. Army Corps of Engineers capacity estimate, for elevation 455.0 feet, of 152,500 acre-feet, a 1970 U.S. Army Corps of Engineers resurvey of 149,189 acre-feet, and a re-analysis of the 1995 TWDB volumetric survey data using current processing procedures that resulted in an updated capacity estimate of 145,532 acre-feet. Results of the 2011 TWDB survey indicate Waco Lake has a current capacity of 135,508 acre-feet at elevation 455.0 feet.

Based on comparison of the 2011 TWDB survey with an extrapolation of the 1962 USACE survey data and on direct measurements of sediment accumulation, for estimating sedimentation rates, TWDB estimates, since 1965, Waco Lake loses between 206 and 334 acre-feet of capacity per year, respectfully, due to sedimentation below conservation pool elevation (462.0 feet above mean sea level, NGVD29). The sedimentation survey indicates sediment accumulation is greater in the South Bosque River branch of the reservoir than in the North Bosque River branch. Sediment accumulation is also greater near the dam on the South Bosque River side of the reservoir. TWDB recommends that a similar methodology be used to resurvey Waco Lake 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 May, 2011, TWDB entered into agreement with the City of Waco, to perform a volumetric and sedimentation survey of Waco Lake (TWDB, 2011). This report describes the methods used to conduct the volumetric and sedimentation survey, including data collection and processing techniques. This report serves as the final contract deliverable from TWDB to the City of Waco and contains as deliverables: (1) an elevation-area-capacity table of the reservoir 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 reservoir bottom [Figure 3], and (4) an estimate of sediment accumulation and location [Figure 10].

Waco Lake general information

Waco Dam and Waco Lake are located on the Bosque River (Brazos River Basin) in McLennon County, within the city limits of Waco, Texas (Figure 1). Waco Dam and Waco Lake are owned by the United States Government and operated by the U.S. Army Corps of Engineers, Fort Worth District. Construction on Waco Dam began on June 13, 1958, and deliberate impoundment began on February 26, 1965. The dam was completed on June 24, 1965 (TWDB, 1973). Prior to construction of Waco Dam and Waco Lake, Lake Waco was completed in 1930 a half mile upstream (USACE, 1970). In 1930, Lake Waco was estimated to have a storage capacity of 39,378 acre-feet at elevation 430.0 feet. In 1952, Lake Waco was reported to be "in a fairly advanced stage of sedimentation, and…nearly 50 percent depleted." (Jones, 1952).

Waco Lake was built primarily for water supply for the city of Waco and surrounding areas, and flood control in the Waco area (USACE, 2012a). . Lake Waco had a conservation pool elevation of 430.0 feet and was completely inundated by the larger Waco Lake with a conservation pool elevation of 455.0 feet (USACE, 1970).

In 1998, the Waco City Council voted to raise the conservation pool elevation of Waco Lake by seven feet. In 2003, impoundment of water began above the original conservation pool elevation of 455.0 feet, to fill the reservoir to the new normal of 462.0

feet (USACE, 2007). Additional pertinent data about Waco Dam and Waco Lake can be found in Table 1.

Water rights for Waco Lake have been appropriated to the city of Waco through Certificate of Adjudication and amendment Nos.12-2315, 12-2315A, 12-2315B, 12-2315C, and the Brazos River Authority through Certificate of Adjudication No. 12-5094. The complete certificates are on file in the Information Resources Division of the Texas Commission on Environmental Quality.

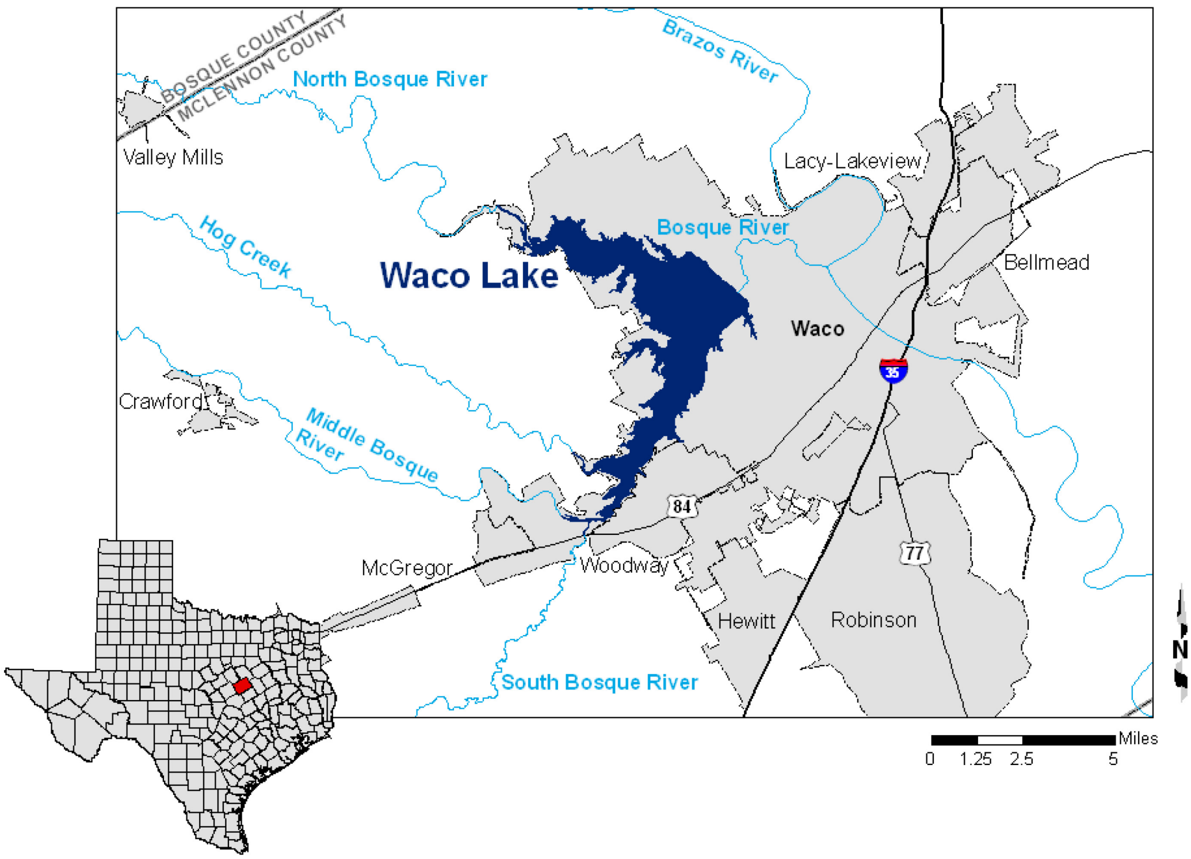

Figure 1. **Location of Waco Lake**

Table 1. Pertinent data for Waco Dam and Waco Lake

Owner
U.S. Government, operated by the U.S. Army Corps of Engineers, Fort Worth District
Engineer (design)
U.S. Army Corps of Engineers
Location of dam
On the Bosque River in McLennon County, within the city limits of Waco, Texas
Drainage area
1,670 square miles

Dam	
Type	Earthfill with concrete spillway left bank
Length	24,618 feet (including spillway)
Maximum height	140 feet
Top width	
Embankment	20 feet
Nonoverflow	16 feet
Spillway	
Type	Ogee
Length (net)	560 feet
Crest elevation	465.0 feet above mean sea level
Control	14 tainter gates, each 40 by 35 feet
Outlet works	
Type	1 gate controlled conduit, 20-feet diameter
Invert elevation	400.0 feet above mean sea level
Control	3 broome-type tractor sluice gates, each 6 feet 8 inches by 20 feet

Reservoir data (Based on 2011 TWDB survey)

Feature	**Elevation (feet NGVD29[a])**	**Capacity (acre-feet)**	**Area (acres)**
Top of dam	510.0	N/A	N/A
Maximum design water surface	505.0	N/A	N/A
Top of flood control storage space	500.0	N/A	N/A
Spillway crest	465.0	N/A	N/A
Top of conservation storage space	462.0	189,773	8,190
Invert elevation	400.0	206	32
Streambed	370.0	0	0
Usable conservation storage space	-	189,567	-

Source: (USACE, 2011b)
[a] NGVD29 = National Geodetic Vertical Datum 1929

Volumetric and sedimentation survey of Waco Lake

Datum

Water surface elevations during the TWDB survey were obtained from the United States Geological Survey (USGS) gage USGS 08095550 *Waco Lk nr Waco, TX*. These data were used to convert survey depths to elevations. The USGS gage records water surface elevations in feet relative to the North American Vertical Datum 1988 (NAVD88). However, elevations herein are reported in feet relative to the National Geodetic Vertical Datum 1929 (NGVD29). The conversion factor between NAVD88 and NGVD29 was obtained from the National Oceanic and Atmospheric Administration National Geodetic Survey VERTCON software using the coordinates referenced to the horizontal datum North American Datum 1983 (NAD83) of the USGS lake gage: Latitude 31º34’46.59484”

Longitude 97º11’52.01962” NAD83 (NGS, 2012a). These coordinates were converted from Latitude 31º34’46” Longitude 97º11’52” North American Datum 1927, as reported by USGS, using the National Oceanic and Atmospheric Administration National Geodetic Survey NADCON software (NGS, 2012b). Elevations were converted from feet NAVD88 to feet NGVD29 by subtracting 0.220. The horizontal datum used for this report is NAD83, and the horizontal coordinate system is State Plane Texas Central Zone (feet).

TWDB bathymetric and sedimentation data collection

TWDB collected bathymetric data for Waco Lake between May 5, 2011, and May 23, 2011. Additional data was collected on June 30, 2011. The daily average water surface elevations during May ranged between 460.37 and 460.58 feet above mean sea level (NGVD29). The daily average water surface elevation on June 30, 2011, was 459.0 feet above mean sea level (NGVD29). 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 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 overlapped with lines run during the 1995 TWDB 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. Figure 2 shows where data collection occurred during the 2011 TWDB survey.

All sounding data was collected and reviewed before sediment core sampling sites were selected. Sediment core samples are collected at regularly spaced intervals within the reservoir, or at locations where interpretation of the acoustic display would be difficult without site-specific sediment core data. Following analysis of the sounding data, TWDB selected six locations to collect sediment core samples. One sample, sediment core 3, was unrecoverable (Figure 2). The sediment core samples were collected on February 27, 2012, with a custom-coring boat and SDI VibraCore system.

Sediment cores are collected in 3-inch diameter aluminum tubes. Analysis of the acoustic data collected during the bathymetric survey assists in determining the depth of penetration the tube must be driven during sediment sampling. The goal is to collect a sediment core sample extending from the current reservoir-bottom, through the accumulated sediment, and to the pre-impoundment surface. After retrieving the sample, a stadia rod is inserted into the top of the tube to assist in locating the top of the sediment in the tube. This identifies the location of the layer corresponding to the current reservoir surface. The aluminum tube is cut to this level, capped, and transported back to TWDB headquarters for further analysis. During this time, some settling of the upper layer can occur.

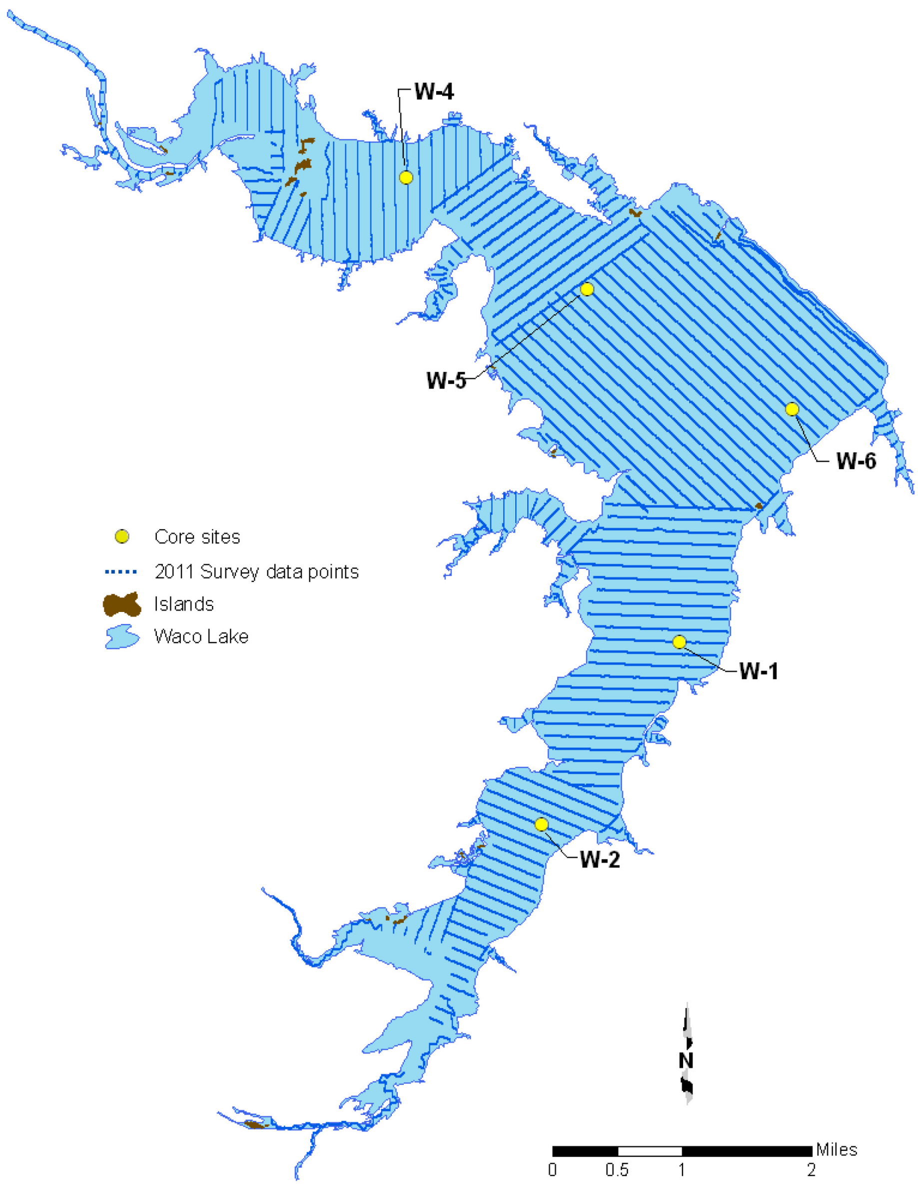

Figure 2. Data collected during 2011 TWDB Waco Lake survey

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 (TNIRIS, 2009) using Environmental Systems Research Institute's ArcGIS 9.3.1 software. The quarter-quadrangles that cover Waco Lake are Waco West (NW, SW), Speegleville (NE, SE), and South Bosque (NE). The DOQQs were photographed on August 1, 2010, while the daily average water surface elevation measured 461.58 feet NGVD29, respectively. 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 (USDA, 2011, TNRIS, 2010). For this analysis, the boundary digitized at the land-water interface in the 2010 photographs is assumed to be a good approximation of the reservoir boundary at conservation pool elevation. Therefore, the delineated boundary was given an elevation of 462.0 feet above mean sea level to facilitate calculating the area-capacity tables up to the conservation pool elevation.

Triangulated Irregular Network model

Following completion of data collection, the raw data files collected by TWDB were edited to remove data anomalies. The reservoir's current bottom surface is automatically determined by the data acquisition software. TWDB developed an algorithm to automatically determine the pre-impoundment surface, i.e. sediment thickness, based on the intensity of the acoustic returns. DepthPic is used to display, interpret, and edit the multi-frequency data by manually removing data anomalies in both the current bottom surface and pre-impoundment surface. An in-house software package, HydroTools, is used to identify the current reservoir-bottom surface, pre-impoundment surface, sediment thickness at each sounding location, and 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. For processing outside of DepthPic, the sounding coordinates were exported. This survey point dataset is 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 spatial interpolation of reservoir bathymetry section below. This technique creates a high resolution, uniform grid of interpolated bathymetric elevation points throughout a majority of the reservoir (McEwen et al., 2011). Finally, the point file resulting from spatial interpolation is 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).

Area, volume, and contour calculations

Using ArcInfo software and the volumetric TIN model, volumes and areas were calculated for the entire reservoir at 0.1 feet intervals, from elevation 385.2 to 462.0 feet. The elevation-capacity table and elevation-area table, updated for 2011, are presented in Appendices A and B, respectively. The area-capacity curves are presented in Appendix C.

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

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 between survey lines. These artifacts reduce the accuracy of the resulting volumetric and sediment TIN models in areas between actual survey data.

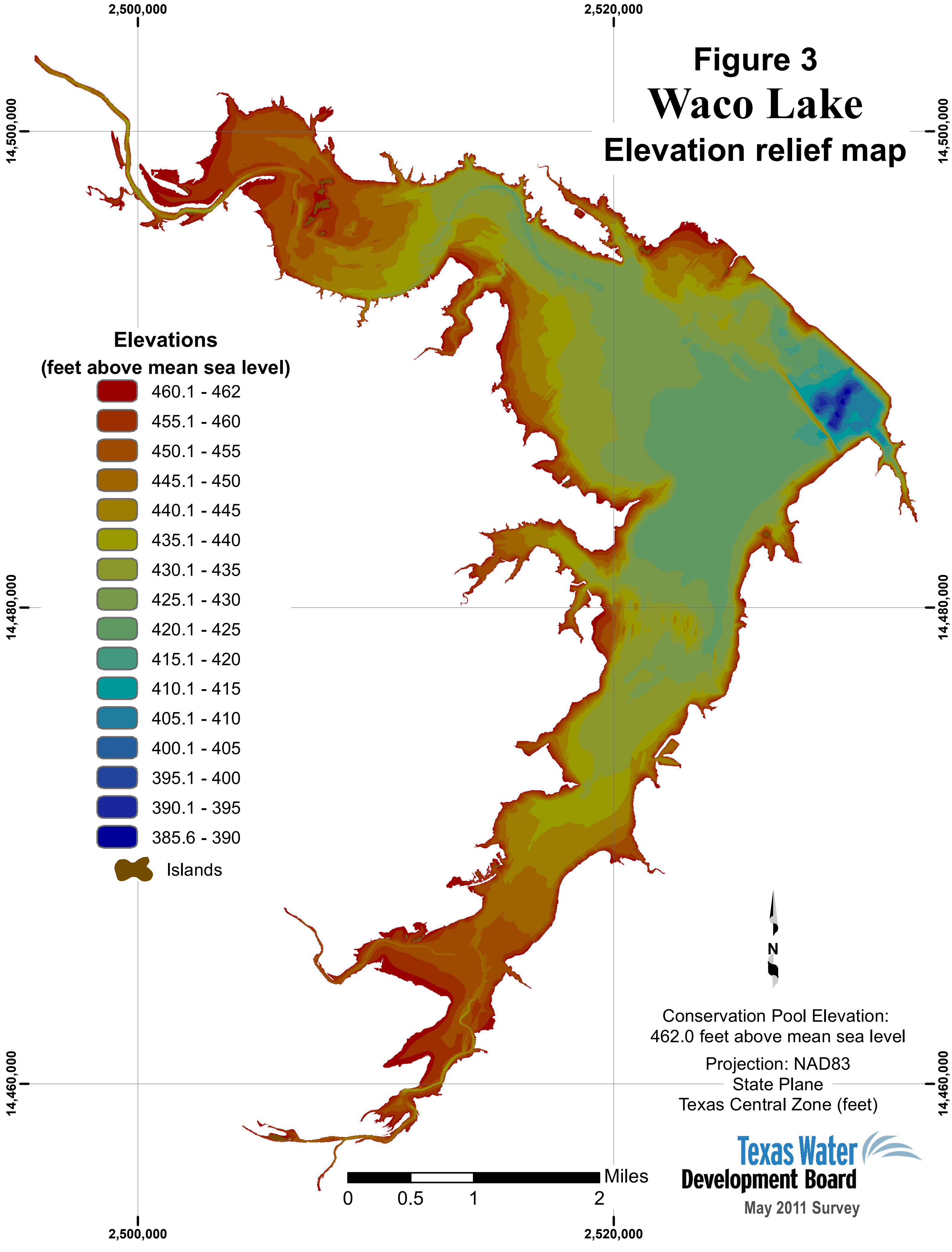
Figure 3
Waco Lake
Elevation relief map
2,500,000
2,520,000
14,500,000
14,480,000
14,460,000
Elevations
(feet above mean sea level)
460.1 - 462
455.1 - 460
450.1 - 455
445.1 - 450
440.1 - 445
435.1 - 440
430.1 - 435
425.1 - 430
420.1 - 425
415.1 - 420
410.1 - 415
405.1 - 410
400.1 - 405
395.1 - 400
390.1 - 395
385.6 - 390
Islands
N
Conservation Pool Elevation:
462.0 feet above mean sea level
Projection: NAD83
State Plane
Texas Central Zone (feet)
Miles
0
0.5
1
2
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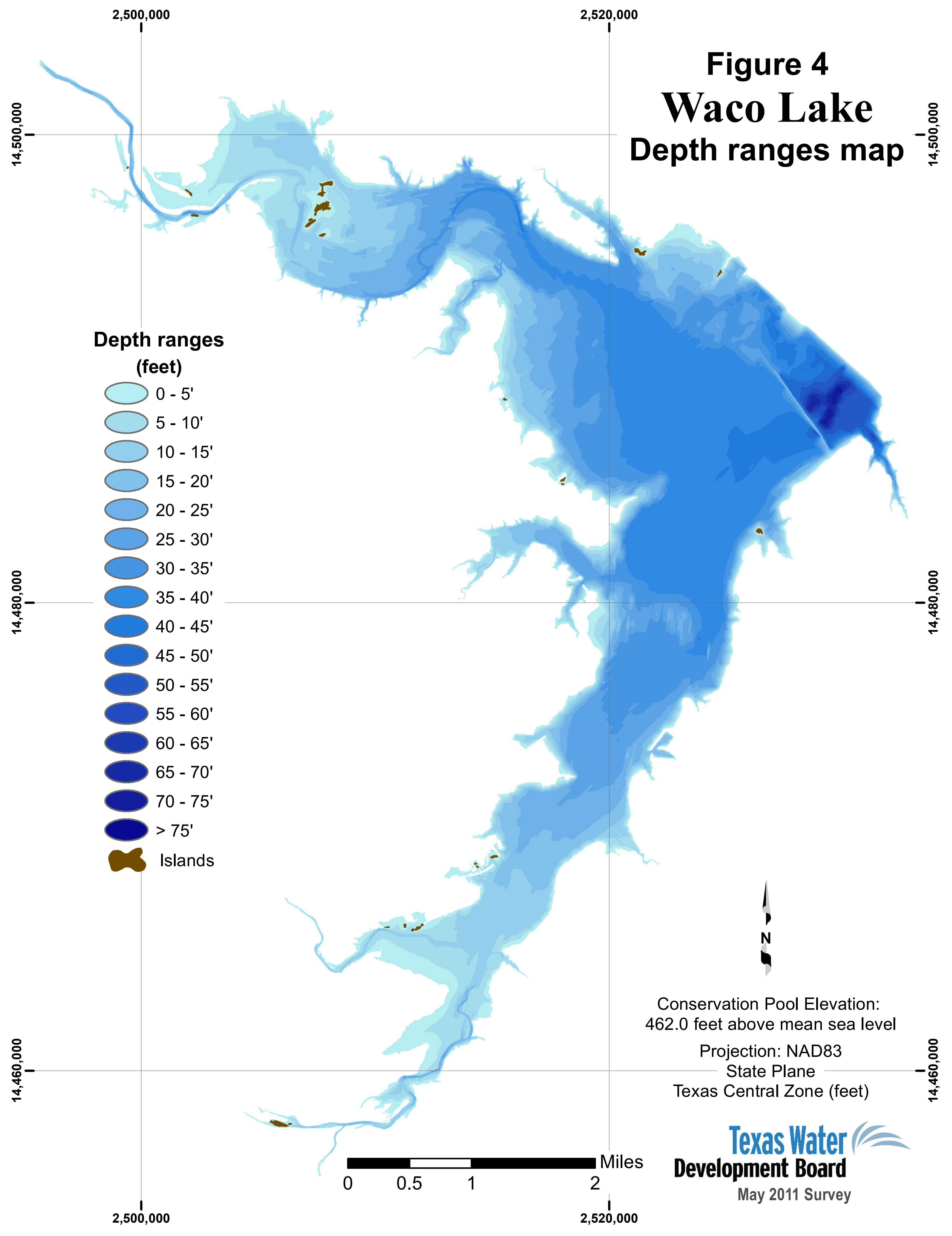
Figure 4
Waco Lake
Depth ranges map
2,500,000
2,520,000
14,500,000
14,480,000
14,460,000
Depth ranges
(feet)
0 - 5'
5 - 10'
10 - 15'
15 - 20'
20 - 25'
25 - 30'
30 - 35'
35 - 40'
40 - 45'
45 - 50'
50 - 55'
55 - 60'
60 - 65'
65 - 70'
70 - 75'
> 75'
Islands
N
Conservation Pool Elevation:
462.0 feet above mean sea level
Projection: NAD83
State Plane
Texas Central Zone (feet)
Miles
0
0.5
1
2
Texas Water
Development Board
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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 from direct examination of survey data or more robustly by examining scanned USGS 7.5 minute quadrangle maps (known as digital raster graphics) and hypsography files (the vector format of USGS 7.5 minute quadrangle map contours), when available (USGS, 2007). Using the survey data, polygons are created to partition the reservoir into segments with centerlines defining directionality of interpolation within each segment. These interpolation definition files are independent of survey data and can be applied to past and future data of the same reservoir. Using the interpolation definition files and survey data, the current reservoir-bottom elevation, pre-impoundment elevation, and sediment thickness 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 volumetric and sediment TIN models representing the reservoir bathymetry and sediment accumulation throughout the reservoir. 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 and sediment accumulation estimations. The linear extrapolation follows a linear definition file linking the survey points file to the lake boundary file (McEwen et al., 2011a). Figure 6 illustrates typical results from application of the anisotropic interpolation and line extrapolation techniques to Waco Lake. The bathymetry shown in Figure 6C was used in computing reservoir capacity and area tables (Appendix A, B).

In Figure 6A, 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 6B, in creation of the volumetric TIN model directs Delaunay triangulation to better represent the lake bathymetry between survey cross-sections.

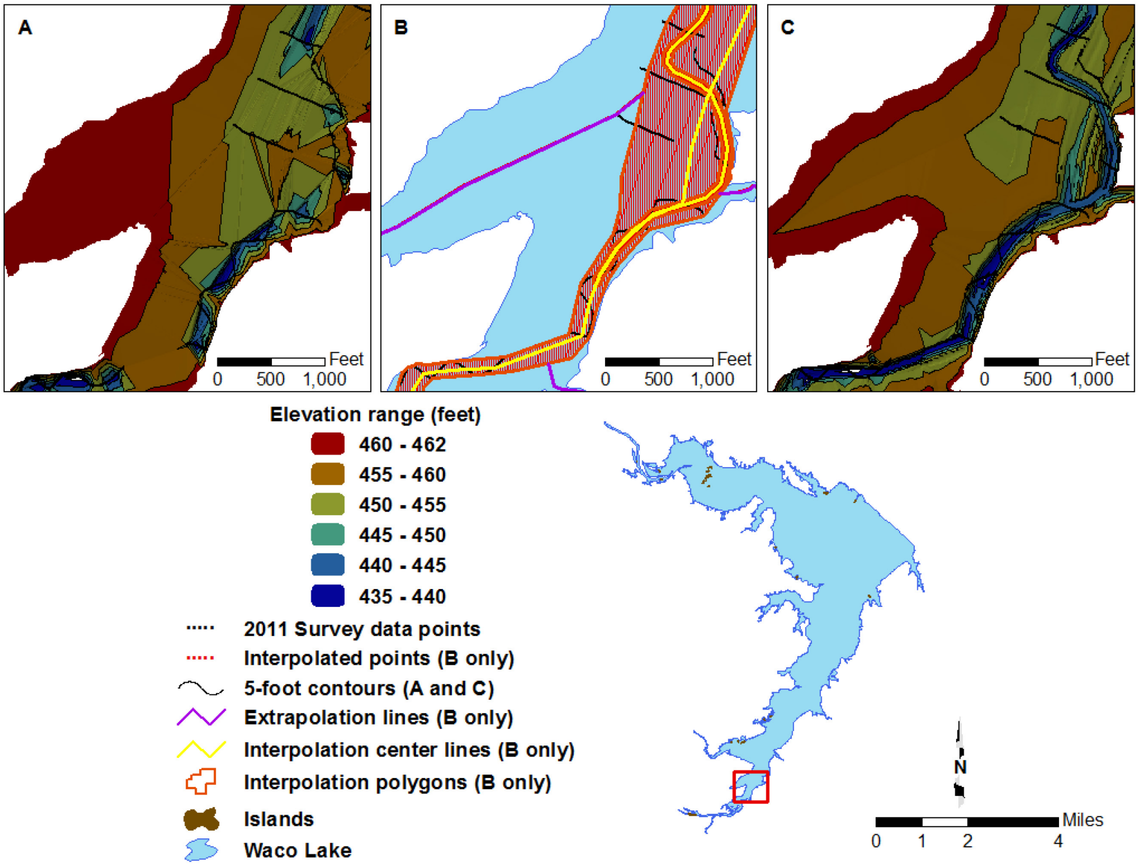

Figure 6. **Anisotropic spatial interpolation and line extrapolation of Waco Lake sounding data – A) bathymetric contours without interpolated points, B) sounding points (black) and interpolated points (red), C) bathymetric contours with the interpolated points**

Analysis of sediment data from Waco Lake

Sedimentation in Waco Lake 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 reservoir, 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 in the reservoir were used to assist in identifying the location of the pre-impoundment surface in the acoustic signals. The difference between the current surface and the pre-impoundment surface yields a sediment thickness value at each sounding location.

Analysis of the sediment core samples was conducted at TWDB headquarters in Austin. Each sample was split longitudinally and analyzed to identify the location of the pre-impoundment surface. The pre-impoundment surface is identified within the sediment core sample by one of the following methods: (1) a visual examination of the sediment core for terrestrial 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). The total sample length, sediment thickness, and the pre-impoundment thickness were recorded. Physical characteristics of the sediment core, including color, texture, relative water content, and presence of organic materials were also recorded (Table 2).

Table 2. Sediment core sampling analysis data – Waco Lake

Core	Easting[a] (ft)	Northing[a] (ft)	Total core sample/ post-impoundment sediment	Sediment core description	Munsell soil color
W-1	3266143.12	10539235.54	50.5"/43"	0-10" gelatinous saturated silt sediment with no structure	2.5y 5/4 (30%) 5y 4/2 (70%)
				10-43" similar to above layer	5y 2.5/1
				43-50.5" dense compacted silty clay soil	2.5y 4/1
W-2	3260637.69	10531709.56	48"/48"	0-2" high water content, silty soil	2.5y 4/3
				2-48" high water content, silty clay loam, no indication pre-impoundment surface was reached	5y 4/2 (60%) 5y 4/1 (40%)
W-4	3254712.02	10557985.00	40.5"/36"	0-21" high water content, loose silty sediment, red worms present at 6"	2.5y 4/3 (30%) 5y 2.5/1 (20%) 2.5y 4/1 (50%)
				21-36" high water content, loose silty sediment	2.5y 4/1 (80%) 5y 4/1 (20%)
				36-40.5" silty clay soil, roots and organic matter present	2.5y 3/1
W-5	3262170.66	10553561.26	20"/20"	0-17" high water content, silty soil	2.5y 4/3 (50%) 5y 2.5/1 (50%)
				17-20" sandy soil with rocks and organics present, no indication pre-impoundment surface was reached	5y 4/1
W-6	3270585.06	10548822.44	72"/72"	0-34" high water content, silty soil	2.5y 4/3 (50%) 2.5y 4/1 (50%)
				34-72" high water content, silty clay soil, no indication pre-impoundment surface was reached	2.5y 4/1 (80%) 5y 4/1 (20%)

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

A photograph of sediment core W-4 is shown in Figure 7 and is representative of the sediment cores sampled from Waco Lake. The 200 kHz frequency measures the top layer as the current bottom surface of the reservoir.

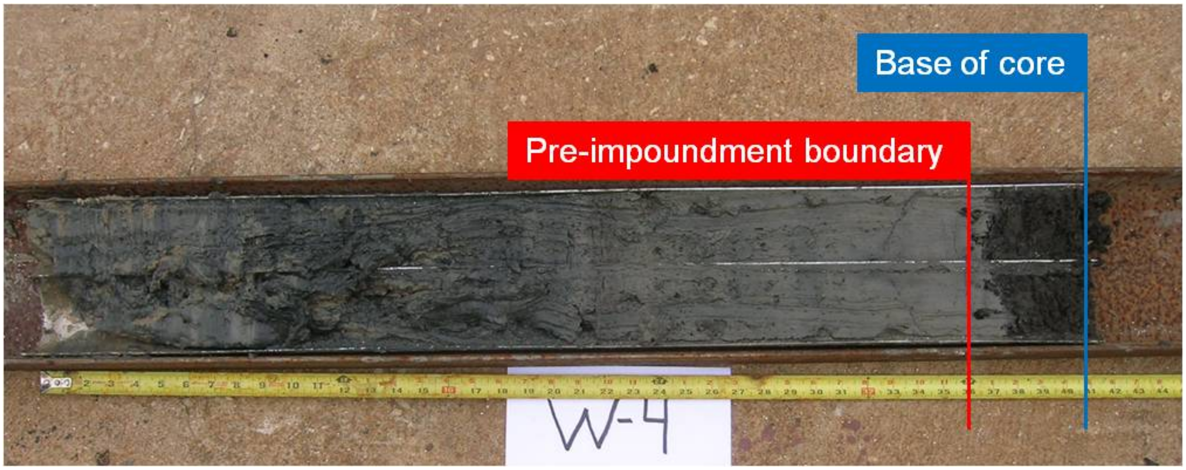

Figure 7. Sediment Core W-4 from Waco Lake

Sediment core sample W-4 consisted of 40.5 inches of total sediment corresponding to the length of the aluminum sampling tube. The upper sediment layer (horizon), 0–21.0 inches, consisted of loose silty soil with a high water content, and measured 2.5y 4/3 (30%), 5y 2.5/1 (20%), and 2.5y 4/1 (50%) on the Munsell soil color chart. The second horizon, beginning at 21.0 inches and extending to 36.0 inches below the surface, also consisted of loose silty soil with a high water content with 2.5y 4/1 (80%) and 5y 4/1 (20%) Munsell soil color. The third horizon, from 36.0 inches to 40.5 inches consisted of a silty clay soil with roots and organic matter present. The base of the sample is denoted by the blue line in Figure 7.

The pre-impoundment boundary (red line in Figure 7) was evident within this sediment core sample at 36.0 inches and 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 8 and 9 illustrate how measurements from sediment core samples are used with sonar data to help identify the interface between the post- and pre-impoundment layers in the acoustic signal. Within DepthPic, the current surface is automatically determined based on 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.

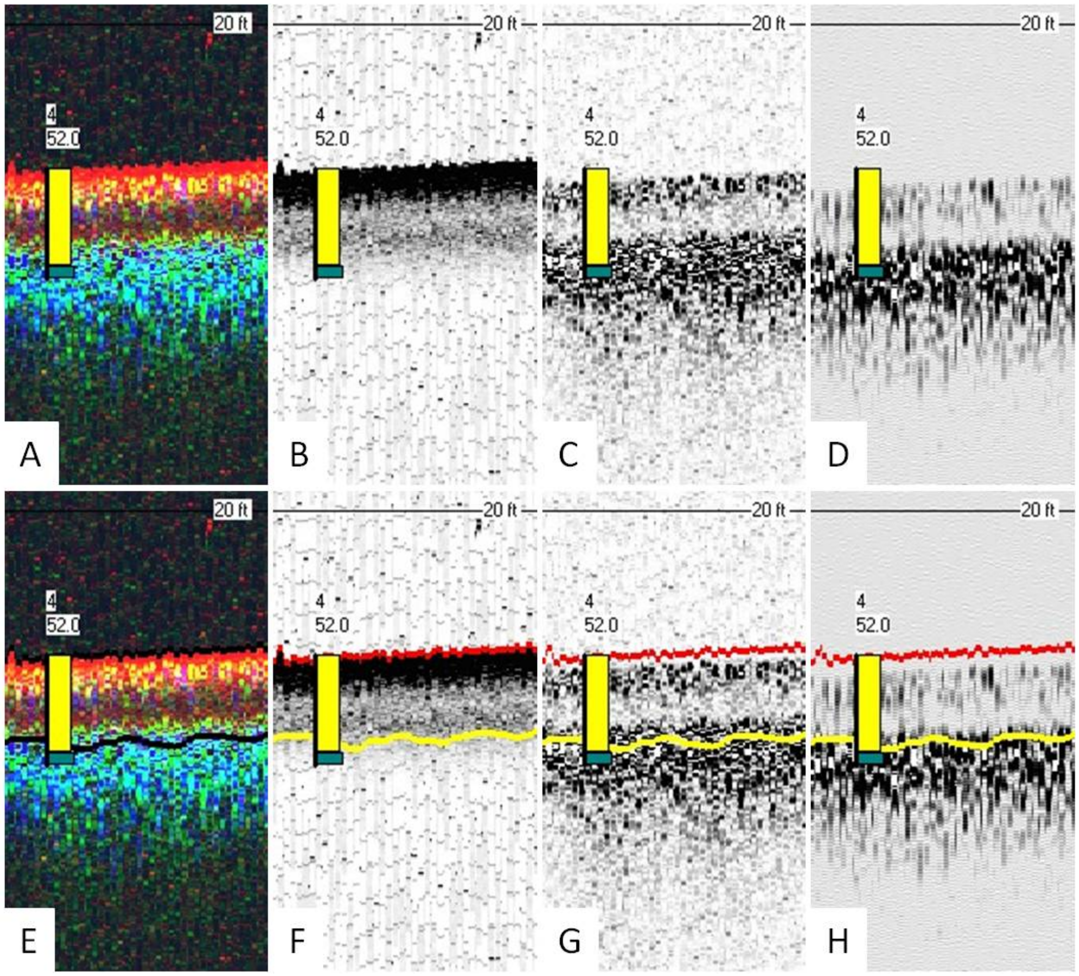

Figure 8. **Comparison of sediment core W-4 with acoustic signal returns A,E) combined acoustic signal returns, B,F) 200 kHz frequency, C,G) 50 kHz frequency, D,H) 24 kHz frequency**

Figure 8 compares sediment core sample W-4 with the acoustic signals for all frequencies combined (A, E), 200 kHz (B, F), 50 kHz (C, G), and 24 kHz (D, H). The sediment core sample is represented in each figure as colored boxes. The yellow box represents post-impoundment sediment, and the blue box represents the pre-impoundment sediment. In figure 8A-D, the bathymetric surfaces are not shown. In figure 8E, the current bathymetric surface is represented as the top black line and in Figures 8 F-H as the top red line. The pre-impoundment surface is identified by comparing boundaries observed in the 200 kHz, 50 kHz and 24 kHz signals to the location of the pre-impoundment surface of the sediment core sample. Each sediment core sample was compared to all three frequencies. The boundary in the 200 kHz signal most closely matched the pre-impoundment interface of the sediment core samples. Therefore the 200 kHz signal was used to locate the pre-impoundment layer.

TWDB used an algorithm based on the intensity of the acoustic returns of the 200 kHz frequency to select the pre-impoundment surface. Using the cumulative distribution of the signal intensity for each acoustic sounding, the location of the pre-impoundment surface was selected as the location in the cumulative distribution above which 95 percent of the reflected intensity was found. Each profile was visually inspected to verify the surface was selected as expected. DepthPic was used to manually edit the surface where this technique was unable to accurately locate the surface, for example, in shallow vegetated areas, and steep slopes such as those found in river channels. The pre-impoundment surface is represented by the bottom black line in Figure 8E, and by the yellow line in Figures 8F-H. Figure 9 shows sediment core sampleW-4 correlated with the 200 kHz frequency of the nearest surveyed cross-section. The pre-impoundment surface identified along cross-sections where sediment core samples were collected is used as a guide for identifying the pre-impoundment surface along cross-sections where sediment core samples were not collected.

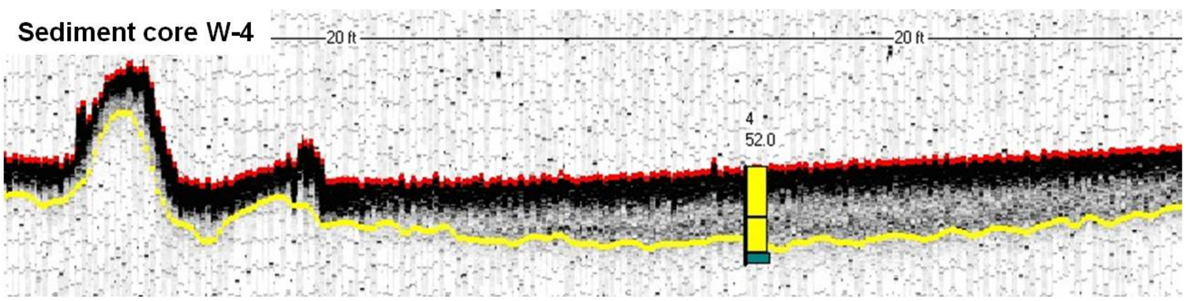

Figure 9. **Cross-section of data collected during 2011 survey, displayed in DepthPic (200 kHz frequency), correlated with sediment core sample W-4 and showing the current surface in red and pre-impoundment surface in yellow**

After the pre-impoundment surface from all cross-sections was identified, a sediment thickness TIN model is created following standard GIS techniques (Furnans, 2007). Sediment thicknesses were interpolated between surveyed cross-sections using HydroTools with the same interpolation definition file used for bathymetric interpolation. For the purposes of the TIN model creation, TWDB assumed sediment thickness at the reservoir boundary was zero feet (defined as the 462.0 foot NGVD29 elevation contour). The sediment thickness 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 of Waco Lake (Figure 10).

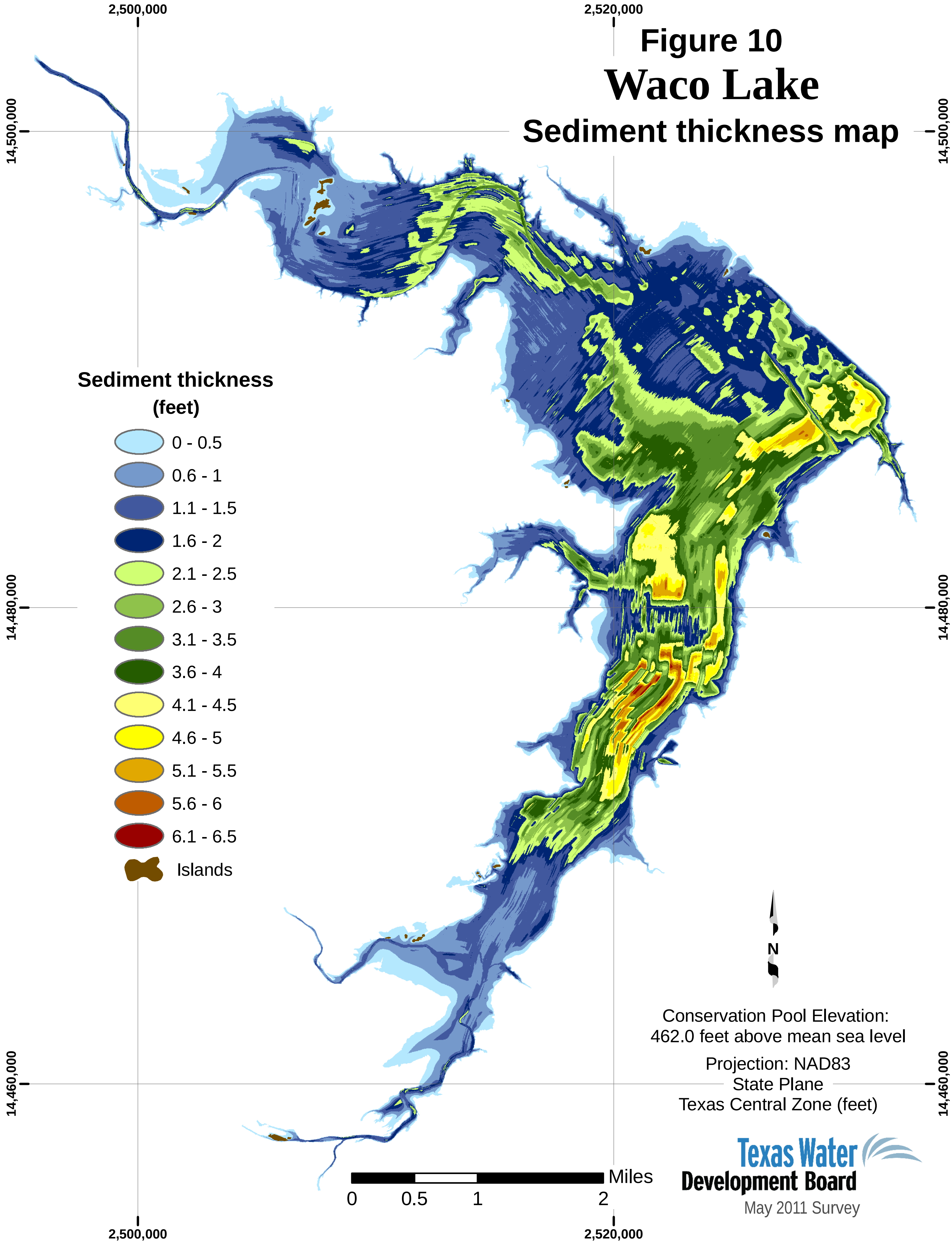

Figure 10
Waco Lake
Sediment thickness map
2,500,000
2,520,000
14,500,000
14,480,000
14,460,000
Sediment thickness
(feet)
0 - 0.5
0.6 - 1
1.1 - 1.5
1.6 - 2
2.1 - 2.5
2.6 - 3
3.1 - 3.5
3.6 - 4
4.1 - 4.5
4.6 - 5
5.1 - 5.5
5.6 - 6
6.1 - 6.5
Islands
N
Conservation Pool Elevation:
462.0 feet above mean sea level
Projection: NAD83
State Plane
Texas Central Zone (feet)
Miles
0
0.5
1
2
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Survey results

Volumetric survey

The results of the 2011 TWDB volumetric survey indicate Waco Lake has a total reservoir capacity of 189,773 acre-feet and encompasses 8,190 acres at conservation pool elevation (462.0 feet above mean sea level, NGVD29).

Previous capacity estimates of Waco Lake at the original conservation pool elevation of 455.0 feet include the original U.S. Army Corps of Engineers 1962 capacity estimate of 152,500 acre-feet and a U.S. Army Corps of Engineers 1970 resurvey of 149,189 acre-feet (USACE, 1970, TWDB, 1973). The results of the 2011 TWDB survey indicate Waco Lake has a current capacity of 135,508 acre-feet at elevation 455.0 feet. Differences in past and present survey methodologies make direct comparison of volumetric surveys difficult and potentially unreliable.

To properly compare results from TWDB surveys of Waco Lake, TWDB applied the 2012 data processing techniques to the survey data collected in 1995. Specifically, TWDB applied anisotropic spatial interpolation to the 1995 survey dataset using the same interpolation definition file as was used for the 2011 survey. A revised volumetric TIN model was created using the original 1995 survey boundary. The 1995 survey boundary was created from 7.5 minute USGS quadrangle maps, with a stated accuracy of ± 1/2 the contour interval (USBB, 1947). Revision of the 1995 survey using current TWDB data processing methods resulted in a volume of 145,532 acre-feet, a 702 acre-feet (0.5%) increase in reservoir capacity (Table 3).

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

Conservation pool elevation (feet above mean sea level)	Survey	Surface area (acres)	Capacity (acre-feet)
462.0	USACE 1962 [a]	8,437	199,227
	TWDB 2011	8,190	189,773
455.0	USACE 1962 [b]	7,270	152,500
	USACE 1970 [c]	7,237	149,189
	TWDB 1995	7,194	144,830
	TWDB 1995 revised	7,193	145,532
	TWDB 2011	7,020	137,022

[a] Source: (TWDB, 1973, USACE, 1970, USACE, 2012b)
[b] Source: (TWDB, 1973, USACE, 1970, USACE, 2012b)
[c] Source: (TWDB, 2003, USACE, 1970)

Sedimentation survey

Based on comparison of the 2011 TWDB survey with an extrapolation of the 1962 USACE survey data and on direct measurements of sediment accumulation, for estimating sedimentation rates, TWDB estimates, since 1965, Waco Lake loses between 206 and 334 acre-feet per year of capacity, respectfully, due to sedimentation below conservation pool elevation (462.0 feet above mean sea level) (Table 4). The sedimentation survey indicates sediment accumulation is greater in the South Bosque River branch of the reservoir than in the North Bosque River branch. Sediment accumulation is also greater near the dam on the South Bosque River side of the reservoir.

In principle, comparing reservoir volumes from multiple reservoir surveys allows for calculation of capacity loss rates. If all lost capacity is due to sediment accumulation, then comparisons of reservoir volumetric surveys would yield sediment accumulation rates. In practice, however, the differences in methodologies used in each reservoir survey may yield greater differences in computed reservoir 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.

Sedimentation rates were calculated based on the differences between the current volumetric survey and each of the previous USACE surveys as well as the revised 1995 TWDB capacity estimate. The original estimate, 1970 USACE estimate, and the revised 1995 estimate were compared at elevation 455.0 feet. The 2003 USACE capacity estimate was compared to the current TWDB survey at elevation 462.0 feet. The current capacity estimate and the 2011 pre-impoundment estimate were compared at both 455 feet and 462 feet (Table 4). Based on the 2011 estimated sediment volume, Waco Lake lost an average of approximately 334 acre-feet of capacity per year from 1965 to 2011 below conservation pool elevation (462.0 feet above mean sea level). Comparison of capacity estimates of Waco Lake derived using differing methodologies are provided in Table 4 for sedimentation rate calculation.

Table 4. Capacity loss comparisons for Waco Lake

Survey	Volume comparisons at 455.0ft (ac-ft)			Pre-impoundment at 455.0 ft (ac-ft)	Volume comparison at 462.0 ft (ac-ft)	Pre-impoundment at 462.0 ft (ac-ft)
USACE 1962[a]	152,500	<>	<>	<>	199,227	<>
USACE 1970[b]	<>	149,189	<>	<>	<>	<>
TWDB 1995 (revised)	<>	<>	145,532	<>	<>	<>
TWDB pre-impoundment estimate based on 2011 survey	<>	<>	<>	152,017[d]	<>	205,127[e]
2011 volumetric survey	137,022	137,022	137,022	137,022	189,773	189,773
Volume difference (acre-feet)	15,478 (10.1%)	12,167 (8.2%)	8,510 (5.8%)	14,995 (9.9%)	9,454 (4.7%)	15,354 (7.5 %)
Number of years	46	41	16	46	46	46
Capacity loss rate (acre-feet/year)	336	297	532	326	206	334

[a] Source: (TWDB, 1973, USACE, 1970, USACE, 2012b), note: Waco Dam was completed on June 24, 1965, and deliberate impoundment began on February 26, 1965.
[b] Source: (TWDB, 2003, USACE, 1970)
[d] 2011 TWDB surveyed capacity of 137,022 acre-feet plus 2011 TWDB surveyed sediment volume of 14,995 acre-feet
[e] 2011 TWDB surveyed capacity of 189,773 acre-feet plus 2011 TWDB surveyed sediment volume of 15,354 acre-feet

Recommendations

To improve estimates of sediment accumulation rates, TWDB recommends resurveying Waco Lake 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 Waco Lake.

TWDB contact information

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

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Appendix A

Waco Lake

RESERVOIR CAPACITY TABLE

TEXAS WATER DEVELOPMENT BOARD — May 2011 Survey

CAPACITY IN ACRE-FEET — Conservation Pool Elevation 462.0 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
385	0	0	0	0	0	0	0	0	0	0
386	0	0	0	0	0	0	0	0	0	0
387	0	0	0	0	0	0	0	1	1	1
388	1	1	1	2	2	2	3	3	3	4
389	4	5	5	6	6	7	7	8	9	9
390	10	11	12	12	13	14	15	16	17	18
391	19	20	21	22	23	24	25	26	27	28
392	30	31	32	33	34	36	37	38	40	41
393	42	44	45	47	48	50	52	53	55	57
394	59	60	62	64	66	68	70	71	73	75
395	77	79	81	83	85	87	90	92	94	96
396	98	101	103	105	107	110	112	114	117	119
397	122	124	127	129	132	134	137	139	142	145
398	147	150	153	156	158	161	164	167	170	173
399	176	179	181	184	188	191	194	197	200	203
400	206	209	213	216	219	222	226	229	232	236
401	239	243	246	250	253	257	260	264	267	271
402	275	278	282	286	290	293	297	301	305	309
403	313	317	321	325	329	333	337	341	345	350
404	354	358	362	367	371	376	380	385	389	394
405	398	403	408	412	417	422	427	432	437	442
406	447	452	457	462	468	473	478	484	489	495
407	500	506	512	518	523	529	535	542	548	554
408	561	568	575	582	589	597	605	612	620	629
409	637	646	654	663	672	682	691	701	711	721
410	731	742	753	764	775	787	798	810	822	834
411	846	858	870	882	895	907	920	932	945	958
412	971	984	997	1,010	1,023	1,037	1,050	1,064	1,077	1,091
413	1,105	1,119	1,133	1,147	1,161	1,175	1,189	1,204	1,218	1,233
414	1,248	1,263	1,277	1,293	1,308	1,323	1,338	1,354	1,370	1,386
415	1,402	1,418	1,434	1,450	1,467	1,483	1,500	1,517	1,533	1,550
416	1,567	1,585	1,602	1,619	1,637	1,655	1,672	1,690	1,708	1,726
417	1,744	1,763	1,781	1,800	1,818	1,837	1,856	1,875	1,894	1,913
418	1,933	1,952	1,972	1,991	2,011	2,031	2,051	2,071	2,092	2,112
419	2,133	2,154	2,175	2,196	2,218	2,239	2,261	2,284	2,306	2,329
420	2,353	2,377	2,401	2,425	2,450	2,476	2,502	2,528	2,556	2,584
421	2,613	2,643	2,673	2,705	2,737	2,770	2,803	2,838	2,874	2,912
422	2,951	2,991	3,034	3,078	3,124	3,172	3,222	3,274	3,328	3,385
423	3,445	3,511	3,580	3,653	3,728	3,807	3,889	3,975	4,064	4,158
424	4,257	4,359	4,467	4,578	4,693	4,813	4,936	5,063	5,194	5,329
425	5,468	5,610	5,757	5,907	6,061	6,218	6,380	6,545	6,713	6,886
426	7,062	7,243	7,426	7,613	7,803	7,995	8,190	8,386	8,584	8,784
427	8,986	9,189	9,394	9,600	9,808	10,017	10,228	10,440	10,653	10,868
428	11,085	11,303	11,522	11,744	11,967	12,191	12,416	12,643	12,871	13,101
429	13,332	13,565	13,799	14,036	14,275	14,516	14,759	15,004	15,251	15,501
430	15,754	16,009	16,267	16,529	16,794	17,061	17,332	17,605	17,881	18,161
431	18,444	18,729	19,018	19,309	19,602	19,899	20,198	20,499	20,803	21,110
432	21,419	21,731	22,046	22,363	22,683	23,005	23,329	23,657	23,986	24,317
433	24,651	24,986	25,323	25,662	26,003	26,347	26,693	27,040	27,389	27,740
434	28,093	28,447	28,803	29,161	29,520	29,881	30,243	30,607	30,973	31,340
435	31,709	32,079	32,451	32,824	33,199	33,576	33,954	34,334	34,715	35,098
436	35,482	35,868	36,255	36,643	37,033	37,424	37,817	38,211	38,606	39,003
437	39,401	39,801	40,202	40,605	41,009	41,414	41,821	42,230	42,640	43,051
438	43,464	43,878	44,293	44,710	45,128	45,548	45,970	46,393	46,817	47,243

Appendix A (Continued)

Waco Lake

RESERVOIR CAPACITY TABLE

TEXAS WATER DEVELOPMENT BOARD — May 2011 Survey

CAPACITY IN ACRE-FEET — Conservation Pool Elevation 462.0 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
439	47,671	48,100	48,530	48,963	49,397	49,832	50,269	50,708	51,148	51,589
440	52,033	52,478	52,924	53,372	53,822	54,273	54,726	55,181	55,637	56,096
441	56,555	57,017	57,480	57,945	58,411	58,879	59,349	59,819	60,292	60,766
442	61,241	61,719	62,197	62,678	63,159	63,643	64,128	64,616	65,105	65,595
443	66,088	66,582	67,079	67,576	68,076	68,577	69,080	69,585	70,091	70,599
444	71,109	71,620	72,132	72,646	73,161	73,678	74,196	74,716	75,237	75,759
445	76,283	76,808	77,334	77,862	78,391	78,921	79,453	79,986	80,520	81,056
446	81,594	82,133	82,673	83,214	83,757	84,301	84,846	85,393	85,941	86,491
447	87,042	87,595	88,149	88,705	89,262	89,821	90,381	90,943	91,506	92,072
448	92,639	93,208	93,778	94,350	94,924	95,499	96,076	96,654	97,235	97,817
449	98,400	98,986	99,573	100,162	100,753	101,346	101,941	102,538	103,136	103,737
450	104,340	104,944	105,551	106,160	106,770	107,383	107,998	108,614	109,233	109,854
451	110,478	111,103	111,731	112,361	112,992	113,626	114,261	114,899	115,538	116,180
452	116,823	117,468	118,116	118,765	119,416	120,069	120,724	121,381	122,040	122,701
453	123,364	124,029	124,696	125,365	126,035	126,708	127,382	128,058	128,736	129,416
454	130,099	130,783	131,469	132,156	132,846	133,537	134,230	134,925	135,622	136,321
455	137,022	137,725	138,430	139,136	139,843	140,553	141,264	141,976	142,690	143,405
456	144,122	144,840	145,559	146,279	147,001	147,725	148,450	149,176	149,903	150,632
457	151,362	152,093	152,826	153,561	154,296	155,034	155,772	156,512	157,254	157,997
458	158,741	159,487	160,234	160,982	161,732	162,484	163,237	163,991	164,747	165,504
459	166,263	167,023	167,784	168,547	169,312	170,078	170,846	171,615	172,386	173,158
460	173,932	174,708	175,485	176,264	177,044	177,827	178,610	179,396	180,183	180,972
461	181,763	182,556	183,350	184,146	184,944	185,744	186,546	187,350	188,156	188,963
462	189,773									

Appendix B

Waco Lake

RESERVOIR AREA TABLE

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

May 2011 Survey
Conservation Pool Elevation 462.0 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
385	0	0	0	0	0	0	0	0	0	0
386	0	0	0	0	0	0	0	0	0	0
387	0	0	0	1	1	1	1	1	1	2
388	2	2	2	3	3	3	3	4	4	4
389	4	5	5	6	6	6	6	7	7	7
390	7	8	8	8	8	9	9	9	9	10
391	10	10	10	10	11	11	11	11	11	12
392	12	12	12	12	12	13	13	13	14	14
393	14	15	15	16	16	16	17	17	17	17
394	18	18	18	18	19	19	19	19	19	20
395	20	20	20	21	21	21	21	21	22	22
396	22	22	23	23	23	23	24	24	24	24
397	25	25	25	25	25	26	26	26	26	27
398	27	27	27	28	28	28	28	29	29	29
399	29	30	30	30	30	31	31	31	31	32
400	32	32	32	33	33	33	33	33	34	34
401	34	34	35	35	35	36	36	36	36	37
402	37	37	37	38	38	38	38	39	39	39
403	40	40	40	40	41	41	41	42	42	42
404	43	43	43	44	44	44	45	45	46	46
405	46	47	47	48	48	49	49	50	50	51
406	51	51	52	52	53	53	54	55	55	56
407	56	57	57	58	59	60	61	63	64	66
408	67	69	71	73	75	76	77	79	81	83
409	85	86	88	90	92	94	96	98	100	103
410	106	108	110	112	113	115	116	117	118	120
411	121	121	122	123	124	125	126	127	128	129
412	130	131	131	132	133	134	135	136	137	137
413	138	139	140	141	142	143	144	145	146	147
414	148	149	150	151	152	154	155	157	158	159
415	160	161	162	164	165	166	167	168	169	170
416	171	172	174	175	176	177	178	179	180	181
417	183	184	185	186	187	188	189	190	192	193
418	194	195	196	197	199	200	201	203	205	206
419	208	210	212	214	216	218	222	226	229	232
420	235	239	243	247	253	258	264	270	278	286
421	294	302	309	316	324	334	344	355	367	381
422	397	416	434	451	469	488	507	529	556	587
423	629	671	711	743	773	805	837	876	918	961
424	1,005	1,050	1,092	1,132	1,175	1,215	1,254	1,291	1,328	1,366
425	1,407	1,448	1,484	1,519	1,555	1,595	1,632	1,669	1,704	1,745
426	1,785	1,821	1,852	1,885	1,912	1,933	1,952	1,973	1,992	2,009
427	2,025	2,040	2,056	2,071	2,085	2,098	2,112	2,127	2,142	2,159
428	2,174	2,188	2,204	2,220	2,236	2,248	2,261	2,275	2,289	2,303
429	2,319	2,336	2,357	2,378	2,399	2,419	2,441	2,463	2,487	2,511
430	2,537	2,569	2,601	2,632	2,662	2,690	2,717	2,749	2,781	2,811
431	2,841	2,869	2,898	2,924	2,950	2,976	3,003	3,029	3,054	3,080
432	3,105	3,133	3,160	3,184	3,209	3,234	3,260	3,282	3,303	3,323
433	3,343	3,363	3,382	3,402	3,423	3,446	3,466	3,483	3,502	3,519
434	3,535	3,552	3,568	3,585	3,601	3,616	3,632	3,647	3,664	3,679
435	3,696	3,712	3,727	3,742	3,756	3,772	3,788	3,804	3,821	3,836
436	3,851	3,864	3,877	3,891	3,906	3,919	3,932	3,947	3,961	3,975
437	3,990	4,005	4,019	4,033	4,048	4,061	4,078	4,093	4,107	4,120
438	4,133	4,147	4,162	4,176	4,191	4,207	4,223	4,237	4,252	4,267

Appendix B (Continued)

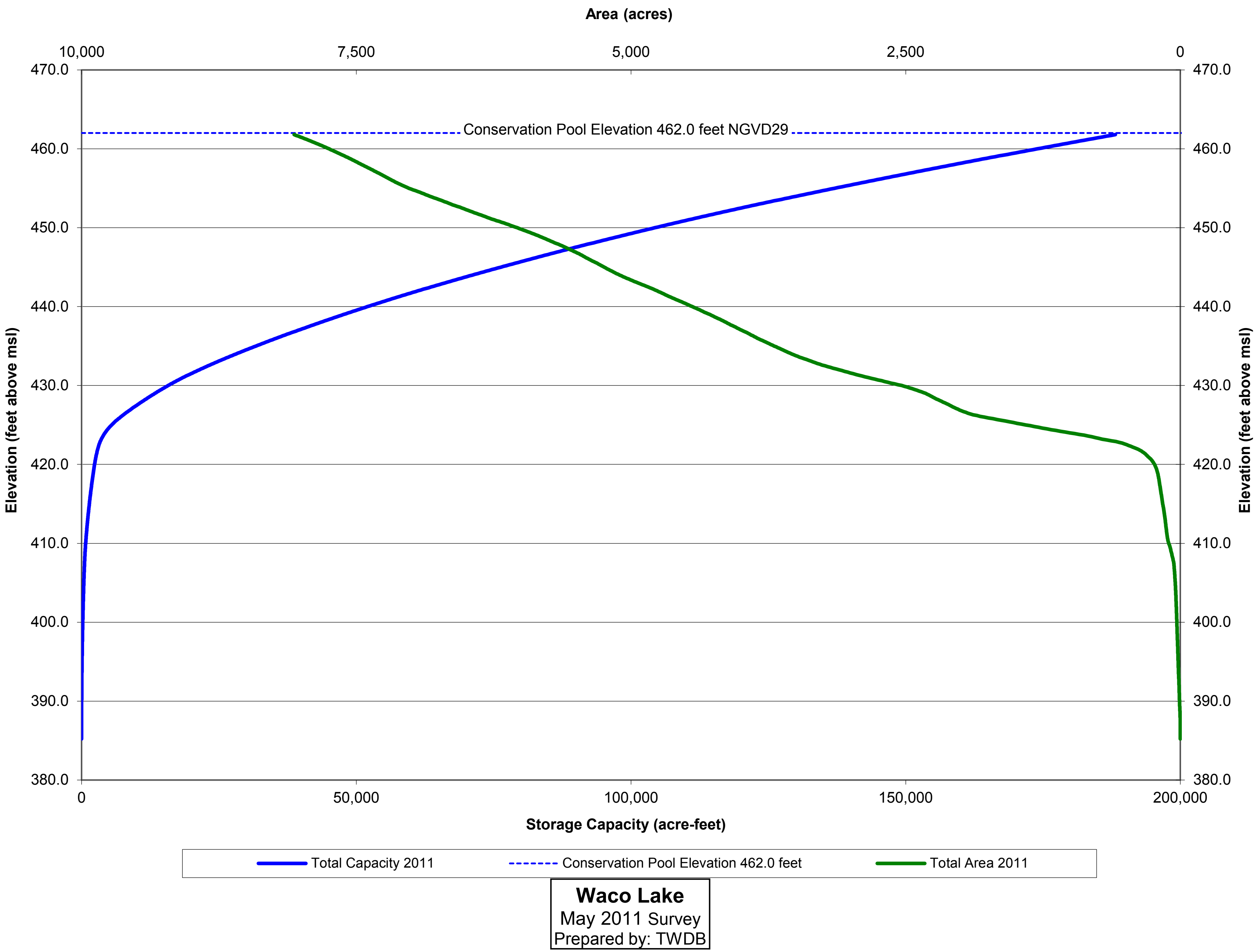
Waco Lake

RESERVOIR AREA TABLE

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

May 2011 Survey
Conservation Pool Elevation 462.0 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
439	4,282	4,298	4,316	4,332	4,347	4,362	4,377	4,392	4,408	4,425
440	4,442	4,457	4,474	4,490	4,505	4,522	4,539	4,556	4,573	4,589
441	4,606	4,623	4,640	4,656	4,672	4,686	4,701	4,716	4,732	4,748
442	4,764	4,780	4,795	4,811	4,827	4,845	4,862	4,881	4,899	4,917
443	4,934	4,953	4,971	4,987	5,004	5,021	5,038	5,056	5,072	5,087
444	5,103	5,118	5,133	5,147	5,161	5,175	5,189	5,203	5,217	5,230
445	5,243	5,256	5,269	5,283	5,296	5,309	5,323	5,339	5,354	5,368
446	5,381	5,395	5,408	5,421	5,434	5,447	5,460	5,474	5,488	5,504
447	5,520	5,535	5,550	5,565	5,580	5,595	5,611	5,627	5,644	5,661
448	5,679	5,696	5,712	5,728	5,744	5,761	5,778	5,795	5,812	5,829
449	5,846	5,864	5,882	5,900	5,919	5,939	5,959	5,977	5,997	6,016
450	6,036	6,056	6,078	6,097	6,116	6,135	6,156	6,178	6,200	6,224
451	6,246	6,267	6,287	6,306	6,325	6,344	6,363	6,384	6,405	6,425
452	6,444	6,464	6,483	6,502	6,520	6,538	6,558	6,580	6,603	6,623
453	6,641	6,659	6,678	6,697	6,715	6,733	6,751	6,771	6,792	6,812
454	6,832	6,850	6,868	6,885	6,903	6,921	6,940	6,961	6,982	7,002
455	7,020	7,036	7,052	7,069	7,085	7,101	7,116	7,131	7,145	7,159
456	7,173	7,187	7,200	7,213	7,227	7,240	7,253	7,267	7,281	7,295
457	7,309	7,323	7,336	7,350	7,365	7,379	7,393	7,408	7,422	7,436
458	7,450	7,464	7,479	7,493	7,507	7,521	7,536	7,550	7,565	7,579
459	7,594	7,609	7,624	7,639	7,654	7,669	7,685	7,700	7,716	7,732
460	7,748	7,764	7,780	7,797	7,813	7,830	7,847	7,864	7,882	7,899
461	7,917	7,935	7,953	7,972	7,990	8,009	8,028	8,047	8,067	8,086
462	8,190									

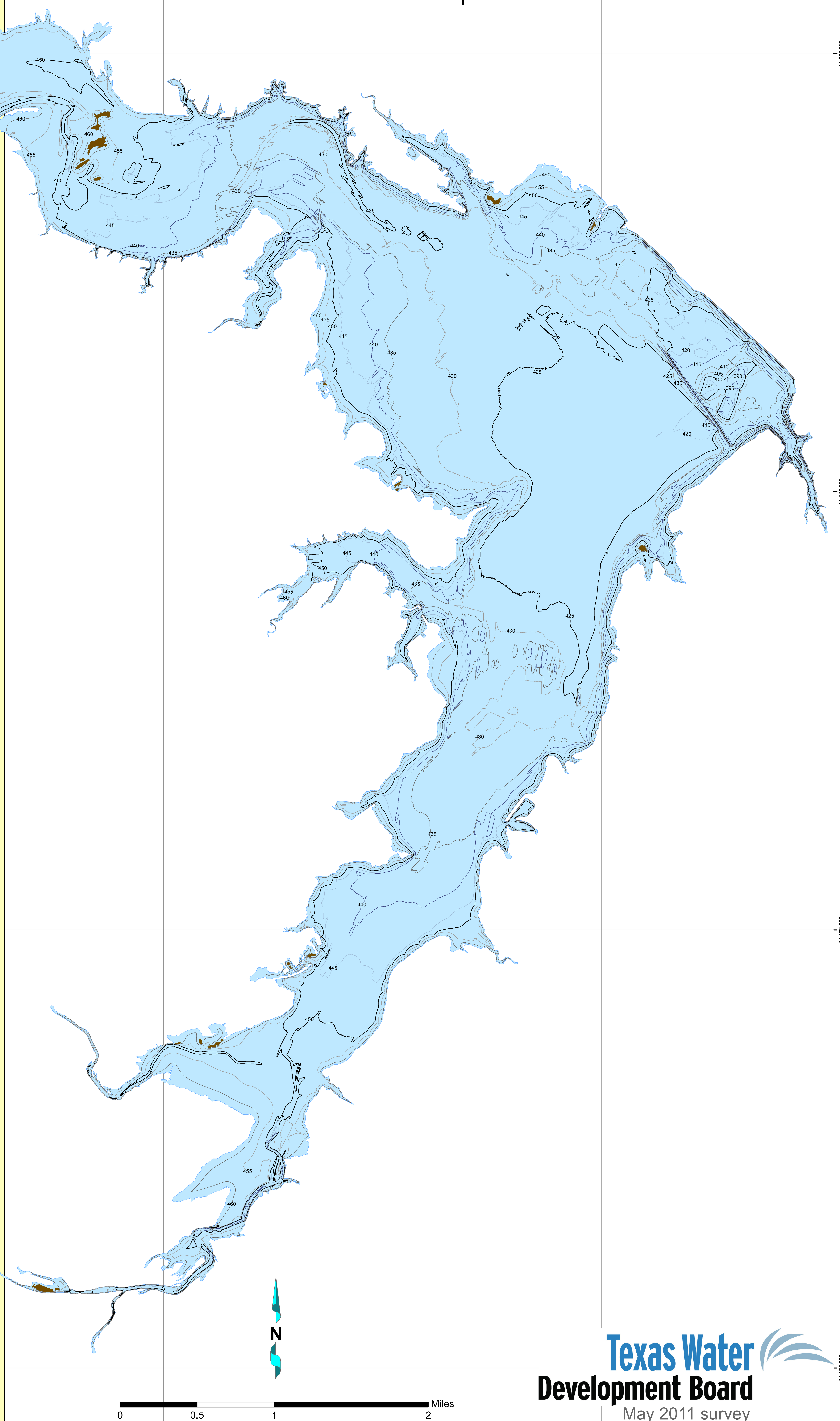


Appendix C: Area and Capacity Curves

Figure 5

Waco Lake

5' - contour map



CONTOURS
(feet above mean sea level)

- 460
- 455
- 450
- 445
- 440
- 435
- 430
- 425
- 420
- 415
- 410
- 405
- 400
- 395
- 390

Islands

Waco Lake

Conservation Pool Elevation:
462.0 feet above mean sea level

Projection: NAD83
State Plane
Texas Central Zone (feet)

McLennon County

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

Texas Water Development Board
May 2011 survey